Research on Movement Rules of Soil Particles during EPB Machine Tunneling with Spoke Cutterhead

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Abstract: To discover the movement rules of soil particles around cutterhead during shield machine tunnelling, the discrete element model of shield machine tunnelling is established. The model is able to simulate the structure of shield machine, the pressure of ground, the excavation operation process and the flow process of soils. The cutterhead torque is obtained by running the model, which is accord with the theoretical calculation results. The displacements of soil particles in the cutterhead system of shield machine at the different tunnelling time are displayed. The movement of soil particle is periodic, and the period is related to the cutterhead rotation speed.

1 INTRODUCTION

The tunnel boring machine (TBM), including the hard rock TBM and the soft ground TBM, is the advanced large special equipment for tunnel excavation. A lot of scholars have conducted extensive research on the hard rock TBM construction and design (Rostami and Ozdemir,1993; Burger,2006; Karlheinz,2009; Abdolreza and Siamak,2012; Peter,2009). For the soft ground TBM, such as earth pressure balance (EPB) machine, there are many research on the relation between the tunneling operation parameters (Hehua, 2007; Hongxin and Deming, 2006). Although the EPB machine is already used to excavate tunnels, and there are some research on the construction technology, the dynamic interaction rules between the shield machine and the soils, which has an important role in improving and optimizing the system structure, is not clear.

The paper simulates the tunneling process of the EPB machine with spoke cutterhead by the discrete element software PFC3D. The displacement distributions of soil particles in the cutterhead and in the chamber at different tunnelling time are obtained. The movement rules of soil particles during the machine tunnelling are revealed.

2 SIMULATION

The Discrete Element Method (DEM) model of EPB shield machine tunnelling, which is shown in Figure1, consists of two parts. One is the simulated ground; the other is the tunnelling shield machine. The model of the shield machine is made up with the cutterhead, the chamber and the screw conveyor. The cutterhead is composed of six spokes. The 84 cutters are located on both edges of the spokes. The opening ratio of the cutterhead is 70%. The structure parameters of the model are listed in Table.1.

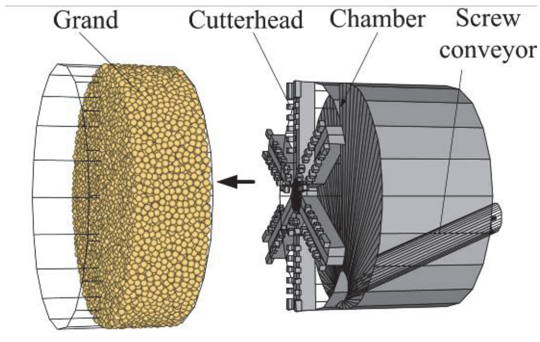

Figure 1: DEM model of shield machine tunnelling.

The DEM model of the shield machine is set up by wall elements in PFC3D. The cutterhead and the chamber board are made up with plane walls. The vertex coordination of the plane walls are obtained

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by CAD model of cutterhead. The shield shell and the outer barrel of screw conveyor are built by cylinder wall, and the screw is built by spiral wall.

A homogeneous packing of 20,715 particles in a cylinder container of 6.28 m in diameter and 2 m in length has been chosen to simulate the soil where the excavation takes place. The compressive strength of the soils is 50kPa. The contact models between particles is selected the standard linear model in PFC3D. The contact model parameters between particles are shown in Table 2. The simulated excavation depth of the ground is 20 m. The ground pressure is controlled by the servo-mechanism, which is realized by adjusting the displacement of the wall constantly to keep the pressure stable (Li, 2013). The rotation speed of the cutterhead is set 2 rpm, the thrust speed is set 60 mm/min, and the rotation speed of screw conveyor is set 5 rpm. In PFC3D, the wall has 6 velocity components, so the machine speed can be realized easily by setting the velocity components of walls.

Table 1: Structure parameters of DEM model.

Shield diameter （m）	Shield length （m）	Conveyor diameter （m）	Conveyor length （m）	Screw pitch （m）	Conveyor angle （°）
6.28	2	0.84	5	0.56	22

Table 2: Particle parameters.

