

## SIMULATION AND ANALYSIS OF THE LUNAR ROCK DRILLING PROCESS IN A COMPLEX LUNAR ENVIRONMENT

by

**Jin-Feng CAO<sup>a</sup>, Wen-Jie LIU<sup>a</sup>, Xi-Long LIU<sup>a</sup>, Hai-Chun HAO<sup>b,\*</sup>,  
Yuan-Bo ZHANG<sup>a</sup>, Yu-Hang SUN<sup>a</sup>, Bo-Yuan HUANG<sup>a</sup>, and Zhao-Yang LI<sup>a</sup>**

<sup>a</sup> School of Mechanical and Automotive Engineering,  
Qingdao University of Technology, Qingdao Shandong, China

<sup>b</sup> State Key Laboratory of Intelligent Construction and Healthy Operation and Maintenance of  
Deep Underground Engineering, College of Civil and Transportation Engineering,  
Shenzhen University, Shenzhen, Guangdong, China

Original scientific paper  
<https://doi.org/10.2298/TSCI2502333C>

*Deep lunar drilling is an effective means of obtaining complete lunar profile samples and high quality exploration data, which is of great historical importance in promoting the development of China's lunar exploration. In this work, a finite element model of moonstone is constructed and a simulation study of drilled moonstone is carried out. In addition, the Drucker-Prager model to describe the intrinsic properties of moonstone is selected, based on the Abaqus finite element software, to complete the numerical simulation of lunar rock cutting by setting different drill feed rates to study their effects on the drill rock fracturing process. The simulation results show that at constant speed, the drilling displacement increases with increasing feed rate. To avoid a drill stop, it must be ensured that the feed speed is at least above 1.6 mm per second. The simulation results show that the drilling offset increases with increasing feed rate.*

Key words: lunar drilling, drilling through rock, feed rate, numerical simulation

### Introduction

The Moon is the closest natural satellite to Earth with unique physical resources, strategic location and unique environmental conditions, and has become the *frontier* for human space exploration [1-3]. It has been shown that the Moon's mineral resources are mainly concentrated in lunar rocks at a depth of 10-15 m below the lunar surface [4, 5]. However, the deepest lunar samples to date have only reached a depth of 3.05 m and did not touch the deep lunar rock [6]. Due to the high cost and difficulty of conducting lunar rock drilling experiments under simulated extreme lunar environmental conditions, it is particularly necessary and important to perform numerical simulation calculations.

In recent years, scientists have conducted extensive research into drilling and coring moonstones. Hao *et al.* [6] analyzed and selected the thermophysical properties of in situ preserved lunar rock analogue samples in the extreme lunar environment, and the results showed that the samples can be used as Earth analogues of lunar rocks. Cui *et al.* [7] used a discrete element method to thermally simulate the drilling of lunar rock simulants, and the simulation

\* Corresponding author, e-mail: haohaichun311@163.com

results showed that in the vacuum simulation, the lunar soil temperature during drilling was much lower than that of the lunar rock simulation, and the lunar soil simulation had less impact on the heat dissipation of drilling tools. Tang *et al.* [8] used a discrete element method to simulate the cutting load characteristics of moonstone and confirmed the existence of a dense core region in the cutting and crushing process of moonstone. Song [9] used the discrete element method to build a simulation model for moonstone drilling, to analyze the influence of the shape, position and size of moonstone on the performance in the drilling process, and to provide a basis for real-time monitoring and control create the drilling process. Wang [10] simulated the crushing of moonstone based on LS-DYNA carbide drill and studied the block size distribution of moonstone after crushing and the crushing area. Li [11] constructed a discrete element simulation model for orthogonal/dimensional cutting and crushing of simulated moonstone, and determined the crushing behavior of simulated moonstone and its loading characteristics in rotary/percussion drilling mode. Zhou *et al.* [12] developed a new auxiliary method for rock fracturing, laser rock fracturing, and experimentally found that this method can significantly reduce the strength of lunar rocks and has obvious effects on improving the efficiency of lunar rock fracturing and reducing in situ disturbance. Wu *et al.* [13] proposed a method for calibrating the parameters of lunar rock analogues in DEM, which is of great importance in providing a basis for core drilling. For the area of terrestrial rocks, Gao *et al.* [14] developed a granite-based discrete element model to reveal the mechanical behavior and fracture mechanism of granite under microwave irradiation.

