Study on the Mechanical Characteristics of the Screw Driving Torque during the Emptying of the Shield Soil Bin

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Abstract. This article studies the changing law of the driving torque of the screw conveyor during the emptying process of the earth pressure balance shield chamber. First, the discrete element method of discrete medium theory and 3D software SolidWorks were used to create the research object and the screw conveyor model, and then the model parameters were determined and calibrated through numerical calculations and indoor experiments. The final numerical calculation results show that: 1) the screw torque will drop in waves with the increase of the calculation time. When the screw conveyor rotates at 360 deg/s, the calculated screw torque fluctuation amplitude is small; 2) when the number of particles in the soil bin is reduced to a certain extent, the use of a higher screw speed to improve the "dumping soil effect" is of little significance; 3) the negative exponential function can be used to better fit the decrease of screw torque with time; 4) for the bulk medium, for a given particle size and screw structure, there is a suitable speed, so that the effect of "machine-soil collision" is small, and the torque change of the screw is relatively stable.

Keywords. Mechanical characteristics; screw conveyor; driving torque; EDEM.

1. Introduction
The structure of the shield screw conveyor is roughly the same as the screw conveyor used for ordinary material transportation, but in the closed chest mode, the pressure in the shield chamber is higher, and its working conditions are quite different from ordinary screw conveyors (Li, 2009) [1]. The driving torque is a mechanical parameter that guarantees the normal function of shield screw conveyor, and it is necessary to systematically study the driving torque change law of shield screw conveyor.

In China, Beijing, Chengdu, Shenyang and other places, there are large areas of sand and gravel formations (Wang Zhenyong et al., 2019) [2]. When tunnel construction is carried out in this kind of stratum, it is often difficult for shield screw conveyors to discharge soil and maintain pressure balance. Due to the high content of coarse particles in the stratum, the excavated soil exhibits a strong granular medium characteristic. The current research on the working mechanism of shield screw conveyors is mostly based on continuum theory (Merritt, 2008) [3]. In the continuum method, the properties of matter are assumed to be a continuous function, and the matter can be divided infinitely without losing any inherent properties, and discontinuous particle properties are not considered. The theory of bulk medium has been applied in the research of shield construction related issues (Liu et al., 2019; Tobias et al., 2016; Talebi et al., 2015; Dang et al., 2017) [4-7], but there are few studies on the changing law
of the driving torque of the screw conveyor when the shield is constructed in the sand and gravel stratum. Due to the large particle size of the muck in this type of formation, it is not suitable for indoor model machine tests. Therefore, it is necessary to conduct in-depth research on the driving torque characteristics of the shield screw machine in sand and gravel formations with the aid of the theory of granular media.

Using the engineering discrete element method (EDEM) of the discrete medium theory, the torque change characteristics of the muck from the soil silo to the exit of the conveyor are simulated when the soil silo is empty during the shield construction process. Both the shield soil bin and the screw conveyor are modeled by 3D software SolidWorks, as shown in figure 1. The size of the soil bin and the screw machine are taken from the shield machine used in the construction of the section between Dongfeng Beiqiao Station and Jingshun Road Station in Section 15 of Beijing Metro Line 14. By changing the speed of the screw conveyor in the model and the number of particles in the soil bin, the driving torque of the screw conveyor under different conditions is calculated, and the influence of different parameters on the calculation results is analyzed.

![Figure 1. 3D model of soil bin and screw machine.](image)

2. EDEM and Typical Models

According to the interaction between the units and Newton’s law of motion, the method of cyclic iteration is used to determine the forces and displacements of all units at each time step, and update them. The use of a suitable element contact model is the key to the simulation of screw driving torque.

2.1. Hertz-Mindlin (No Slip) Model

In this model, the normal force component is based on the Hertzian contact theory, and the tangential force model is based on the research work of Mindlin-Deresiewicz (Mindlin, 1949; Mindlin and Deresiewicz, 1953) [8-9]. Both normal force and tangential force have damping components. For example, Tsuji et al. (1992) [10] described the relationship between the damping coefficient and the restitution coefficient. The rolling friction force is determined by the contact independent directional constant torque model (Sakaguchi, et al, 1993) [11].