Normal stiffness （N/m）	Shear stiffness （N/m）	Friction coefficient	Particle density （kg/m^3）	Particle radius （m）
540000	540000	0.5	2637	0.0625

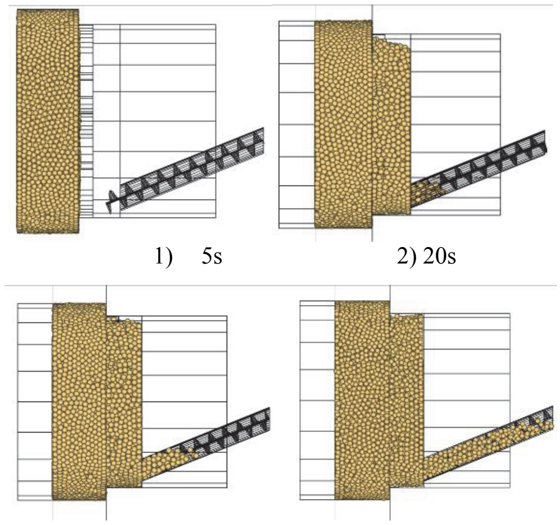


Figure 2: Shield machine tunnelling process.

The DEM model can reproduce the dynamic tunnelling process of the shield machine, which is shown in figure 2.

The DEM model of the EPB shield machine tunnelling is run for 120 s. When the run time is 120 s, the chamber and screw conveyor are filled with particles. This means that the cutterhead system comes into the stable state.

3 MODEL VERIFICATION

3.1 Simulated Torque

The cutterhead torque is measured in the process of the tunnelling simulation. The simulation torque is compared to the theoretical calculation to verify the DEM model. The cutterhead torque is extracted every 5 s from 0 s to 120 s (Figure 3). The average simulated cutterhead torque is 1435kNm.

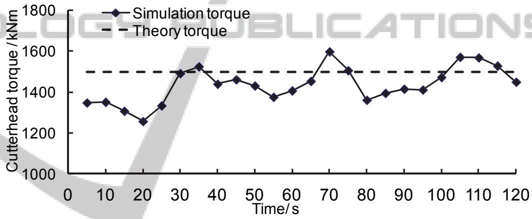


Figure 3: Simulated cutterhead torque.

3.2 Calculation Torque

In the DEM model, the simulated cutterhead torque is composed of cutting torque, the friction torque of the front side and the back side of the cutterhead. The theoretical calculation equation of the above mentioned torque is concluded (Kui, 2011).

The cutterhead cutting torque T_1 is shown in Equation (1).

$$T_1 = nq_u h_{\max} D^2 n^2 \tag{1}$$

Where q_u is the compressive strength of soils, kPa; h_{max} is the penetration of cutterhead, m, $h_{max}=v/n$, v is the thrust speed, m/h, n is the cutterhead rotation speed, rpm; D is the diameter of the cutterhead, m.

The friction torque of the front side of cutterhead is illustrated in Equation (2).

$$T_1 = nq_u h_{\max} D^2 n^2 \tag{2}$$

Where α is the non opening ratio; μ_1 is the friction coefficient between soils and the cutterhead; R_c is the radius of the cutterhead, m; R_d is the active pressure of soils, kPa.

The friction torque of the back side of the cutterhead is regard as the same as that of the front side.

Through calculation, the cutting torque is 473 kNm, the friction torque for each side of cutterhead is 512 kNm. So the total torque is 1497 kNm. The average error between the simulated torque and the calculation torque is 4%, which illustrates the DEM model is correct.

4 PARTICLE MOVEMENT RULES

During the DEM simulation, the displacement distributions of soil particles in the chamber and in the cutterhead are displayed at tunnelling time 0s, 10s, 15s, 20s, 30s, 45s and 60s.

As shown in Figure 4, at time 0 s, the cutterhead, the shield and the screw conveyor haven't started to work, the particles in the cutterhead and in the chamber both move downward to the chamber board under the gravity and the ground pressure. The soil displacement in the cutterhead is higher than that in the chamber.

At time 10 s (Figure 5), the particles in the cutterhead rotate along the axis of y anticlockwise. It is because that the friction torque caused by the cutterhead conquers the interaction force between particles, and the cutterhead leads the particle to move. The bottom particles in the chamber march toward the screw entrance for the screw rotation. The above particles in the chamber rotate anticlockwise.

