Experiment on Particle Conveying Mechanism for Lunar Soil Containing Basalt Particles

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Abstract

Based on the analysis results of components and the particle diameter distribution of lunar soil, some basalt particles with different diameters are mixed into homogeneous soil to simulate the drilling process and particles conveying condition. Lunar soil containing basalt particles with different diameters can affect drilling process, penetration rate and conveying power consumption. The experiment results revealed that basalt particles move upward in an irregular spiral state during drilling; the basalt particles can convey smoothly and has little effect on drilling process, penetration rate and power consumption when the particle diameter is less than 5mm. The basalt particles can’t convey smoothly and has great effect on penetration rate and power consumption while particle diameter is bigger than 10mm. Particles in lunar soil will lead to torque increasing sharply and drilling pressure on bit adding to achieve continuous drilling.

Key words: Lunar Soil; Partical Conveying Mechanism; Basalt Particle Diameter; Penetration Rate

1. Introduction

The complexity features of lunar soil can affect particle conveying continuously and drilling process. The basalt particles sizes will decrease particle conveying continuity and reduce the reliability of drilling process. Jaffe, LD (1966) reported the maximum particle size near Surveyor 1 footpad can reach 10mm broken by the footpad movement \cite{1}. C Meyer(2009), Vinogradov AP (1971), Barsukov VL (1977), Nagle JS (1978) found the
existence of big particles when analyzing sample luna16, 20,24 and summarizing the relevant outcomes [2-7]. When summarizing the particle size in Apollo series of samples, Morris R V, et al (1983) found the density of big particles increased as the drilling depth increases [8].

Zhao Zeng (2012) took drilling experiment on three kinds of simulated lunar soil with different particle densities and different diameters particle to get reasonable drilling process parameters [9]. Iai, Masafumi (2010) added particles of 2-10mm in diameter into JSC-1A lunar soil to simulate the variety of the reacting force on the excavation tool, and found the sizes and the content of particles will greatly affect power consumption [10]. The particle diameters above experimental studies are less than 10mm, while particle diameters bigger than 10mm are not mention.

Based on the data analysis and research on lunar soil characteristic, experiments on homogeneous simulated lunar soil containing basalt particles (5 ~15mm) are carried out to obtain the particle conveying mechanism. The basalt particles diameter will influence the penetration rate, power consumption and drilling process. The experimental results will provide important basis for drilling parameters choice.

2. Experimental Apparatus and Program

2.1. Experimental Apparatus

The experimental apparatus consists of hydraulic system, power head and data acquisition system (Fig.1). The hydraulic system can controls weight on bit (WOB) and the vertical movement of the drilling rig. The power head which connected to the drilling rig can exert torque and WOB. Data acquisition system can collect the data of displacement, WOB and torque.

![Fig.1 Experimental Platform](image1)
![Fig.2 Drill Rod](image2)
![Fig.3 Core Bit](image3)

The drill rod used in the experiments is double screw (Fig.2). The screw parameters consist of core-hole diameter Φ19mm, inner diameter Φ24mm, outer diameter Φ28mm, pitch of screw 9mm, and the thickness of blade 1.5mm. The core bit used in experiments is shown as Fig.3.

2.2. The Preparation for Simulated Lunar Soil and Mechanical Parameters

Based on the physical and mechanical properties of lunar soil, main parameters of prepared simulated lunar soil are shown in Tab.1.

The ingredient of particle in lunar soil is similar to basalt, so we added some basalt particles into the prepared simulated lunar soil. The simulated lunar soil contains tiny basalt particles, shown as Fig.4. The shape of particles look like flat or strip, the maximum diameter is about 5-6mm. The basalt particle sizes added are 15mm (shown as Fig.5) or 10mm, most of the particles are flat and irregular prism, triangular pyramid, four-prism, pyramid, etc. For
the irregular prism, the maximum diameter range is 8-9mm, the minimum diameter range is 6-7mm, the range of ratio of the maximum diameter and the minimum diameter is 1.20-1.67. For irregular pyramid, the maximum diameter is 8-9mm, the minimum diameter approximately almost coincide at one point. The ratio of length and width ranges from 1.07 to 1.41.

