Drilling and Migration Characteristics of Critical Size Lunar Soil Particles

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Abstract. Critical size lunar soil particles refer to particles with a particle size similar to the diameter of the drill bit, which is an important factor affecting lunar soil drilling sampling, and its influence is uncertain. In this paper, the discrete element method is used to simulate the drilling sampling process of the critical size lunar soil particles and the influence of the size, position and shape of the lunar particles with critical diameter on the drilling load is analysed. It is found that the critical size lunar soil particles have special migration trajectories and load characteristics during drilling sampling. The size and shape of lunar soil particles are the key factors affecting the drilling load. This study can support the design of drilling tools for lunar soil exploration and sampling.

Keywords: discrete element method; drilling sampling; lunar soil particles

1. Introduction
At present, the main task of the lunar exploration project is the sampling and return of lunar soil [1], in which drilling sampling is the preferred method to achieve lunar soil sample collection. Sampling drilling tools for lunar drilling are generally hollow spiral drilling tools, with a sampling port at the front of the drill bit [2]. In the early experiments, it was found that the lunar soil particles have a great influence on the sampling process, especially when the drilling tool encounters particles with a critical particle size close to the size of the drill bit, it will cause a large load change. In severe cases, it may cause the drilling load to exceed the driving capacity of the system. In addition, the large particles will block the sampling channel, making the lunar soil unable to enter the drilling tool, thus preventing sampling. In the former Soviet Union's Luna20 sampling activity [3], it also encountered stuck pipe conditions, which resulted in the drilling activity not reaching the expected target. It is judged that the failure is most likely caused by the blockage of the lunar soil particles of critical size.

There are two main types of simulation research on the drilling process of lunar soil, the finite element method and the DEM method. Quan et al. [4-5] studied the quasi-static stress distribution of the soil near the drill bit based on the finite element system. The finite element method cannot describe the rheological mechanical properties of lunar soil materials during drilling, so it is impossible to accurately simulate the characteristics of the actual lunar soil drilling force load. Wei et al. [6] used the DEM method to simulate the drilling process, and the obtained drilling pressure and torque increased with the increase of the drilling depth. The simulation did not consider the impact of the existence of critical particle size in the lunar soil. In this paper, the DEM method is used to study the impact of the critical particle size, shape and relative position on the drilling process, especially the drilling load.
2. Calibration of lunar soil mesoparameters

To establish a discrete element model [7] of lunar soil, in order to ensure that the model is close to lunar soil in mechanical properties, it is necessary to calibrate the meso parameters of the model. Use the bucket lifting method to carry out the stacking simulation test, and set the diameter range of the lunar soil particles to 0.1mm-1mm. As shown in Figure 1, the diameter of the drum is 50mm and the height is 100mm, and lunar soil particles are generated in the bucket. Lift the bucket at a speed of 0.1m/s, and measure the stacking angle after the lunar soil particles are stably accumulated on the bottom plate.

Since the main influencing factors of the static stacking angle of lunar soil particles are the inter-particle restitution coefficient, static friction coefficient and rolling friction coefficient, these three parameters are calibrated in this test, and other parameters remain unchanged during the test. According to Box-Behnken's central combination test, 17 sets of simulation tests are designed. The test result was subjected to multiple regression fitting analysis to obtain the regression model of lunar soil accumulation angle:

$$\Phi = 17 - 0.625A + 2.63B + 6.25C - 0.75AB - 0.5AC + 4.5BC - 0.875A^2 - 1.38B^2 + 1.37C^2$$

(1)

Where, $A$ is the restitution coefficient between lunar soil particles ($e$); $B$ is static friction coefficient between lunar soil particles ($\mu_s$); $C$ is rolling friction coefficient between lunar soil particles ($\mu_r$).

The predicted value of the multiple linear regression equation (1) using the stacking angle of the lunar soil is compared with the experimental value, as shown in Figure 2. It can be seen that the predicted value and the actual value have a good fit. The measured stacking angle of lunar soil can be used to inversely determine the mesoscopic parameters of lunar soil according to the regression equation.

![Figure 1. Simulation of stacking angle with bucket lifting method.](image1)

![Figure 2. Comparison between predicted and test value of lunar soil stacking angle.](image2)
In order to obtain the meso-parameters of the lunar soil particle interaction model in the DEM simulation, this study takes the CUG-1A lunar soil simulant as the object, and uses the bucket lifting method mentioned above to conduct a stacking angle experiment on the simulated lunar soil after drying. The average stacking angle of lunar soil was measured 5 times and the average value was 29°. A set of optimal solutions can be obtained as: $A=0.3$, $B=0.8$, $C=0.3$, and the mesoparameters of the discrete elements of lunar soil are shown in Table 1.

| Young's modulus(Pa) | Poisson’s ratio | Restitution coefficient ($e$) | Static-friction coefficient ($\mu_s$) | Rolling-friction coefficient ($\mu_r$) |
|---------------------|----------------|-------------------------------|--------------------------------------|--------------------------------------|
| $10^8$              | 0.5            | 0.3                           | 0.8                                  | 0.3                                  |

### 3. Simulation and analysis

#### 3.1. Drilling model

The critical particle size is defined as large particles with a diameter similar to the end size of the sampling tool. In this paper, the critical particle size is 10-20mm, which is similar to the drill bit size. Figure 3 shows three typical shapes of lunar rock samples: (a) spheroid, (b) angular and (c) elongated. In the simulation test, simulated particles of ellipsoid, tetrahedron and oblique body were established for the three lunar rocks.