At time 15 s (Figure 6), in the cutterhead, the particles displacement in XZ plane is radiate. This is because that in the circumferential direction, the distance between particles increases with the cutterhead rotation further, leading to the interaction force between particles increases; When the interaction force is larger than the friction caused by the cutterhead rotation, the particles slow down the movement anticlockwise until the velocity of the particles in circumferential direction reach 0. At this time, the displacement of particles is subjected to the radial ground pressure, so the displacement of particles is radial in XZ plane. The displacement of particles in the chamber is similar to that at time 10.

At time 20 s (Figure 7), the particles rotate clockwise in the cutterhead. This is because that the interaction force between particles is much larger than the force caused by the cutterhead rotation. At time 15 s, the force between particles reaches maximum. By the particles rotate clockwise, the distance between particles reduces, and the interaction force between particles reduces too. When the interaction force reaches 0 N, the particles begin rotate anticlockwise again. In the chamber, the bottom particles move toward the inlet of the conveyor for the screw rotation, and the movement direction of the above particles is caused by the ground pressure mainly.

At time 30 s and 60 s (Figure 8 and Figure 10), the displacement distribution of particles is similar to that at time 0 s. As shown in Figure 9, the displacement is similar to Figure 6. It implies that the motion period of the soil particles is 30 s.

In order to study the relation between the rotation speed of the cutterhead and the soil particles movement rules, the DEM model is run again setting the cutterhead rotation speed 1 rpm. The displacement distribution of soil particle at run time 30 s is shown in Figure 11. It is shown that the displacement at time 30 s when cutterhead rotation speed is 1 rpm is similar to the displacement at time 15s when cutterhead rotation speed is 2 rpm. So the particle movement period T can be deduced as equation (3)

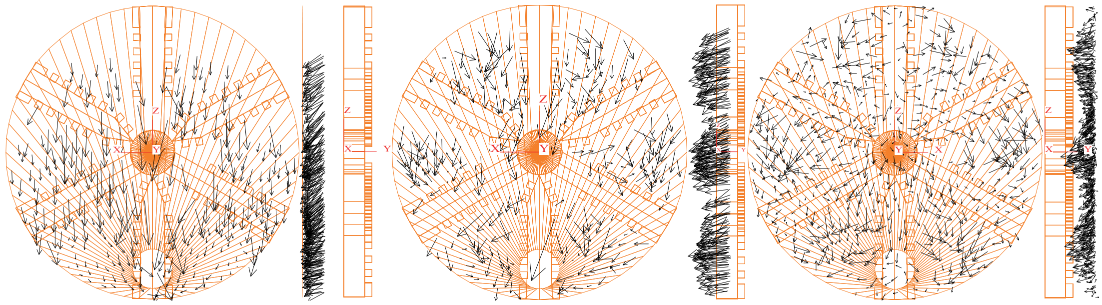
$$T = \frac{60}{n} \tag{3}$$

5 CONCLUSIONS

The DEM model of the EPB shield machine tunnelling was established, and the simulated cutterhead torque was consistent with the theoretical calculation results, which illustrated the model was correct.

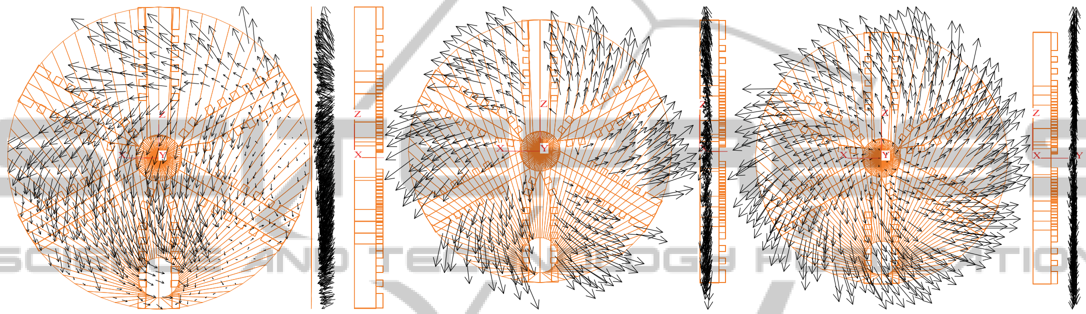
The displacement distribution of soils in the chamber and in the cutterhead during the shield machine tunnelling was obtained. The distribution presented periodic variation, and the movement period of soil particles is related to the cutterhead rotation speed.

