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Soil chip convey of lunar subsurface auger drill

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Abstract

Celestial body subsurface drilling and sampling is a key aspect of near-earth exploration projects. In these sample return missions, the auger drill system is universally used due to the environment and detector load limits. The common failure that the auger faces is chip chocking, which can raise the torque and cause the drill to stick. This paper builds auger drill models describing chip flow in the auger groove to balance geometric parameters, functional capability, and reliability. The features of chip flow are summarized and verified by a series of discrete element method simulations. In contrast to previous auger design, a convey capability factor is defined to indicate the auger's chip removal capacity, and the role of pitch angle and other parameters is assessed through motion analysis of the lunar soil flow process. The theory is verified by testing the drill penetrating speed limit, which combines drill geometry and motion parameters. This work provides a new method for design and optimization of low speed auger drill systems and research on particle flow with small scale mechanical constraints.

Keywords: Auger drill design; Auger convey capability; Lunar subsurface drilling; Soil chip removal

1. Introduction

In terms of extraterrestrial auger drill stem design, the former Luna and Apollo series and the later ExoMars exploration project all used terrestrial experiments or geological engineering experiences as reference (Crouch, 1968; Zacny, 2005; Duan et al., 2014). The parameter calculations were similar to powder screw conveyor design. This design method has limitations, such as assuming the centripetal force generated from the associated movement of the chips with the auger blade is the main cause of friction slip, and the structural parameters of the drill stem were dictated by the system's critical revolving speed (Moysey and Thompson, 2008; Zacny and Cooper, 2007). However, due to environmental and technical constraints, the revolving speed of an extraterrestrial drill is generally below 500 rpm, e.g. the ALSD system (Apollo series) was 280 rpm (Allton, 1989), and the CE5 lunar exploration drill was 100–120 rpm. The outer diameter of the drill stem was also limited below 50 mm, e.g. the drill stem diameter for Luna 24 was 24 mm, and ALSD was 33–44 mm (Allton, 1989). For this motion and dimension scale, centripetal force is no longer the core parameter. Therefore, in this paper, the lunar soil chip convey process is modeled based on quasi-static analysis.

The motivation for this work is the Chinese Lunar Exploration Program (CE). The drilling and sampling process is part of the 3rd phase of the CE program. The aim of the drill program is to obtain 2.5 m length core under the lunar surface (Shi et al., 2014; Zheng et al., 2008). The ideal drilling target is assumed to be the lunar soil mixing with gravels under 30 mm in diameter. And in tough cases that

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the drill met lunar rock, it is recommended that the drill can penetrate 80 mm in 20 min.

The following section introduces the background of extraterrestrial subsurface drilling and the apparatus used in this research. Then there is the theory section, containing discussions on lunar soil chip flow features and soil chip flow model. After that, in Section 4, the chip follow feature is supported by discrete element simulation, and the soil chip flow model result is presented and verified.

2. Background and apparatus

For extraterrestrial subsurface drilling, the Luna series unmanned drilling sampling project from the former Soviet Union (Anttila et al., 2005), the Apollo manned series from the United States (Fujiwara et al., 2004), and the recent program including the ExoMars (Magnani et al., 2004; Richter et al., 2002), SD2 drill on Rosetta lander (Ulamec et al., 2012), and the MOONBIT project supported by ESA (Poletto et al., 2015), etc. without exception, adopted the auger drill chip removing method. This method of chip removing is rarely used in terrestrial geological exploration, and different applications are decided by environmental differences (Zacny and Cooper, 2006; Duffard et al., 2011). In extraterrestrial drilling, the high vacuum and low gravity environmental have to be faced with. Fluid flow may be simply expressed for atmospheric conditions, and this convenience has two major influences on the drilling process, particularly evident in rock drilling. Heat generated from the working of the drilling area can be evacuated by liquid or gaseous medium, allowing high power drilling systems without concerns of overheating, and hence, such systems have relatively higher revolving speeds and penetration rates. Furthermore, chip removal can be achieved via water or airflow. Neither of these assumptions hold for most extraterrestrial drilling environments (Zacny et al., 2008; Bar-Cohen and Zacny, 2008).

The outer working interface of the lunar regolith drilling tool contains the drill stem and bit, as shown in Fig. 1, illustrating one of the CE drill schemes. The purpose of auger parameter optimization is to achieve chip removal within the small structure dimensions i.e., the outside diameter of the drill stem, and improve its efficiency and reliability under special working conditions. If the structural and motion parameters are mismatched, drilling torque will rise rapidly due to chip chocking, and result in drill failure (Nathan et al., 1992). In addition, lower drill auger blade height also benefits avoiding the drill from being stuck by the scratches of rock corners.

Fig. 1. Drill bit and stem (CE5).

The lunar subsurface drilling targets can generally be divided into two categories, soil, and rock, according to the cutting properties (Zou et al., 2011; Scott and Roberson, 1968). The chip convey demand of rock is much lower than that of soil drilling, since its drilling feed rate is very low under low power conditions (Klein et al., 2012). In terms of chip transportation, there is no difference between rock fragments and the soil debris (Costes et al., 1970). The compactness of the in situ lunar regolith increases with the depth, and relative density reaches more than 90% 60 cm beneath the surface (Houston et al., 1974; Carrier et al., 1991; Carrier et al., 1973). Considering the functional design requirements of the auger blade, the drilling target considered here is confined to 100% compact lunar soil (Jiang et al., 2010).

Fig. 2 shows the lunar regolith drilling and sampling platform used in the drilling tests. The maximum stroke of the platform was 2.5 m. The particle size of lunar soil simulant used in this research is 0.01–1 mm, composed of basalt debris. The lunar soil simulant is prepared using a three-dimensional (3D) vibration table, which raise the soil average relative density to 100.32%. For more information on lunar soil simulant preparation please find the work done by Tian et al. (2015) and Guo et al. (2012). Fig. 3 shows two of the stems used in the penetrating limit test, with the same geometry (auger blade height, coring diameter, outer diameter, etc.) except auger pitch angle.

Fig. 2. Lunar regolith drilling and sampling platform.