International Journal of Rock Mechanics & Mining Sciences 86 (2016) 204–209

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Theoretical derivation of the cuttings transportation trajectory for lunar sampling auger drilling

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ARTICLE INFO

Article history:
Received 6 August 2015
Received in revised form
1 April 2016
Accepted 15 April 2016
Available online 30 April 2016

Keywords:
Lunar exploration
Space sampling drilling
Cuttings transportation
Auger drilling mechanism

1. Introduction

An auger driller is mainly composed of a drill stem with continuous helical blade and a bit with cutters. The main drilling parameters and the geometric items of auger stem are displaced in Fig. 1. Nowadays, auger drilling has become one of the most widely used drilling techniques in pile foundation engineering and geological sampling for sand and soil.[1–3] Moreover, because of continuous cuttings transportation without the need to use a flushing medium during drilling, auger drilling is considered as one of the best drilling approaches for space sampling.[4–10] However, few researches have been reported for the power and mechanics analyses of auger drilling in a detailed theoretical way. Cuttings discharge power, which is closely related with motion trajectory of cuttings, accounts for the most important part of the total power consumption of auger drilling. Consequently, the present study mainly focuses on the theoretical derivation of the cuttings motion trajectory in auger drilling employed for lunar sampling drilling. The influences of various feed rates and rotation speeds on cuttings' discharge and motion vector are analyzed in detail. It is expected that this study will be helpful to the understanding of auger drilling mechanism, as well as the accurate calculation of the cuttings transportation power.

There is an important concept about critical rotation speed in the field of auger drilling. It means that the single grains will start to move up along the helical blade when the rotation speed reaches or exceeds the critical value. In the typical model, the cuttings are supposed to be single grains. As a result of centrifugal force, the grains trend to move towards the hole wall. The centrifugal force will result in a frictional driving force exerted on the grains once they get in contact with the hole wall. After having overcome several other forces, the grains finally will be transported from the hole bottom towards the surface.[11–15]

When the single grain is under an upward critical condition, its force analysis is depicted in Fig. 2(a). As shown in Fig. 2(a), the single grain simultaneously withstands several forces, including centrifugal force (F_c), self-gravity (mg), braced force from the helical blade (F_b), frictional force between the grain and hole wall (F_1), as well as the frictional force between the grain and the helical blade (F_2). Its force equilibrium equations can be obtained as follows:

$$\begin{cases} F_2 + mg\sin\alpha = F_1\cos\alpha \\ F_1 = f_1F_c = f_1mw_c^2R_5 = f_1m\left(\dfrac{n_c\pi}{30}\right)^2R_5 \\ F_2 = f_2F_b = f_2(mg\cos\alpha + F_1\sin\alpha) \end{cases} \tag{1}$$

where m is the mass of the single grain (kg), g is the gravitational acceleration (m/s^2), f_1 is the friction coefficient between cuttings and the hole wall, f_2 is the friction coefficient between cuttings and the helical blade, w_c is the critical angular velocity for upward motion (rad/s), n_c is the critical rotation speed for upward motion (rpm).

Thus, the critical angular velocity and rotation speed can be calculated by solving Eq. (1) to find:

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http://dx.doi.org/10.1016/j.ijrmms.2016.04.015

