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Study on Auger Drilling Technology for Sampling Drilling in the Lunar Stimulants

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Abstract

Under the limitation of rockets carrying capacity, the rated torque and power offered by drilling rigs, Therefore, the optimizations of auger driller's structure size and drilling parameters are necessary to realize deep lunar coring drilling under qualified condition. Study results indicate that the bit inner diameter is determined by target sampling mass and the density of drilling objects. Outer diameters of the bit and the helical blades are determined by the required power and torque for auger driller's restart from its state buried. To utilize the accommodated capacity of cuttings and dissipating the heat produced by bit during drilling process as much as possible, the lead angle is recommended to be 15°~20°. The helical blade width should be obtained after other drill pipe parameters are determined. Feeding rate should be determined at first, and rotation speed is decided by the auger driller's structure size and feeding rate. Rotational speed will be enough as long as it can satisfy the normal discharge of the cuttings, otherwise its increasing would significantly increase drilling power.

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Keywords: Drilling Parameters; Bit Optimization; Auger Driller; Lead Angle

1. Introduction

Man-made earth satellite, manned space flight and deep space exploration are the three main fields of aerospace activity. Because the Moon is the nearest celestial body from the Earth, lunar exploration is the first steep for human

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to stride out the Earth cradle and to achieve deep space exploration [1]. Similar to Mars and comet, lunar surface has a series of particular characteristics, such as high vacuum, low gravity acceleration, strong radiation, and huge difference of temperature between day and night. Lunar sampling drilling has followed difficulties compared with earth drilling [2-3]. Firstly, because of the limited carrying capacity of rocket, drilling tools has particular characteristics of small rated power and torque, as well as the diminutive size and light mass. Secondly, since lunar surface is not available to get drilling fluid like earth drilling, methods of how to achieve normal cuttings transportation and cooling the drill bit should be taken full account to ensure consistent drilling. Thirdly, lunar surface is under low gravity environment, the gravitational acceleration on it is only one-sixth of on earth surface. Thus, auger driller's dead weight is too light to offer the needed drilling pressure during lunar drilling, and the smallest additional drilling pressure should be taken into account. Fourth, there is a loose powder lunar soil layer with thickness of 1 to 20 meters on lunar surface, should consider how to achieve loose stratum coring drilling and samples return. Due to its continuity of transportation of soil as well as the high efficiency of construction, auger drilling is widely used in pile foundation engineering [4], geological sampling for sand soil, and even regarded as one of the best drilling approaches for space sampling [5].

2. Application of Auger Driller in Space Drilling

In the achieved lunar exploration drilling tasks, the United States astronauts on the Apollo 15, 16 and 17 had operated rigs for deep sampling drilling on lunar surface. The rigs employed were combination of "core tube with outer spiral and sampling unit + carbide bit" [6]. Material for drill pipe was titanium alloy, and material for drill bit was low-alloy high-strength steel which brazed with tungsten carbide blades. In the automatic sampling drilling tasks of Soviet's the Luna 16, 20 and 24 lunar explorations, the employed drill rigs combination was "hollow auger driller and its matched device + carbide bit" [7-8]. Under the premise analysis of lunar surface environment and existed drilling technology, researcher of the Chinese Academy of Space Technology determined a dry-type rotary drilling technology [9-10]. In this drilling method, hollow auger driller was used for cuttings transportation, while soft bag was used for automatic sampling recovery.

In addition to lunar exploration, considerable research works have been carried out towards Mars, comets and other celestial bodies in recent years. The Honeybee Robotics team and NASA have developed a Mars automatic sampling device, and have carried out a number of test works [11-12]. The employed drill pipe is hollow auger driller, and the employed drill bits include impregnated diamond bit, polycrystalline diamond compact (PDC) bit and hybrid bit. Inspired by revolver, researchers of ESA developed a Mars sample acquisitor for deep drilling by connecting short drill pipes to ensemble [13]. On the detector of the "Rosetta exploration program", there was a SD2 (Sampler, Drill and Distribution) system, in which auger driller was also employed [14-15].

3. Structure Optimization of Auger Driller Drilling in the Lunar Stimulants

When auger driller is used for space coring drilling, hollow auger drilling can obtain undisturbed samples, while normal solid auger drilling can obtain disturbed samples [16]. Under the influence of rockets carrying capacity, the rated torque and power offered by drilling tools are relatively small. Therefore, the structure optimization of auger driller is necessary to realize deep lunar coring drilling under qualified condition.

3.1. Bit optimization

(1) Bit height

Bit structure includes bit inner and outer diameter, bit height, cutter types and arrangements, etc. If there are helical blades on bit outside, and the parameters of it are the same with auger drill pipe, the bit height only affect the total core recovery (TCR) to a certain degree, but not affect drilling procedure. For example, suppose that bit height is hb, drilling depth is H, theoretical core recovery is 100%, the TCR can be expressed as equation (1). As shown in equation (1), longer bit height results in lower TCR. The bit height usually no higher than 50 mm for drilling depth of 2000 mm, so its influence to TCR is negligible of no more than 2.5%.

$$TCR = (1 - \frac{h_b}{H}) \times 100\% \quad (1)$$

Where, TCR is the total core recovery of drilling test, %; h_b is bit height, mm; H is drilling depth, mm.

