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Optimal control of an earth pressure balance shield with tunnel face stability

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A R T I C L E I N F O

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A B S T R A C T

To ensure security during the excavation process of an earth pressure balance shield, this paper presents an optimal control method that accounts for the tunnel face's stability. The tunnel face is controlled by an optimal screw conveyor speed derived from the particle swarm optimi
zation algorithm for a designed stable normal vector angle range on the distribution surface of the chamber pressure field. These normal vector angles can be computed online by measuring the changes to the earth pressure in the shield's chamber using a BP neural network model of the chamber pressure field distribution. An experimental example that uses excavation data from an actual EPB shield is given to illustrate the effectiveness of the proposed method.

1. Introduction

A shield machine is a type of large engineering machinery used in underground tunnel boring. More specifically, the earth pressure balance (EPB) shield is widely used in the development of underground spaces and has the advantages of a minimal influence on the environment, high excavating efficiency and wide stratum adaptability. However, certain extremely unpredictable geological and hydrogeological conditions during EPB shield excavation can result in tunnel face instability. The chamber pressure cannot maintain a balance with the soil and water pressure in front of the tunnel face, leading to disasters such as ground caving or heaving. Therefore, it is essential to ensure the stability of the tunnel face before the excavation process of the EPB shield commences.

The earth pressure of the work chamber is controlled mainly by a screw conveyor discharging the soil out of the chamber and/or the shield's advance speed [1]. In the shield tunneling process, the work chamber is filled with the wet soil yielded by the cutting operation, and the soil in the chamber is mixed with bentonite using a blender to become ready for transmission. The principle of the EPB shield's function is shown in Fig. 1.

To make the shield tunneling machine excavate along the set working line, a hydraulic thrust control system on pressure and flow compound is proposed in [2]. A model of the cutter head's torque is established in [3] by considering the cutter head's structure, cutting scheme and the interaction between the cutter head and soil. Researchers have made progress in the concept of intelligent control in the tunneling process. The BP neural network method is used to model the EPB shield's tunneling process in [4]. Furthermore, an earth pressure prediction model for advancing speed and screw conveyor speed based on the least squares support vector machine (LS-SVM) to maintain the earth pressure balance on the tunnel face and avoid ground deformation is considered in [5].

However, a key problem in the practical tunneling process involves stabilizing the tunnel face such that the chamber pressure will change between the active earth pressure and the passive earth pressure. The pressure distribution in the work chamber of an EPB shield can be made variable by controlling the screw conveyor speed, hydraulic thrust speed and cutter head speed acting on the tunnel face so that an earth pressure field will form in the work chamber. It is necessary to find a method that can describe such an earth pressure field to stabilize the tunnel face during the tunneling process.

In fact, the earth pressure field is distributed in the form of an irregular surface along pressure sensors located on the work chamber clapboard. A numerical method is presented in [6] in which the normal vector representing the geometric characteristics of the pressure field surface is used to analyze the tunnel face stability of the EPB shield. This vector can be derived easily using the discrete derivatives calculated from the signals sampled through the pressure sensors. This paper suggests using the normal vector of the pressure field surface to perform real-time analysis on the changes to the active and passive earth pressures in the ground in front of the tunnel face, and then control the screw conveyor speed subject to the tunnel face's stability.

In the shield tunneling process, the hydraulic thrust speed and cutter head speed are designed a priori based on the local geological and

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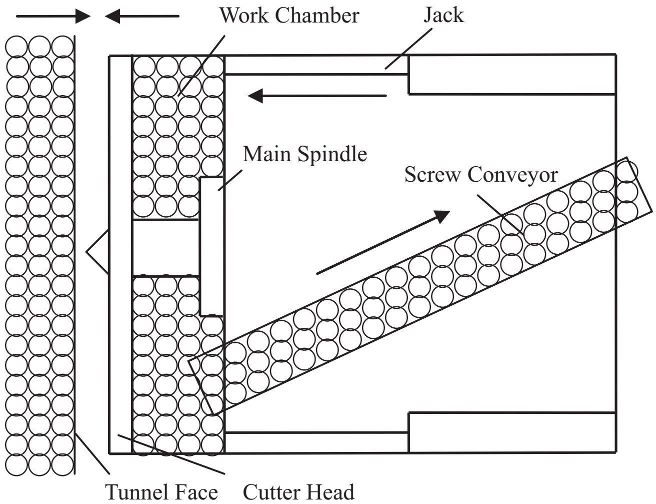

Fig. 1. Principle of the EPB shield.