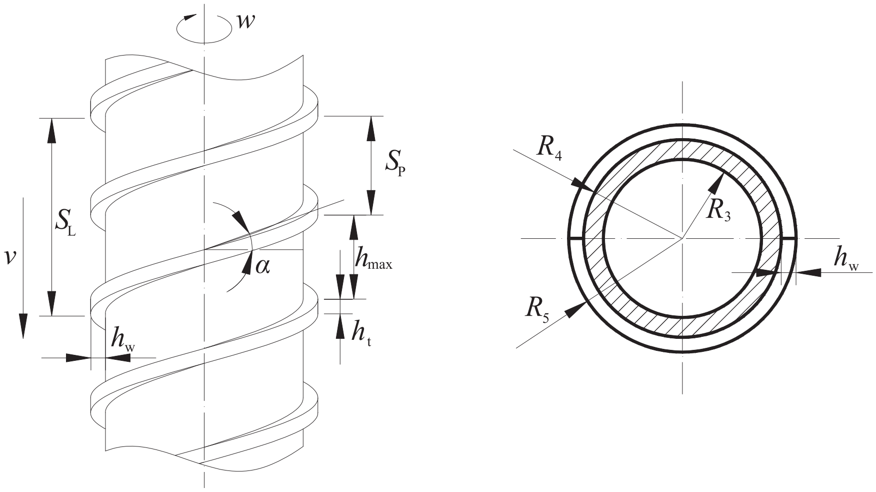
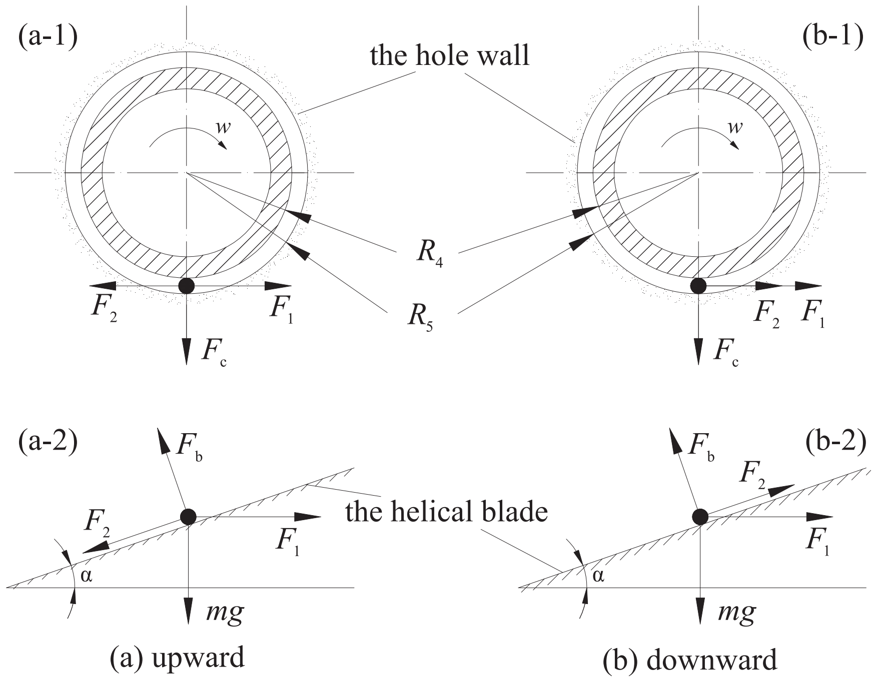


Fig. 1. Main structure components and their parameters mark of auger driller. Note: w is the angular velocity of auger driller (rad/s), ν is the downward feed rate of auger driller (m/s), S_L is screw lead (m), S_P is screw pitch (m), α is screw lead angle (°), h_t is helical blade thickness (m), h_w is helical blade width (m), h_{max} is the maximum height for cuttings storage space (m), R_5 is the outer diameter of helical blade (m), R_4 is the inner diameter of helical blade (m), R_3 is the inner diameter of the hollow auger stem (m). It should be noted that for an ordinary solid auger drill stem, R_3 is zero.



(a) upward (b) downward

Fig. 2. Force analyses of the single grain under upward and downward critical conditions respectively. Note that the visual angles of (a-1) and (b-1) are top views, while (a-2) and (b-2) are tangential directions of the single grain's motion vector on the helical blade.

$$\begin{cases} w_c = \sqrt{\dfrac{g(\sin\alpha + f_2\cos\alpha)}{f_1 R_5(\cos\alpha - f_2\sin\alpha)}} & (rad/s) \\ n_c = \dfrac{30}{\pi}\sqrt{\dfrac{g(\sin\alpha + f_2\cos\alpha)}{f_1 R_5(\cos\alpha - f_2\sin\alpha)}} & (rpm) \end{cases} \tag{2}$$

As can be seen from Eq. (2), the critical rotation speed and the angular velocity are dependent upon the gravitational acceleration, the geometric dimensions and shape of the auger driller, the coefficient of friction between cuttings and the hole wall, and the friction coefficient between cuttings and auger driller.

2. Cuttings motion trajectory

Fig. 3 illustrates the cuttings' motion vectors and its various components. Combining the influencing factors of the auger driller's rotation speed and feed rate with respect to cuttings transportation, four states of cuttings transportation could be obtained as follows:

2.1. $n \le n_c$, $\nu = 0$

In this case, the auger driller's rotation speed is lower than the critical rotation speed for cuttings automatic transportation. For a single grain, it may tend to move upward or downward along the helical blade since the feed rate (ν) is zero.

The critical upward condition of the single grain has been analyzed in Section 1. On the contrary, its force analysis under downward trend is depicted in Fig. 2(b), and its force equilibrium equations can be expressed as