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Discrete element model for performance analysis of cutterhead excavation system of EPB machine

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ABSTRACT

With the aim of probing for design theory of cutterhead excavation system of earth pressure balance (EPB) machine, the parameters representing the system performance are concluded firstly. Then a 3D model for cutterhead excavation system of EPB machine is presented with the discrete element method (DEM) software PFC^{3D}, which is capable of simulating the tunneling ground in site, the machine structure and the excavation operation. The performance parameters indicating stability of excavation face, soil discharging rate, cutterhead system torque and cutter wear are measured by running the DEM code. The results obtained with the DEM model are accord with situ data. It indicates that the DEM model is a promising method replacing the field experiment to analyze the influences of the structural parameters on system performances, which are essential for structure optimization design of the cutterhead system of EPB machine.

1. Introduction

The full face tunnel boring machine (TBM) includes the soft ground TBM and the rock TBM. The soft ground TBM includes the EPB machine and the slurry machine according to different supporting ways of excavation face. Performance prediction of the rock TBM has already been studied. Rostami and Ozdemir (1993), Burger (2006), Karlheinz (2009), Peter (2009), Abdolreza and Siamak (2012) and Bilgin et al. (2012) are among the researchers who realized the pioneering works with respect to rock TBM performance. Contrary to rock TBMs, the soft ground TBM performance forecasting is a new science. It is rather difficult in capturing the complex interaction between the pressurized shield drive and the ground. Since the early 20th century, the soft ground TBM cutterhead design has historically been driven by iterative designs based on empirical data, observations over various projects and industry rules of thumb (Glenn and Mustafa, 2011). Nishitake (1987) in Mitsubishi Heavy Industries Ltd., described several types of EPB shields which can cope with large size boulders, and the existing machine is modified to deal with the problem. Dowden and Cass (1991) in Robbins Corp. reviewed the current designs of shielded type machines and their application, and discussed new developments which blended hard and soft ground tunneling technology. Burger (2007) in German Herrenknecht Corp. described the technical points of the cutterhead design of the slurry shield and the EPB shield machine.

Nowadays a lot of scholars try to find out the relations between the tunneling parameters, the soil parameters and the structure parameters of cutterhead system. Wang and Fu (2006) formulated mathematical models with respect to the total thrust, the soil pressure in chamber, the rotation speed of screw conveyor and the advance speed by theoretical analysis, and the formula is validated by in situ measured data. Zhang et al. (2005) proposed mathematical models of the advance speed and the torque of EPB cutterhead respectively. Yang et al. (2006) analyzed the thrust force, the torque of cutterhead and soil pressure in chamber in two different cutterhead opening rates of 30% and 70% by model tests. Shi et al. (2011) introduced an improved torque calculation formula taking account of cutterhead structures and cutting principle of tools. Lambrughi et al. (2012) developed a three-dimensional FEM numerical model of EPB machines simulating the overall process of excavation and construction of a tunnel. The influence on calculated ground displacements is investigated by means of a series of operation parameters analyzes. Manuel and Luis (2005) established a DEM model to study the problem of soil stability at the tunnel face, the thrust and the torque needed to excavate the tunnel. The research works described above give the factors affecting the cutterhead torque, the thrust and ground stability. However, the performance index of the cutterhead excavation system is not definitely proposed from the view of system design.

Recently, Ulrich and Marc (2011) pointed out the key performance indicators for estimating the performance of EPB tunneling based on the evaluation of data from a great number of projects. Glenn and Mustafa (2011) examined how discrete element analysis can be applied to cutterhead performance optimization. This

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paper establishes a DEM model of the cutterhead excavation system, taking an EPB machine tunneling in Beijing metro construction as prototype. The performance parameters representing the stability of excavation face, the soil discharge rate, the system torque and the cutterhead wear are shown by running the DEM model. Parameters of EPB tunneling are measured in situ to validate the model. The DEM model is an effective tool for performance prediction and design of cutterhead system.

2. Performance indicators

The cutterhead system of EPB machine is mainly composed of the cutterhead, the soil chamber and the screw conveyor, the function of which is cutting ground, supporting excavation face and discharging soils (Fig. 1). The performance is related to the structure parameters, the operation parameters and the soil parameters. The design of cutterhead system is concerned of the cutterhead structure style, the opening location and size, the tool selection and layout, the arrangement of muddlers in the chamber, the chamber structure and size. The operation parameters include the thrust speed, the cutterhead rotation speed and the screw conveyor rotation speed. The soil parameters contain the strength, cohesion, particle diameter, etc.

The performance indicators of cutterhead system design are concluded as follows.