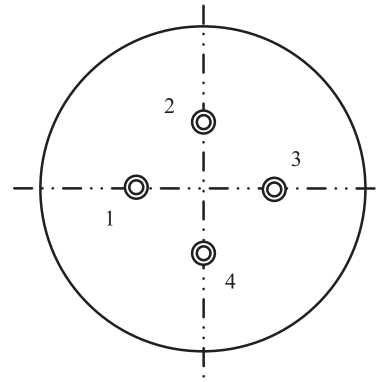

Fig. 2. Pressure sensor distribution of a certain type of EPB shield.

hydrogeological conditions. In this way, the chamber pressure is controlled mainly by adjusting the rotating speed of the screw conveyor. In the traditional control method, the operator's experience is often used to select an appropriate screw conveyor speed, so it is difficult to ensure the pressure field's stability and tunneling safety during construction. Optimal earth pressure balance control methods for shield tunneling based on LS-SVM, PSO and neural network models are proposed in [4,5]. However, the optimization methods based on precise mathematical models are unsuitable for the shield tunneling processes due to their complicated tunneling mechanisms and variable working conditions. More recently, the particle swarm optimization algorithm has been applied to many areas of industrial engineering because of its high precision and rapid convergence [7].

This paper presents an optimization control method based on the particle swarm optimization algorithm for the screw conveyor rotating speed when considering tunnel face stability. The chamber pressure field stability analysis is performed based on the pressure field's normal vector changes using online measurement data from pressure sensors. A criterion for the active and passive earth pressures' balance is given by means of the stable range of the normal vector angle, after which the particle swarm optimization algorithm is used to find the optimal screw conveyor speed needed to stabilize the earth pressure field of the work chamber. Finally, a simulation analysis is performed to illustrate the effectiveness of the proposed method.

2. Estimation method for the pressure field's normal vector

A numerical method based on the chamber pressure field's normal vector is presented in [6] to analyze the tunnel face stability during the EPB shield tunneling process. In this paper, further work is performed to optimally control the EPB shield tunneling process with tunneling face stability in mind.

2.1. Normal vector of the chamber pressure field

An example of the EPB shield considered is shown in Fig. 2, in which the cutter head diameter is 6.28 m, four pressure sensors are located on the horizontal and vertical axes of chamber clapboard, and the distance from each sensor to the center point is 0.9 m. Detailed specifications on the EPB are given in Section 4. Due to the location of the main spindle, no pressure sensor is installed on the center of the clapboard. A virtual earth pressure sensor, named sensor 0, is set on the center of the clapboard for the subsequent analysis, and its sample values is taken as the average value of the four real pressure sensor values. A three dimensional rectangular coordinate system is constructed in which the clapboard center is located at the origin, the horizontal and vertical lines crossing the clapboard center are the assumed to be the X axis (unit: m) and Y axis (unit: m), respectively, and the advance axis of the EPB shield is assumed to be the Z axis (unit: bar). As an example to show how the normal vector is determined, four groups of shield tunneling data and the positions of the five sensors are taken as shown in Table 1, after which [6] a discrete curve model is derived to estimate the center normal vector, including two discrete curves denoted as curve 1-0-3 and curve 2-0-4 in Fig. 3.

The cumulative chord length parameterization is first carried out for each discrete curve, after which the tangent vector on the center of each discrete curve is calculated. Finally, an optimization problem is established in which the object function is the sum of the product between the unknown normal vector and the tangent vector for each discrete curve in Fig. 3, and the length of the unknown normal vector is standardized. The chamber pressure field surfaces and the center normal vectors for Table 1 are shown in Fig. 4, where the red areas represent the pressure in the lower part of the chamber and the blue areas represent that in the upper part of the chamber.

A contour map of the pressure distribution on the chamber clapboard is shown in Fig. 5. It can be observed that because the wet soil is deposited in the work chamber along the vertical direction and the pressure of the chamber pressure field changes when the screw conveyor placed on the bottom discharges the soil out of the work chamber, the pressure distributes irregularly along the vertical direction and symmetrically along the horizontal direction during the stable tunneling process. As a result, the earth pressures experience a more obvious change in the vertical direction than in the horizontal direction. Therefore, the angle between the normal vector and the vertical direction, called the normal vector angle, can be selected as an index to reflect the stability of the chamber pressure field during the stable tunneling process. The direction of the center normal vector changes with the pressure in Fig. 4. As the pressure's change in the work chamber's vertical direction is decreasing, the normal vector angle is increasing, but it experiences less change in the horizontal direction.

Table 1
Shield tunneling data and position of each sensor.

Sensor	X (m)	Y (m)	Z1 (MPa)	Z2 (MPa)	Z3 (MPa)	Z4 (MPa)
1	−0.9	0	0.12	0.13	0.12	0.14
2	0	0.9	0.10	0.11	0.10	0.12
3	0.9	0	0.13	0.12	0.12	0.15
4	0	−0.9	0.17	0.15	0.13	0.14
0	0	0	0.13	0.13	0.12	0.14