One-meter Drilling Experiments in Simulated Lunar Environment

Sachiko Wakabayashi, Takeshi Hoshino, and Shoichi Yoshihara

JAXA Space Exploration Center (JSPEC), Japan Aerospace Exploration Agency (JAXA)

Abstract

The Advanced Subsurface Exploration Test Facility (ASSET) was developed to obtain basic data for designing drilling mechanisms as well as to evaluate their performance in simulated lunar environment on the ground. The facility simulates the charateristics of soil, vacuum, and temperature of the lunar environment and enables vertical drilling of up to two meters. Standard drilling test was conducted to evaluate auger performance using the standard sand and the simulated lunar soil.

標準オーガによる月面模擬掘削試験

若林　幸子、星野　健、吉原　正一

宇宙航空研究開発機構　月・惑星探査プログラムグループ

月の地下探査は表面探査に続く課題であり、地盤調査や機器埋設、サンプル採取に加え、将来的には拠点構築や資源利用等での地下の利用が含まれる。月面での調査・活動は２次元から３次元へ広がって行くことになり、掘削技術は今後の月探査ミッションにおいて重要な役割を果たすと予想される。本報告では、2m までの掘削が可能で月面環境を模擬する掘削試験装置の概要、及び標準オーガを用いた試験結果について報告する。

1. Introduction

Subsurface exploration on the Moon will be the next step after conducting surface exploration. Drilling technology will play an important role to achieve future mission goals. To develop mission-qualified drilling mechanisms, the accumulation of basic drilling data to support the design and the establishment of a method of evaluating drilling performance on the ground are crucial.

Lunar subsurface drilling dates back to the 1970s, when Apollo 15 astronauts drilled a hole on the Moon to a depth of up to 3 m [1], [2]. Even though the drill they used consumed about 500 W and were operated by human, several problems happened such as misalignment of auger flutes. The first fully automatic drilling operation was done on the Luna 24 in 1976. The drill was mounted along the side of the lander which weighed 6 tons on Earth and consumed around 150 W. Those past drilling operations usually made use of large weight and high power consumption. For future subsurface exploration, however, drilling equipment should weigh much lighter and consume much lesser power.

There are several essential differences about drilling operation between on Earth and on the Moon, the durability of the cutting bit, the effect on cuttings removal of completely dry soil, the drilling effect on the drilled sample, and how to ensure the drilling reaction force in the low gravity environment on the Moon [3].

Considering the above mentioned differences, ground testing in simulated lunar environment is necessary to obtain data on drilling performance on the Moon. The key factors to simulate the lunar environment are soil, vacuum, temperature and low gravity. Among these four factors, low gravity is the most difficult to simulate on the ground because each soil particle needs sustained low gravity compensation, but the other three factors are relatively easier to simulate.

The Advanced Subsurface Exploration Test Facility (ASSET) (Figure 1) was developed at JAXA for testing drilling mechanisms for the subsurface exploration on the Moon, simulating lunar environment. This paper also describes the preliminary test results to confirm the facility design and to evaluate auger performance of several drills.

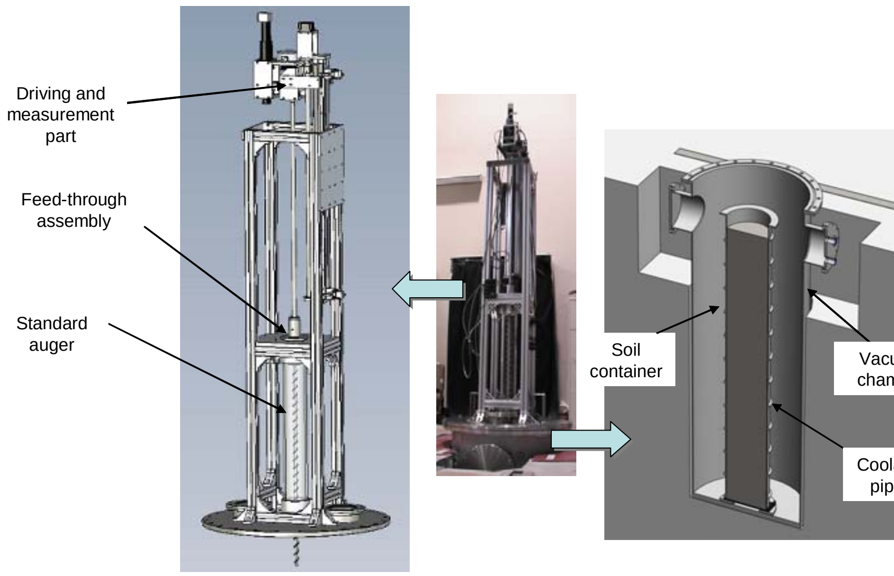


Figure 1. External appearance of the Advanced Subsurface Exploration Test Facility (ASSET)

(Left: Drilling mechanism, Middle: External appearance, Right: Vacuum chamber with soil container)

2. Design of the Advanced Subsurface Exploration Test Facility

The Advanced Subsurface Exploration Test Facility (ASSET) simulates soil, vacuum, and temperature of the lunar environment, enabling vertical drilling of up to two meters (Figure 1). The vacuum chamber is buried below the floor and the drilling mechanism is placed on it whose base serves as the lid of the vacuum chamber. The specification of the Advanced Subsurface Exploration Test Facility is summarized in Table 1.