Table 1. Simulated Lunar Soil Parameters

| Parameters                  | Value       |
|-----------------------------|-------------|
| Particle size range (mm)    | 0.01—5      |
| Cohesion (kpa)              | 1.46        |
| Density (g/cm³)             | 1.85        |
| Friction angle              | 30—42°      |
| Relative density            | 91%         |
| Moisture content            | 0.4%—0.6%   |

Fig.4 Basalt Particles in Nominal Regolith (5mm)  
Fig.5 Basalt Particle Diameter of 15mm

2.3. The Experimental Procedure

The simulated lunar soil were filled in a transparent tube which length is 1000mm, and 4-6 basalt particles which diameter is 10mm, 15mm were painted in green, white, yellow and so on, then buried them to the depth of 20cm, 40cm, 60cm in the transparent tube.

The maximum density of simulated lunar soil can reach 1.8348g/cm³ by the hammer and the vibrating table, which is close to the density of the nominal lunar soil. Some parameters of the nominal regolith are suitable for the simulated lunar soil containing basalt particles.

Before the experimentation, the transparent tube are fixed on the platform and level it to make sure the platform is horizontal and the axis of the transparent tube is in a straight line with the axis of drill rod. Drilling experiment are carried out in homogeneous simulated lunar soil, containing10mm particles and containing 15mm particle simulated lunar soil separately at a constantly rotary speed (100r/min). The drilling depth is 56.7cm and drilling time is 397s when drilling in the homogeneous simulated lunar soil. The drilling depth is 30.1cm and drilling time 205s when drilling the simulated lunar soil containing10mm particles in diameter. The drilling depth is 30cm and drilling time 162s when the simulated lunar soil containing 15mm particles in diameter.

3. The Experimental Results

3.1. The Experimental Results of Homogeneous Simulated Lunar Soil Drilling

The drilling experiments were carried out on the homogeneous simulated lunar soil, those curves of torque, WOB and displacement (shown as Fig. 6-7) could be obtained.
3.2. The Experimental Results of Drilling Lunar Soil Containing Basalt Particles

The drilling experiments were carried out on simulated lunar regolith containing 10mm and 15mm diameter particles separately, the curves of torque (shown as Fig.8), displacement (shown as Fig.9) and WOB (shown as Fig.10) varied with time can be obtained.
After drilling experiment, the particles which couldn’t be conveyed from the transparent tube were taken out (shown as Fig.11). The basalt particles 15mm couldn’t be crushed and were pressed into a deeper position in the tube, while some of the basalt particles 10mm were broken and conveyed (shown as Fig.12). The maximum diameter of the crushed particles was about 6mm, and the smaller pieces were 2-3 mm, their edges were sharper than before. The experiments show that basalt particles of 5mm in diameter in nominal regolith could be discharged smoothly, basalt particles of about 6mm seldom influence drilling process and conveying, some particles 10mm have little change and couldn’t be convey, shown as Fig.13.

![Fig.11 The Undamaged Basalt Granules](image1)

![Fig.12. The Broken Basalt Granules](image2)

![Fig.13 The Worn Basalt Granules](image3)

![Fig.14 The Irregular Spiral Scratches](image4)

When basalt particles were conveyed with lunar soil in tube, some discontinuous scratches were appeared on the inner wall of the transparent tube owing to the increased pressure between the inner wall and the drill rod. The scratches which marked in tube look like an irregular spiral (shown as Fig.14).

4. Analysis on Experimental Results

4.1. Analysis on Mechanism of Particle Conveying

According to the experimental results, we deduce that the particles about 5mm can be smoothly conveyed, the particles about 10mm may be conveyed and particles bigger than 10mm can be hardly to be conveyed. The experiment results are similar to the result which the particles collected by Luna 24, the maximum diameter of particles is 10mm. In addition, basalt particles which the maximum diameter is 10mm are selected to experiment by Zhao Zeng and Iai, Masafumi.
During the experiment, the larger basalt particles were broken and conveyed with lunar soil, as they were squeezed between the drill rod and the transparent tube, basalt particles left an irregular spiral scratches on the inner wall of the tube, as shown in Fig.14. The results indicate that real migration status of crushed basalt particles is irregular spiral, which is similar to the model of delivering soil on the earth.