(2) Bit inner and outer diameters

The bit inner and outer diameters not only determine the amounts of targeted sampling, but also determine the quality of cuttings produced during drilling process. According to theoretical design, soft bag coring drilling obtains undisturbed sample, bit inner diameter should be determined by target drilling depth and sampling mass, as well as sample density. Assume that bit inner and outer radiuses are R1 and R2, inner tube's inner radius is R3, drilling depth is H, sample's undisturbed density is ρ, target sampling mass is m, there is a following relationship between those above mentioned variables.

$$m = \pi R_1^2 \cdot (H - h_b) \cdot \rho \quad (2)$$

Where, m is the target sampling mass, kg; R_1 is the bit inner radius, m; ρ is the undisturbed sample density, kg/m3.

The smallest bit inner radius can be obtained as equation (3).

$$R_1 = \sqrt{m / \pi\rho (H - h_b)} \quad (3)$$

After the determination of bit inner diameter, suppose that feeding rate is constant, the bit outer diameter determines the volume of lunar soil cut by bit, as well as the cuttings volume produced per unit time. Under constant rotation speed, the cuttings transportation capacity of auger driller is limited, thus the outer diameter of bit and drill pipe, and the width of helical blade etc. are closely related to drilling parameters.

Preliminary test indicated that, though the bit outer diameter, drill pipe's outer diameter, and helical blade width can affect drilling performance significantly, drilling power is far below from 350 W during normal drilling. However, influences of the outer diameters of bit and drill pipe to the required power and torque for auger driller's restart from buried are remarkably.

(3) Selection of bit type

Rotary drilling is necessary for deep lunar sampling drilling. In the Earth's environment, common rotary coring bits are carbide bit, PDC bit, roller bit and impregnated diamond bit. The impregnated diamond bits are mainly used for hard and extremely hard formations. The roller bits are mainly used for large-diameter oil & gas drilling. The carbide bits are usually used in Quaternary soil and partly weathered rock drilling. The PDC bits are suitable for soft to middle hard rock drilling.

Actual lunar soil is plastic soil with lower strength, and occasionally encountered lunar rocks also have lower strength compared with ordinary rocks on earth surface, equivalent to the fifth grade rocks according to the rock drillability classification [17]. Therefore, the carbide bit and the PDC bit can both be employed for lunar drilling. Considering that self-sharpening performance of the carbide bit is poorer, while the PDC bit can overcome this insufficient, so the PDC bit should be employed for the deep lunar coring drilling task. To adapt the drilling task on lunar surface under high vacuum and low gravity environment without flushing media, thermal stable polycrystalline diamond compact cutter should be used. To achieve steady drilling and reduce the cutting depth of individual cutters, multiple cutters should be symmetrically arranged around the bit circumference.

3.2. Optimization of auger drill pipe

(1) Lead angle of helical blade

If bit size and diameter of auger driller are determinate, the lead angle of helical blade will decide the critical rotation speed for cuttings automatic transportation. It also is one of the key factors to decide auger driller's accommodated capacity of cuttings. Because drilling fluid is not available on lunar surface drilling, smoothly drilling cuttings discharge can increase drilling efficiency and bring heat out of hole to a certain extent, so as to benefit drilling process.

Taking the double helix auger driller which employed for soft bag coring drilling test as example, suppose that the outer diameter of auger driller is 32 mm, the width of helical blade is 3.5 mm, the thickness of helical blade is 3

mm, the density of lunar soil is 1900 kg/m3, drilling depth is 2 m, then the effect of helical blade lead angle to auger driller's accommodated capacity of cuttings and to the critical rotation speed for cuttings automatic transportation are shown as fig. 1.

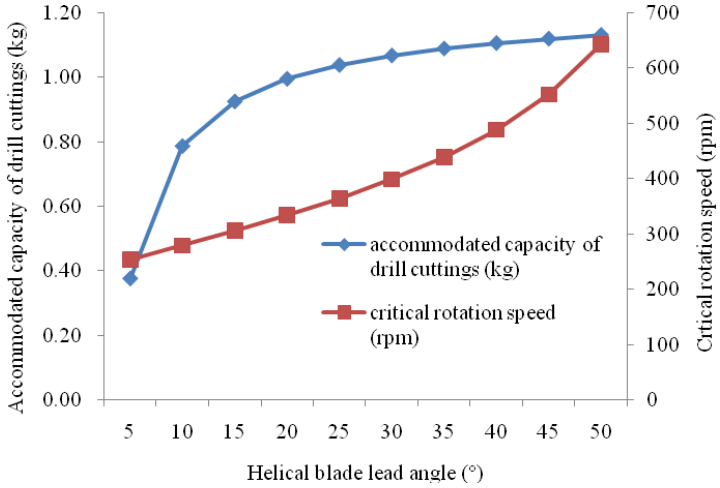

Fig.1. Effects of Helical Blade Lead Angle to Auger Driller's Accommodated Capacity of Cuttings and to the Critical Rotation Speed for Cuttings Automatic Transportation