Seen from the figures of displacement distribution, the soil displacement in the cutterhead is determined by the cutterhead rotation, the



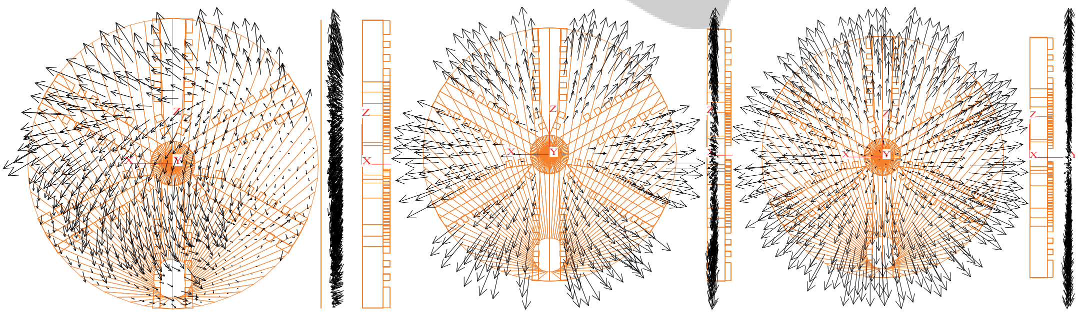
1) in chamber 2) in cutterhead 3) in front of cutterhead

Figure 4: Displacement distribution of soil particles at 0 s.



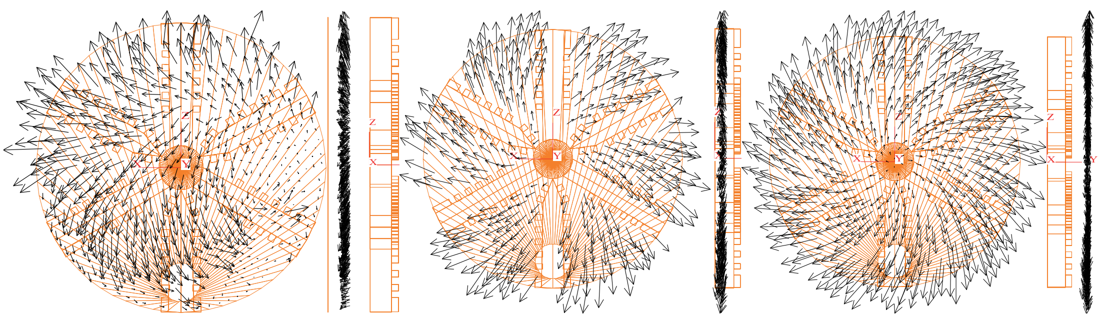
1) in chamber 2) in cutterhead 3) in front of cutterhead

Figure 5: Displacement distribution of soil particles at 10 s.



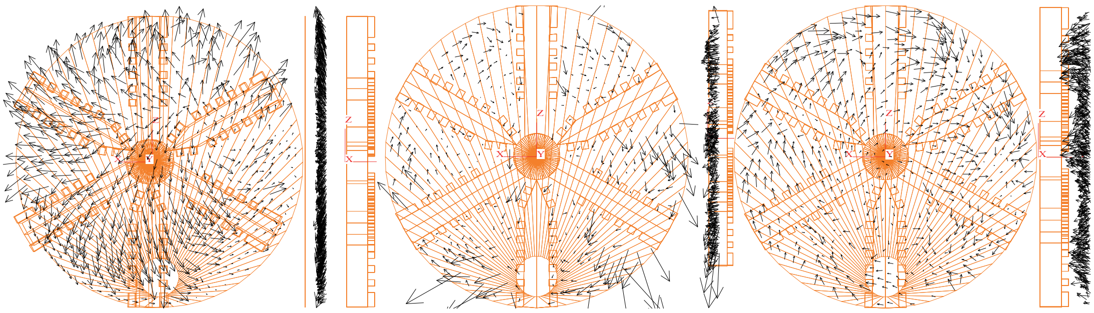
1) in chamber 2) in cutterhead 3) in front of cutterhead

Figure 6: Displacement distribution of soil particles at 15 s.