4.2. The Effect of the Particle on Drilling Process Parameters

Comparing the WOB curve in Fig.6 with the curve in Fig.10, the increasing trend is similar overall. The density of lunar soil increases with drilling depth increases. The drilling needs to increase WOB to obtain stable penetration rate. However, in the case of the same drill depth (30cm), the WOB range of lunar soil containing basalt particles 15mm (shown as Fig.8) is 625N-714N, while the WOB range of homogeneous regolith (shown as Fig.6) is 100N-350N, the former is twice as much as the latter. It is obvious that simulated lunar soil containing basalt particles needs higher WOB. We can infer that the existence of basalt particles has a more important effect on WOB than the density increasing with depth.

Because of the existence of basalt particles, the WOB curve of the simulated lunar soil containing particles changes in every range of time. When bit encountered basalt particles during drilling, the bit will slip on the basalt particles if WOB wasn’t enough to crush these basalt particles, the WOB curve appears a line of displacement stagnation. Therefore, the drilling process needs to increase WOB properly, but it will lead to the increase of power consumption, while the smaller WOB may not be able to meet the requirement of the penetration rate.

The torque curve of homogeneous lunar soil shows an increasing trend overall, this is because the density increases along with the increase of depth; while the torque curve in Fig.10 can be taken as a horizontal straight line when drilling lunar soil containing particles 5mm under the condition of the similar variation of WOB in Fig. 6. It’s obvious that among the factors affecting the torque, the effect of particle diameter is greater than of the increasing density. The torque of homogeneous regolith ranges from 10Nm to 20Nm, while drilling lunar soil containing particles 5mm, 10mm and 15mm, their torque peak value are about 50Nm, 55Nm and 60Nm. The increase of particles diameter will increase torque and the torque peak value of lunar soil containing larger particles is 2-3 times than value of the homogeneous simulated lunar soil.

4.3. The Effect of the Particle on Penetration Rate and Power Consumption

The displacement curve of homogeneous simulated lunar soil in Fig.7 appears an approximately straight line, indicating the penetration rate was constant. The drilling depth is 56.7cm and drilling time is 397s, and the average drilling speed is 0.143cm/s. The horizontal lines in Fig.9 indicate no increase in displacement, its average penetration rate of lunar regolith containing particles 15mm is 0.185cm/s, illustrating that need a higher penetration rate to prevent the drilling rig from stagnation and sticking. The average penetration rate is 0.221cm/s before encountering the particles 15mm, contrasting with the average penetration rate-0.185cm/s, illustrates that bigger particles will decrease the penetration rate.

Comparing with the two displacement curves in Fig.9, we can find the displacement curve of lunar soil containing particles 15mm has more obvious stagnation than the 10mm’s, reflecting the bigger particle has more obvious impediment to the penetration rate. The drilling rig encountered the basalt particles around 22cm depth in both of the two experiments, and when the depth increased from 21cm to 22cm, WOB of lunar soil containing particles 15mm changes from 680N to 691N in 22s, while WOB ranges from 683N to 692N in 10s when drilling lunar regolith containing particles 10mm, the former penetration rate is as twice as the latter. So we can make a conclusion that the existence of particles will greatly affect the penetration rate.

The conveying power consumption curves of lunar soil containing particles 15mm and homogeneous lunar soil shown as Fig.15. By comparing the two power consumption curves, it is easy to find that the particles greatly increase power consumption, the peak value of power consumption of lunar soil containing particles is about 3 times higher than homogeneous simulated lunar soil, even doubling the drilling depth of homogeneous lunar soil, the peak value of power consumption is still half of the former.
5. Conclusions

(1) The basalt particles in the simulated lunar soil rise spirally during drilling process, which meets with migration status of spiral particle conveying, the conveying mechanism is similar to the model of delivering soil on earth.

(2) On the simulated experimental conditions, the particles less than 5mm can be directly conveyed without being broken; particles 10mm have a possibility of being conveyed; particles bigger than 10mm are difficult to be broken and conveyed.

(3) When drilling into the same depth of simulated lunar soil containing particles, the highest WOB is about 2 times and the biggest torque is about 2-3 times comparing with drilling homogeneous simulated lunar soil. When drill bit encounters basalt particles, increasing WOB appropriately to break up the particles is needed, but it will lead to the increase of power consumption.

(4) When drilling simulated lunar regolith containing particles, the larger particles (15mm) can lead to lower displacement and penetration rate, and the average penetration rate decreased from 0.221cm/s to 0.185cm/s. The particles will lead to the power consumption greatly increase, and the power consumption can reach 2-3 times as drilling into homogeneous simulated lunar soil.

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