2.1. Stability of excavation face

In the process of EPB tunneling, the chamber soils pressure applied to the tunnel face counterbalances, in theory, the existing overburden and hydrostatic pressures of ground. However, we cannot measure the pressure at the tunnel face. Instead, the pressure on the chamber board is measured. In fact, there is a pressure difference between the excavation face and the chamber board. The equivalent pressure at the excavation face is larger than the equivalent pressure on the chamber board. The pressure difference is related to the cutterhead opening rate. The larger the opening rate, the smaller the pressure difference (Wu et al., 2009). The smaller the pressure difference, the easier the ground stability, because we control the chamber board pressure instead of the excavation face pressure. So the performance indicator of cutterhead system design is characterized as the pressure difference between the excavation face and the chamber board, as shown in formula (1):

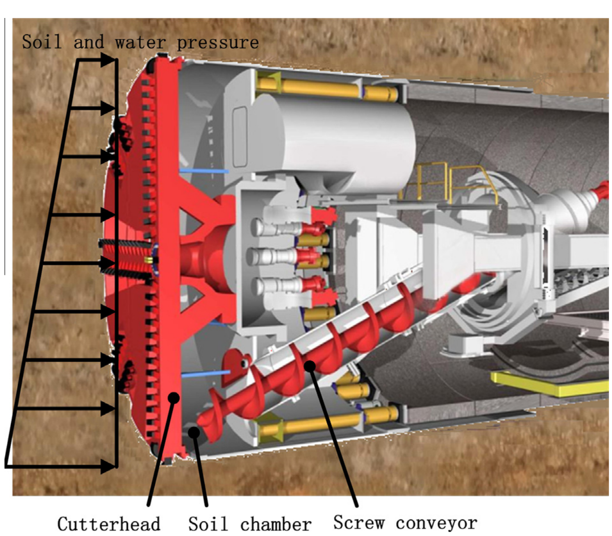

Fig. 1. Cutterhead system of EPB shield machine, modified from Herrenknecht website (http://www.herrenknecht.com).

$$\Delta P = p_e - p_c \quad (1)$$

where ΔP is the pressure difference between the excavation face and the chamber board, p_e is the excavation face pressure, p_c is the chamber board pressure.

2.2. Soil discharging rate

The soil discharging rate is defined as the ratio of the soil going out from the chamber system and the soil coming into the chamber system, as shown in formula (2):

$$R = Q_{out}/Q_{in} \quad (2)$$

where R is the soil discharging rate, Q_{in} is the soil quality coming into the chamber system, Q_{out} is the soil quality going out from the chamber system.

Theoretically, for the excavation face stability, the soil coming into the chamber system should equal the soil going out from the chamber system. In other words, the amount of soils in the chamber system should keep stable during tunneling. In actual, the soil discharging rate is usually not 100%, because of the compressibility of soils, the opening position on cutterheads, and the mismatch of speed between shields tunneling and the screw rotation. In the view of design, the mechanical structure of cutterhead systems should adapt to the rules of soils motion. The chamber system should not have "dead space" which holds back the flow of soils.

2.3. Cutterhead system torque

The system torque is comprised of the cutterhead torque and the screw conveyor torque, which is defined as formula (3):

$$T = T_c + T_s \quad (3)$$

where T is the cutterhead system torque, T_c is the cutterhead torque, T_s is the screw conveyor torque.

The cutterhead torques contain the friction torque on frontal surface, on circular surface and on back surface, the cutting torque, the shearing torque on opening, the agitating torque and the torque of rotational bearing. The screw conveyor torque is mainly constituted of the friction torque on the screw, on the driving shaft and on the inner wall of screw machine. The factors causing the torque applied on the cutterhead system include soils, system structures, overburden depths, additives and other aspects. In cutterhead system design, in order to reduce the stress and deformation of the system structure, decrease the energy consumption, the system torque smaller is better.

2.4. Cutter wear

When cutting grounds, in the action of the cutterhead thrusting and the chisel tools (ripper, scraper) dragging, the soils deform, slip and break into chip. There are frictions on the front facet and the back facet of tools, which leads to the wear of tools. As the friction is caused by the positive pressure, the normal force (F_n) and the cutting force (F_c) applied on tools is regarded as the indicator of the abrasion. The greater the force is, the worse the potential abrasion. The amount of abrasion is related to the depth of cut, the character of soils, the material of tools and the mounting position of cutters on the cutterhead. For structure design, we should optimize the position of tools to decrease the cutter abrasion.

3. DEM model for performance analysis

The DEM model of cutterhead excavation system tried to reproduce the tunneling ground (Fig. 2) from the north station of