In summary, the special environment of the Moon, such as low temperature and microgravity, makes the test extremely difficult and expensive, and it is very important and necessary to use numerical simulation study the process and parameters of lunar rock drilling. However, most current studies use discrete elemental methods, and most experimental studies are conducted for moonstone analogs, and the studies mainly deal with cutting loads and thermal simulations. Because moonstone is a continuous medium, it is more appropriate to use the finite element method to simulate its core drilling process, and feed rate is one of the key factors in the success of moonstone drilling and core drilling. Therefore, in this paper, we chose the large-scale non-linear finite element analysis software ABAQUS [15] to simulate the drilling process in which the moonstone interacts with the drill bit and to study the influence of feed rate on the drilling process.

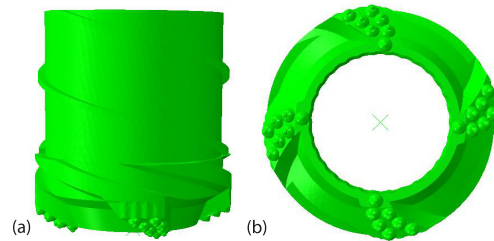
### Building simulation models

Diamond is an ideal material for drilling due to its excellent abrasion resistance [16, 17]. Therefore, diamond is used as drilling material in this work. Considering the strength theory and the damage criterion of moonstone, the Drucker-Prager criterion [18] is chosen as the intrinsic model of moonstone. The parameters of its mechanical properties are shown in tab. 1. Figure 1 shows the drill configuration.

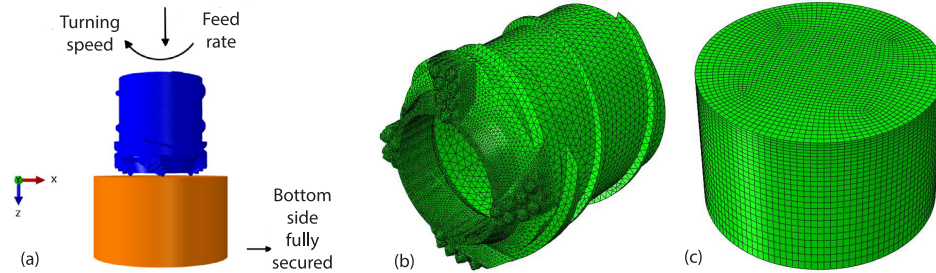
**Table 1. Mechanical parameters of drills and lunar rock [19]**

Material	Modulus of elasticity [MPa]	Poisson's ratio	Density [tonne per mm <sup>3</sup> ]	Drucker-Prager guidelines		
				Friction angle	Flow stress ratio	Expansion angle
Diamond	1000000	0.2	$3.5 \cdot 10^{-09}$	–		
Moonstone	41400	0.29	$3.3 \cdot 10^{-09}$	48°	0.8	48°

Figure 2 shows the geometric model, finite element model, and meshing of the drill bit and lunar rock created in this paper. Among them: the drilling network is divided into tetrahedral cells, the cell type is C3D4 and the number of cells is 155772. The moonstone is a cylinder with dimensions R40 mm × H50 mm, which is divided into ortho-hexahedral cells, the cell type of which is C3D8R and the number of cells is 53750. During the drilling process, the drill drills vertically into the rock, limiting its displacement in the *X*- and *Y*-directions and its rotation in the *X*- and *Y*-axes, but can still move in the *Z*-direction and rotate around the *Z*-axis.



**Figure 1. Drill configuration;**  
 (a) front view and (b) top view

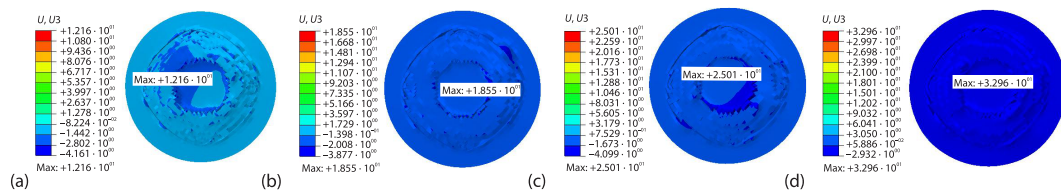


**Figure 2. Drills, lunar rock modelling and networking;**  
 (a) modelling the interaction between drill and rock, (b) meshing of the drill, and  
 (c) moonstone grid

### Analysis of the simulation results

Assuming that the drilling rotation speed is 110 rpm, four different feed speeds of 0.8 mm per second, 1.2 mm per second, 1.6 mm per second, and 2.2 mm per second are set to achieve the analyzed obtain results such as drill displacement and display the associated curves. and to derive the influence law of different feed rates on drilling moonstone.