A set of standard augers with different design parameter are manufactured to measure and compare the level of thrust force, rotational torque and power for a 1-meter drilling (Figure 2).

Table 1. Specification of the Advanced Subsurface Exploration Test Facility (ASSET)

Item	Specification
Height (including vacuum chamber)	6 m (for 2 m drilling)
Drilling depth	up to 2 m
Soil container diameter	up to 700 mm
Vacuum condition	< 10 Pa
Soil container coolant	LN2 or Hydro fluoro ether

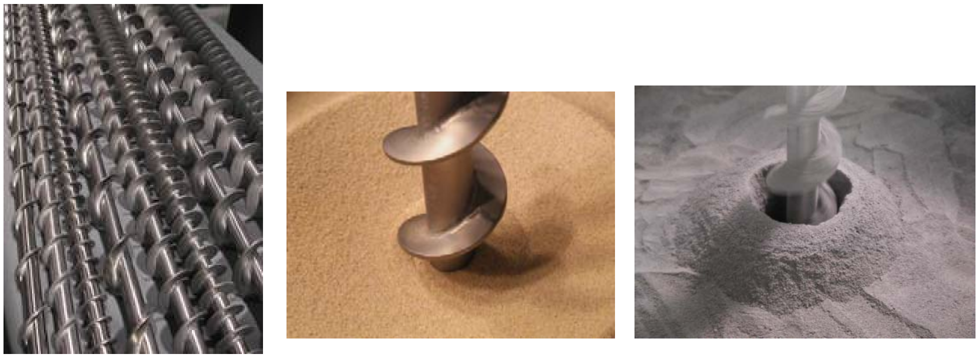


Figure 2. Standard auger lineup (left) and their operation with the standard sand (middle) and simulated lunar soil (right)

3. Drilling Test with the Standard Sand

Drilling operation consists of two processes. Firstly, the drill bit breaks the rock and, secondly, the auger removes the drilled cuttings to the surface. For a drilling of a sand-dominated soil, cuttings removal is just as important as breaking the formation with a drill bit.The design of augers still depends on empiricism and they do not work well at low rotational speeds with small diameters, both of which are considered essential for an extraterrestrial drilling.

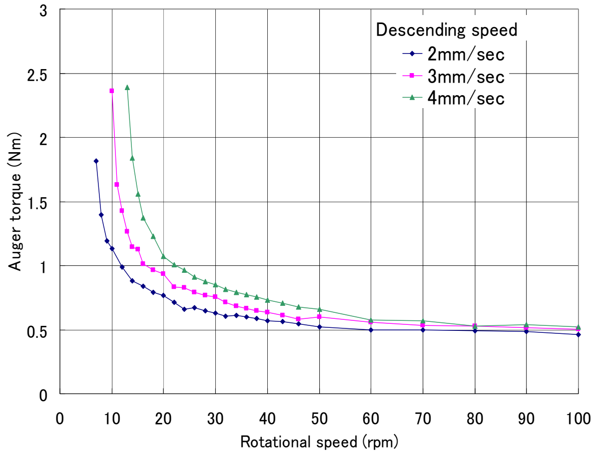
Drilling test was conducted in the air to evaluate the auger performance, focusing on evaluating the effect of auger spiral pitch using the three drills summarized in Table 2. The typical drilling operation is shown in Figure 2. The drills were controlled at a constant rotational speed with a constant descending speed.

Table 2. Geometrical parameters of the tested drills

Item	Drill 1	Drill 2	Drill 3
Length	1 m		
Diameter	37.5 mm		
Spiral pitch	20 mm	40 mm	60 mm

The Figure 3 shows the auger toque and power of the Drill 2 as a function of the rotational speed for different descending speeds. Sharp increase of auger torque was observed at a rotational speed of less than about 20 rpm at any descending speed. It limits the minimum allowable rotational speed to design drilling equipment. The sharp increase of auger torque at the lower rotational torque indicates the occurrence of auger choking. This choking point may depend on the soil characteristics, auger design, or auger surface characteristics.

In general, while higher rotational speed implies more efficient cuttings removal, it also requires higher power consumption because rotational speed is directly proportional to power. Higher rotational speed produces more heat flow into the formation as well. Lower descending speed allows lower rotational speed and lower power consumption, but the sudden increase of power at the lower rotational speed gets sharper at the lower descending speed. This suggests that an optimal design point exists to manage both power efficiency and operational safety. The possible lowest power consumption is estimated around 1 W/m from Figure 3.