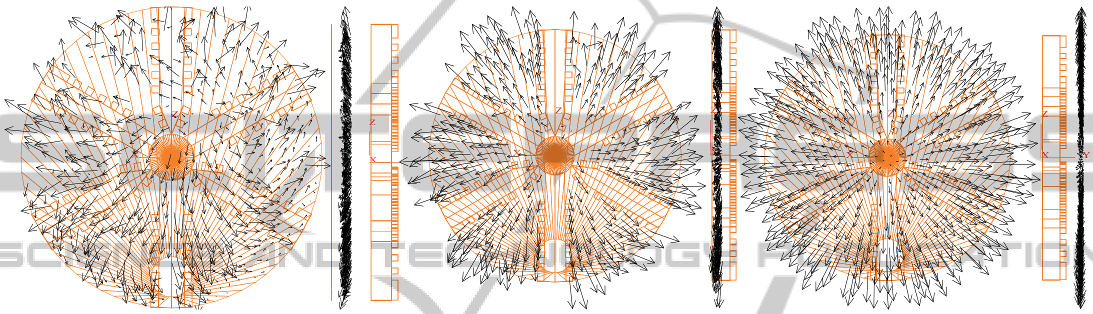
1) in chamber 2) in cutterhead 3) in front of cutterhead

Figure 7: Displacement distribution of soil particles at 20 s.



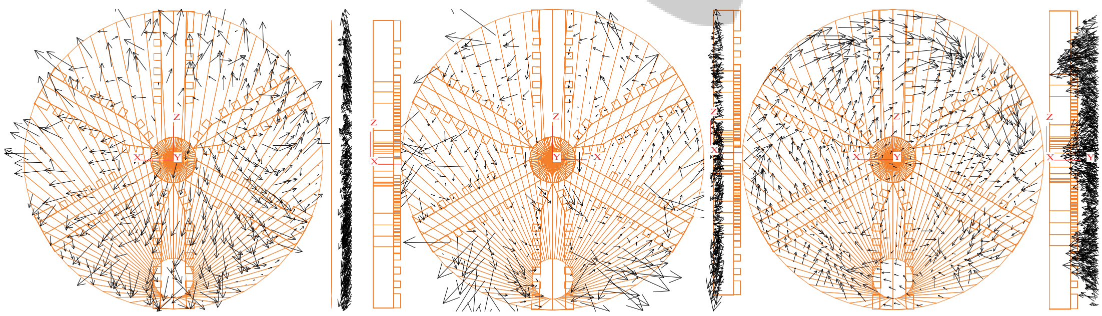
1) in chamber 2) in cutterhead 3) in front of cutterhead

Figure 8: Displacement distribution of soil particles at 30 s.



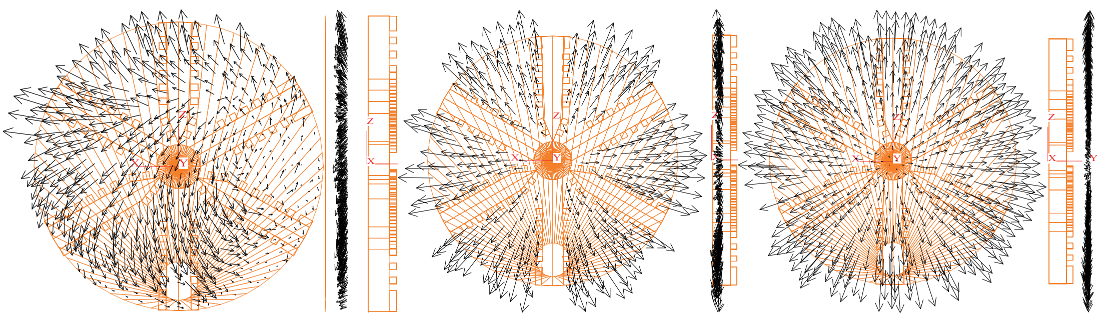
1) in chamber 2) in cutterhead 3) in front of cutterhead

Figure 9: Displacement distribution of soil particles at 45 s.



1) in chamber 2) in cutterhead 3) in front of cutterhead

Figure 10: Displacement distribution of soil particles at 60 s.



1) in chamber 2) in cutterhead 3) in front of cutterhead

Figure 11: Displacement distribution of soil particles at 30 s with cutterhead rotation speed 1rpm.

interaction forces between particles and the ground pressure; in the chamber, the displacement of above soils were subjected to the ground pressure mainly, and the displacement of the bottom particles were caused by the rotation of the screw conveyor.

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