At the same time of analysis (15 seconds), the results of the drilling displacement analysis with a diamond core bit are shown in fig. 3. It can be seen that the maximum drilling displacements are 12.16 mm, 18.55 mm, 25.01 mm, and 32.96 mm under four feed speeds.

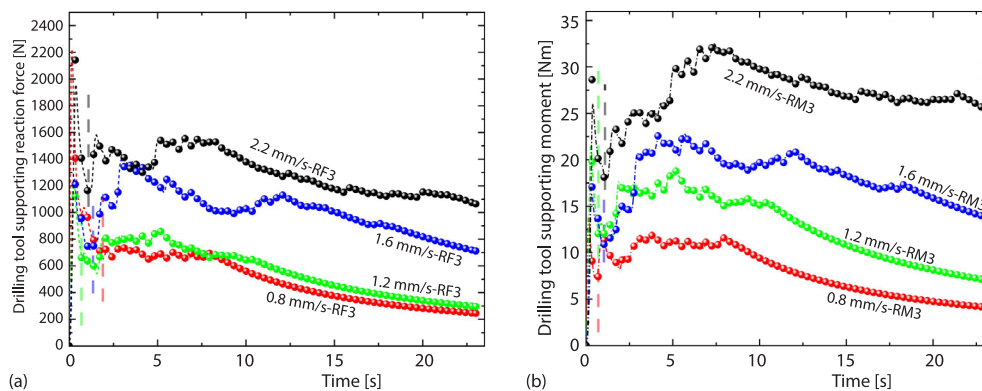


**Figure 3. Diamond bit drilling displacement analysis results;** (a) feed rate of 0.8 mm per second,  
 (b) feed rate of 1.2 mm per second, (c) feed rate of 1.6 mm per second, and  
 (d) feed rate of 2.2 mm per second

Figure 4 shows the curves of diamond bit supporting reaction force and supporting reaction moment vs. time, and it can be seen that:

- At a given speed of 110 rpm, both the bit supporting reaction force and supporting moment The reactionrque decreases gradually increases with increasing feed speed.
- When the feed rate is unchanged, the rule of time change of the support reaction force and support reaction moment can be divided into two-stages: unstable stage and stable stage.

For the unstable stage: the support reaction force and support reaction moment change drastically and the value increases rapidly. The reason is: when the drill touches the surface of the moonstone, it creates a large impact force. At this time, the branch reaction force and branch reaction moment increase rapidly in a short time when the two achieve a stable contact relationship. At this time, the branch reaction force and branch reaction moment are in a stable state. At this time, the drill penetrates the moonstone and the moonstone resistance to the drill remains stable, which is in line with the results of scientists' previous research [20]. At the stage when the values of support reaction force and support reaction moment are stable, the combined effect of feed speed and rotation speed is not enough to drill through the lunar rock, at this time the drill will stop feed, and the following may happen see: when the feed speed is lower than 1.6 mm per second, the diamond drill will stop drilling at a certain time.



**Figure 4. Course of the support reaction force and the support reaction moment over time during the drilling process; (a) curve of support reaction force vs. time and (b) variation curve of support moment vs. time**

## Conclusion

In this paper, for the main influencing factors of force loading when drilling deep lunar rocks in the complex environment of the Moon, a numerical simulation analysis of the process of crushing lunar rocks with a diamond drill is carried out based on the finite element software ABAQUS and the influence law. The influence of the Feed rate on the branch reaction force, branch reactionrque and drilling displacement is studied, and the conclusions of the study are at constant speed, the drilling displacement increases with increasing feed speed and drilling efficiency also improves with increasing feed speed. In moonstone drilling, the interaction between drill and moonstone is divided into an unstable phase and a stable phase, the former being the fluctuating phase in which the interaction between the two has just begun, and the latter being the stable phase, the drilling phase in which the two have a stable phase have established a contact relationship. The support reaction force and the support reaction moment increase as the feed rate increases. For the drill type selected in this paper, it should be ensured that the feed speed is not less than 1.6 mm per second to avoid drilling stop during the drilling process in lunar rock.

## Acknowledgment

The work was supported by the National Natural Science Foundation of China (Nos. 52225403, 52404365, 52434004), the National Key Research and Development Program of China (2023YFF0615404) and the Scientific Instrument Developing Project of Shenzhen University.