In particular, the normal force $F_n$ is a function of the normal overlap amount $\delta_n$, and the expression is

$$ F_n = \frac{4}{3} E^* \sqrt{R^*} \delta_n^3 $$  \hspace{1cm} (1)

where $E^*$ is the equivalent Young’s modulus, $R^*$ is the equivalent radius, which is defined as,

$$ \frac{1}{E'} = \left(1 - \nu_i^2\right) E_i + \left(1 - \nu_j^2\right) E_j $$  \hspace{1cm} (2)

$$ \frac{1}{R'} = \frac{1}{R_i} + \frac{1}{R_j} $$  \hspace{1cm} (3)

Where $E_i, E_j$ and $\nu_i, \nu_j$ respectively represent the elastic modulus and Poisson’s ratio of the two
contacting convex bodies; \( R^* \) is the equivalent radius, and \( R_i, R_j \) represent the convex body radius.

In addition, the expression of damping force \( F^d \) is

\[
F^d_n = -2\sqrt{\frac{5}{6}} \beta \sqrt{S_n m^* v_n^{rel}}
\]

(4)

where \( m^* = \left( \frac{1}{m_i} + \frac{1}{m_j} \right)^{-1} \) is the equivalent mass; \( v_n^{rel} \) is the normal component of the relative velocity. \( \beta \) and \( S_n \) (normal stiffness) are expressed as follows:

\[
\beta = \frac{\ln e}{\sqrt{\ln^2 e + \pi^2}}
\]

(5)

\[
S_n = 2E^* \sqrt{R^* \delta_n}
\]

(6)

where \( e \) is the coefficient of recovery. The tangential force \( F_t \) depends on the tangential overlap \( \delta_t \) and the tangential stiffness \( S_t \).

\[
F_t = -S_t \delta_t
\]

(7)

and

\[
S_t = 8G^* \sqrt{R^* \delta_n}
\]

(8)

where \( G^* \) is the equivalent shear modulus. In addition, the tangential damping expression is

\[
F^d_t = -2\sqrt{\frac{5}{6}} \beta \sqrt{S_t m^* v_t^{rel}}
\]

(9)

where \( v_t^{rel} \) is the tangential component of the relative velocity. The tangential force is limited by the Coulomb friction \( \mu_s F_n \), where \( \mu_s \) is the static friction coefficient.

For numerical calculations, rolling friction is important, and it is achieved by applying a moment on the contact surface.

\[
\tau_i = -\mu_i F_n R_i \omega_i
\]

(10)

where \( \mu_i \) is the coefficient of rolling friction; \( R_i \) is the distance from the contact point to the center of mass; \( \omega_i \) is the angular velocity vector of the object at the contact point.

2.2. Hertz-Mindlin with JKR Cohesion Model

The Hertz-Mindlin with JKR (Johnson-Kendall-Roberts) Cohesion in EDEM is a cohesive contact model that can consider the influence of van der Waals forces in the contact area and allows users to simulate a strongly viscous system. In this model, the realization of the normal elastic contact force is based on the Johnson-Kendall-Roberts theory (Johnson et al, 1971) [12].

The relationship between the JKR normal force \( F_{JKR} \) and the amount of overlap \( \delta \), interaction parameters and surface energy density \( \gamma \) is

\[
F_{JKR} = \frac{4a^3 E^*}{3R} - \sqrt{8\pi a^3 \gamma E^*}
\]

(11)

\[
\delta = \frac{a^2}{R} - \sqrt{2\pi a \gamma / E^*}
\]

(12)
where \( \gamma \) is the surface adhesion energy, and the other symbols have the same meaning as above. When using spherical particles of the same material and the same size for simulation, the equivalent Young's modulus \( E^* = E / (1-\nu^2) \), the equivalent radius \( R^* = R/2 \), where \( E, \nu \) and \( R \) are the Young's modulus, Poisson's ratio and radius of the spherical particles, respectively.