As shown in the fig. 1, increasing of helical blade lead angle results to large critical rotation speed for cuttings automatic transportation. That means the increasing of helical blade lead angle is disadvantaged to cuttings discharge. When the helical blade lead angle is smaller than 20°, the accommodated capacity of cuttings of auger driller is monotonely increased with lead angle apparently, otherwise it is indistinctively. To utilize the accommodated capacity of cuttings and dissipating the heat produced by bit during drilling process as much as possible, the lead angle is recommended to be 15°~20°.

(2) Helical blade width

When the helical blade width is smaller, it will affect the auger driller's accommodate capacity of cuttings remarkably. However, under the condition of certain drilling parameters, the increasing of helical blade width could only decrease the accommodate thickness of cuttings on helical blade, while have no effect to the required drilling power. Thus the helical blade width can be obtained after other drill pipe parameters are determined, the detailed process are as follows: firstly, outer diameter of helical blade should be determined by bit outer diameter, taking it equal to bit outer diameter, or a little less than bit outer diameter of 0 ~ 1 mm. Secondly, inner diameter of the drill pipe should be determined by taking normal slipping space between soft bag and inner tube. Thirdly, under the condition of ensuring drill pipes strength, choosing smallest drill pipe thickness to obtain the inner diameter of helical blade, and then obtain helical blade width. In this case, because bit outer diameter is relatively bigger, while helical blade inner diameter is relatively smaller, results to bigger helical blade width, so as to benefit the auger driller's accommodated capacity of cuttings. Additionally, choosing the smallest helical blade thickness also increases the accommodated capacity of cuttings.

4. Selection of Auger Drilling Parameters

The required smallest axial pressure for lunar drilling is closely related to feeding rate, faster feeding rate requires higher drilling pressure. Therefore, reasonable feeding rate should be determined at first. During the deep lunar drilling task, 2 meters of drilling footage requires to be finished within 1 hour, so the average feeding rate should no slower than 33.33 mm/min. Considering that lunar rocks should not be drilled under high feeding rate, primary feeding rate of 100 mm/min is recommended in loose lunar soil drilling, so as to make allowance time for encountered lunar rocks drilling.

Assume that the feeding rate is 100 mm/min, employing the auger driller with soft bag and PDC bit for lunar drilling. Because the void ratio of lunar soil exponentially decreases with drilling depth, the ultimate strength of lunar soil increases with the drilling depth exponentially also. Therefore, auger driller's dead weight can be employed for loose minus-cement lunar soil drilling.

After the determination of auger driller outer diameter, the critical rotation speed of cuttings automatic transportation is determined. To make cuttings discharge normally, the rotation speed of auger driller should be higher than the critical value. Higher rotation speed decreases the cutting depth per revolution of individual cutters, so as to decline the required smallest drilling pressure. When drilling in lunar rocks or lunar soil with certain cement strength, if the compressive strength and shear strength of drilling object are relatively high, and the dead weight of auger driller cannot satisfy the normal drilling under assumed feeding rate, then the biggest drilling pressure should be employed.

During drilling process, the power of cuttings discharge is far smaller than the power of bit cutting lunar soil and friction power caused by bit rotation. Optimization about drilling parameters indicated that rotational speed should be determined according to the structure parameters of drilling tools and the designed feeding rate. Rotational speed would be enough as long as it can satisfy the cuttings discharge to be normal, otherwise its increasing will significantly increase drilling power. If feeding rate is already determined, in order to ensure normal drilling, the critical rotational speed which makes cuttings discharge mode alter from extrusion to normal should be calculated at first, and then rotational speed could be increased on that base with 5%~10%.

5. Conclusions

(1) The bit inner diameter is determined by target sampling mass and the density of drilling objects. The bit outer diameter is determined by the power for auger driller's restart from its state buried. The PDC bit is preferable for the deep lunar coring drilling task.

(2) The helical blade lead angle decides the critical rotation speed for cuttings automatic transportation, as well as the auger driller's accommodated capacity of cuttings. The helical blade width should be obtained after other drill pipe parameters are determined.

(3) To utilize the accommodated capacity of cuttings and dissipating the heat produced by bit during drilling process as much as possible, the lead angle is recommended to be 15°~20°.

(4) Feeding rate should be determined at first, and rotation speed is decided by the auger driller's structure size and feeding rate. Rotational speed will be enough as long as it can satisfy the normal discharge of the cuttings, otherwise its increasing would significantly increase drilling power.

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