## References

- [1] Ouyang, Z. Y., *Introduction Lunar Science*, (in Chinese), China Astron Publishing House, Beijing, China, 2005
- [2] Xie, H. P., et al., Scheme and Design of a Lunar Large-Depth and in-Situ Condition-Holding Coring Robot System (in Chinese), *Adv. Eng. Sci.*, 52 (2020), 1, pp. 1-8
- [3] Xie, H. P., et al., Conceptualization of in-Situ Energy Support Technology on the Moon (in Chinese), *Adv. Eng. Sci.*, 52 (2020), 3, pp. 1-9
- [4] Li, R., et al., Preparation and Characterization of a Specialized Lunar Regolith Simulant for Use in Lunar Low Gravity Simulation, *International Journal of Mining Science and Technology*, 32 (2022), 1, pp. 1-15
- [5] Gao, N., et al., Recent Advance and Prospect of the Lunar Mineral Resources Exploration (in Chinese), *Mineralogical Review*, 42 (2022), 2, pp. 222-230
- [6] Hao, H. C., et al., Selection and Thermal Physical Characteristics Analysis of In-situ Condition Preserved Coring Lunar Rock Simulant in Extreme Environment, *International Journal of Mining Science and Technology*, 33 (2023), 11, pp. 1411-1424
- [7] Cui, J. S., et al., Thermal Simulation of Drilling into Lunar Rock Simulant by Discrete Element Method, *Acta Astronautica*, 160 (2019), July, pp. 378-387
- [8] Tang, D. W., et al., Numerical Simulation of Lunar Rock Simulant Cutting Load Based on Discrete Element Modelling and Experimental Validation (in Chinese), *Journal of Mechanical Engineering*, 52 (2016), 15, pp. 192-203
- [9] Song, J. W., Simulation Analysis on Lunar Drilling Power Dissipation Based on PFC3D (in Chinese), M. Sc. thesis, China University of Geosciences, Beijing, China, 2017
- [10] Wang, S., Analysis and Optimization on Cutting and Crushing Rock of Carbide Drill Based on LS-DYNA (in Chinese), M. Sc. thesis, China University of Geosciences, Beijing, China, 2016
- [11] Li, P., Research on Efficient Drilling Characteristic of Lunar Regolith Coring Bit With Low Acting Force (in Chinese), M. Sc. thesis, Harbin Institute of Technology, Harbin, China, 2017
- [12] Zhou, X. M., et al., Experimental Study on Characteristic and Mechanism of Simulated Lunar Rock Destruction Under High Energy Laser Irradiation, *Thermal Science*, 27 (2023), 1B, pp. 455-463
- [13] Wu, Y., et al., A DEM Parameters Calibration Method for 3-D Model of the Lunar Rock Based on the Approximate Model, *Engineering Analysis with Boundary Elements*, 156 (2023), 9, pp. 537-547
- [14] Gao, Y. N., et al., Mechanical Behavior and Fracture Characteristics of Granite Under Microwave Treatment Based on Continuous-Discrete Method (in Chinese), *Coal Journal*, 48 (2023), 2, pp. 693-713
- [15] Cao, J. F., *Common Issues and Practical tips for Abaqus Finite Element Analysis* (in Chinese), Beijing, China Machine Press, Beijing, China, 2020
- [16] Tang, F. L., et al., Analytical Research on Design of Diamond Drill Bit With the System Theory Approach, Exploration Engineering (in Chinese), *Rock and Soil Drilling and Tunneling*, 47 (2020), 1, pp. 13-19
- [17] Zhu, H. Y., *Research and Application of Diamond Bit for Deep Geological Drilling* (in Chinese), China University of Geosciences Press., Wuhan, China, 2014
- [18] Zhang, Z. Z., Study on Thermal Damage and Temperature and Field Thermal Stress Field of PDC Cutter Breaking Rock in High Temperature Formation (in Chinese), Ph. D. thesis, Jilin University, Jilin, China, 2021
- [19] Li, B. B., et al., The Drill Ability Research of Simulated Lunar Rocks Based on Physics and Mechanics Properties (in Chinese), Ph. D. thesis, China University of Geosciences, Beijing, China, 2017
- [20] Wang, J., et al., Ductile-Brittle Failure Transition of Rocks in Process of Drilling with High Confining Pressure: Model and Experiment, *Geoenergy Science and Engineering*, 223 (2023), 4, ID211505