The normal force \( F_n \) in formula (1) of Hertz-Mindlin (no slip) contact model can be rewritten as

\[
F_{Horizon} = \frac{4E^* \sqrt{R^* \delta^2}}{3}
\]  

The two particles of the JKR model can maintain a stable limit loading force \( F_c \) and limit spacing \( \delta_c \) (both \( F_c \) and \( \delta_c \) are positive) during stretching, respectively.

\[
F_c = 2\pi \gamma R^*
\]  

\[
\delta_c = \frac{3(\pi \nu/2)^{2/3} (R^*)^{1/3}}{4(E^*)^{1/3}}
\]

From formulas (11), (12), (14) and (15), eliminate \( a, E^*, R^* \), the following formulas can be gotten.

\[
\frac{\delta}{\delta_c} = (3\lambda -1)(1+\frac{\lambda}{9})^{1/3}, \lambda \geq 0
\]  

\[
\frac{\delta}{\delta_c} = -(3\lambda +1)(\frac{1-\lambda}{9})^{1/3}, 0 \leq \lambda \leq \frac{2}{3}
\]

and \( \lambda = \frac{F_c + F_{JKR}}{F_c} \)

Eliminate \( E^* \) and \( R^* \) from equation (13), equation (14) and equation (15), the following can be gotten.

\[
F_{Horizon} / F_c = \frac{1}{\sqrt{3}} (\delta / \delta_c)^{3/2}
\]

3. The Calculation Model of the Screw Machine Discharge under the Empty State of the Soil Bin

The number of particles in the soil silo decreases continuously with the rotation of the screw. Take the spiral axis tilted 30° as an example, the number of particles decreases as the screw machine rotates and the torque change of the screw machine is calculated. Particles accumulate naturally in the soil bin. In the model, the rotation speed of the screw machine is considered 144deg/s, 288deg/s, 324deg/s, 360deg/s and 432deg/s. The number of initial particles in the soil bin is 732,000, and the soil bin is basically in a full state. Taking the screw speed of 144deg/s as an example, after calculating 361s, the number of particles in the soil bin is reduced to 62,721. At this time, the soil bin is almost empty and the number of particles is small.

With the rotation of the screw and the extension of the calculation time, the number of particles in the soil bin is decreasing, and the number of particles discharged from the soil bin per second is also decreasing, as shown in figure 2. It can be seen from figure 2(a) that when the particles in the soil silo are reduced to about 100,000, the reduction rate of the number of particles tends to be flat; from figure 2(b) it can be seen that when the calculation time is between 150s~300s, the reduction of particles per second in the soil bin is sharply decreasing.
The calculation results of the number of particles in the soil bin and the change of screw torque with time at different screw speeds, as well as the exponential and linear fitting results of the change of screw torque with time are shown in figures 3–7.

**Figure 2.** Change rule of particle number in soil chamber.

**Figure 3.** Calculation and fitting results with a rotational speed of 144 deg/s.

**Figure 4.** Calculation and fitting results with a rotational speed of 288 deg/s.
Summarizing the calculation and fitting results in figures 3~7, it can be found that the use of a negative exponential function can better fit the decrease in screw torque over time. The negative exponential function can be expressed as

\[ y = ae^{-bt} \]  \hspace{1cm} (19)
where \( a \) and \( b \) are calculation constants and \( b < 0 \); \( t \) represents time; \( y \) is screw torque.

4. Conclusion

(1) When the soil bin is emptied, the screw torque will drop in waves with the increase of the calculation time. When the screw conveyor rotates at 360 deg/s, the calculated screw torque fluctuation amplitude is small.

(2) As the calculation time progresses and the number of particles in the soil bin decreases, the rate of decrease in the number of particles in the soil bin (discharge rate) has been decreasing. For actual engineering, when the number of particles in the soil bin is reduced to a certain extent, the use of a higher screw speed to improve the "soil effect" is of little significance.

(3) With the passage of calculation time, the number of particles in the soil bin decreases, and the driving torque of the screw machine shows a wave-like downward trend. Comparing the results of exponential and linear fitting, it can be seen that the negative exponential function can be used to better fit the decrease of screw torque with time.

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