![Figure 3](image-url)

**Figure 3.** Typical critical size particle morphology of lunar soil.

Figure. 4 shows the drilling model of critical size lunar soil particles. Lunar soil drilling conditions are: simulated drilling depth is 40 mm, feed rate is 60 mm/s, rotation rate is 1000 rpm, lunar soil barrel radius is the same as the influence domain radius, lunar soil particle radius is set to 0.5-0.15 mm, and generate critical particle size particles in the subsurface layer. Nine sets of experiments were designed to explore the effect of critical particle size, relative position and shape on drilling load. The detailed design scheme is as follows: (a) non-critical size particles, (b) spherical particles with a diameter of 10 mm at the center, (c) spherical particles with a diameter of 15 mm at the center, (d) spherical particles with a diameter of 20 mm at the center, (e) Spherical particles with a diameter of 15mm at a center offset of 7.5mm, (f) Spherical particles with a diameter of 15mm at a center offset of 15mm, (g) Oval particles with a center offset, (h) Tetrahedral particles with a center offset, (i) Hexahedral particles with a center offset.
Drill Lunar soil Critical size particle

3.2. The migration trajectory of critical size lunar soil particles

As shown in Figure 5, the movement trajectory of the critical size particles in each working condition during the drilling process. It can be seen that the flow characteristics of critical size particles during drilling are divided into three cases. The first is that the critical size particles smaller than the cutting circle are located directly in front of the drill bit and enter the sampling tube to produce spiral movement. The second is that the critical size particles larger than the cutting circle are located directly in front of the drill bit, and they will be stuck at the drill bit and move down with the drill bit. The third type is the critical size particles located on the side of the drill bit, which will move upward spirally after moving outward under the screw action of the drill.

Figure 5. The trajectories of critical size lunar soil particles with different shapes.

3.3. Critical scale lunar soil particle velocity analysis

Lunar soil particles will squeeze and slip during the drilling process, and eventually enter the sampling tube or be transported around the drilling tool. Figure 6 shows the speed curve of the critical size lunar soil particles during the drilling process with time. Obviously, the velocity of particles entering the sampling tube and being squeezed to the outer surface of the drill bit is generally larger. Figure 7 shows the Z-axis velocities of critical size lunar soil particles with three shapes. During the drilling process, the particles will be spirally moved upward by the surrounding particles.
3.4. Drilling load
Drilling load is an important indicator of the drilling process, including bit load and bit torque. Figure 8 shows the bit load under different critical particle size conditions. The smaller particle has little influence on the drilling load, and the feed force increases with the drilling depth. When the particle size increases to 15mm, the load increases significantly. When the particle size reaches 20mm, the bit load increases sharply, and severe sticking occurred. The relative position and shape have little effect on the drilling load. However, angular particles will amplify the fluctuation of drilling load. This is due to the fact that the particles with critical diameters are turned by the surrounding small particles during the drilling process, and the irregular shape causes uneven turning resistance, which leads to fluctuations in the bit load. It shows that the shape of particles with critical particle size will not affect the drilling load and its tendency but will cause jitter of the drilling tool.
During lunar drilling, if the drill bit is stuck or blocked, the torque of the drill bit will rise sharply. As shown in Figure 9, when 15mm and 20mm particles were placed in front of the drill bit, the drill bit blocked and the torque increased sharply. The size of the center-mounted particles is smaller than the cutting circle and offset particles of any size will not affect the bit torque. The shape of the critical size particles has no effect on the torque of the drill bit, but the more irregular the particles, the more obvious the fluctuation of the torque value.

4. Conclusion
In this paper, the discrete element method is used to simulate and analyse the drilling process of critical size lunar soil particles. According to the size, relative position and shape of the particles, 9 sets of simulation conditions were designed. By comparing the trajectory and load of particle velocity in each working condition, the conclusion is as follows. (1) The movement trajectory of critical size lunar soil particles during drilling is divided into two categories: one is that the particles move linearly with the drill bit during plugging, and the other is the spiral upward chip removal movement. (2) The critical size particles larger than the sampling port of the drill bit are easily stuck and blocked when the particle is directly in front of the drilling tool, and the load increases sharply. However, the particles smaller than the sampling port have no significant effect on the drilling load at any position. (3) Although the shape of the critical size particles is not affect the load and its trend, it will increase the fluctuation of the load curve and make the drill jitter.

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