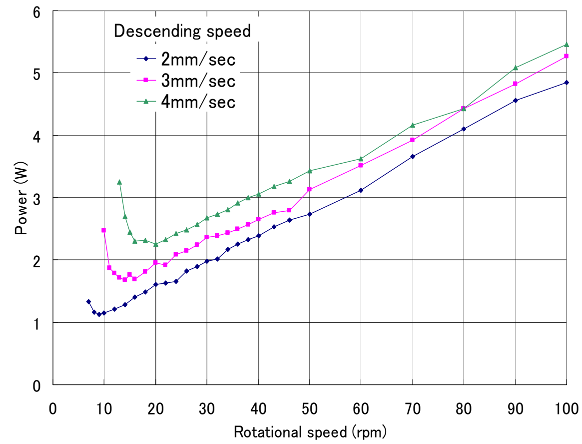


Figure 3 Experimental data showing auger torque (left) and auger power (right) as a function of rotational speed for different descending speed (Drill 2)

4. Drilling Test with the Simulated Lunar Soil

Drilling tests were also conducted using the simulated lunar soil to compare the results with those with the standard sand. Figure 2 shows the typical drilling operation using the simulated lunar soil. Note that a self-supporting bore hole was formed in the soil after drilled as shown in Figure 4. This is due to the effect of compaction, which is not observed with the standard sand.

Figure 4 Bore hole left after drilling

Typical histories of drilling force and torque using the Drill 2 with the simulated lunar soil are shown in Figure 5, compared with those with the standard sand. The required rotational torque is almost linear to the drilling depth and the thrust force is positive at the beginning and gradually getting negative along the drilling depth. This means that the force pushing the drill into the soil works only when the drilling depth is small and that the force pulling the drill into the soil increases linear to the drilling depth during the whole operation.

The thrust force shows higher maximum pushing force with the simulated lunar soil. This means that the simulated lunar soil needs more pushing force to break its compacted structure. The rotational torque is roughly 60 % of that with the standard soil. The results may depend on the initial soil condition, such as bulk density, but the trend is identical. The needed power consumption is estimated less than 10 W/m under present experimental condition. Drilling with standard sand can simulate the ultimate loose-sand condition for cuttings-removal performance.

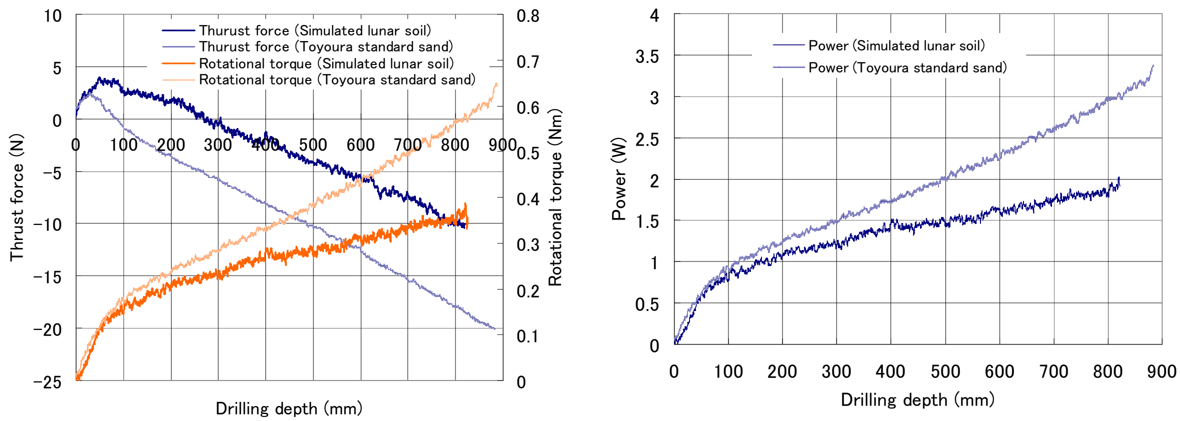


Figure 5 Experimental data showing thrust force and rotational torque as a function of drill depth (Drill 2, 80rpm, 2mm/sec)

5. Conclusion

The Advanced Subsurface Exploration Test Facility (ASSET) was developed to obtain basic data for designing drilling mechanisms and to evaluate their performance in simulated lunar environment on the ground. The facility simulates soil, vacuum, and temperature of the lunar environment and enables vertical drilling of up to two meters.

Standard-auger drilling tests were conducted to evaluate auger performance using standard sand and simulated lunar soil. They reveal that pulling force appears as the drilling proceeds and rotational torque increases abruptly at lower rotational speed and that simulated lunar soil needs more pushing force to break its compacted structure. An optimal design point exists to manage both power efficiency and operational safety. Further studies will be continued with various drilling equipment as well as theoretical analysis.

References

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