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A force transmission assessment method for thrust system in shield machines based on the relative coefficient in compound ground

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ABSTRACT

An evaluation method for force transmission in the thrust system of tunneling machines in compound ground was investigated in this study. First, the mechanical model for a pushing system in heterogeneous ground was constructed. Then, the relative coefficient of eccentricity on a conical surface was determined based on the mechanical model. Subsequently, the uniformity degree of force transmission in the thrust system was measured using the relative thrust coefficients of eccentricity. Eventually, the performance of force transmission under various arrangements with an equal number of jacks was discussed in detail by applying the conical model of eccentricity to the thrust mechanism of a tunneling machine used in engineering projects. The 3D parameter models for the thrust system of an earth pressure balance shield machine (diameter: 6.34 m) were established using SolidWorks. In addition, a propelling system with 22 hydraulic cylinders was simulated via the automatic dynamic analysis of mechanical systems (ADAMS). Results of the numerical analysis agree well with those simulated by ADAMS. The results provide a theoretical basis and support for choosing a non-equidistant driving system in a composite stratum.

1. Introduction

Earth pressure balance (EPB) shield machines have been commonly adopted in recent years [1]. Among the applications of these machines, EPB tunneling is continual conducted in rock masses, particularly when preliminary investigations detect the presence of substances (e.g., asbestos) and deleterious or explosive gases that can endanger the health and safety of workers. The first EPB shield machine was invented in Japan in 1975, and considerable research on EPB shield machines has followed since then [2,3]. Tunnel boring machines (TBMs) with single and double shields for rock tunneling have the same structure as EPB shield machines, and a suitable model has to be selected from a variety of open or closed models based on specific conditions [4,5]. The definite relationship between thrust and the advance rate of a TBM cutter head has been studied through experimental determination, and the action beneath disc cutters that originates from cutter head thrust has been researched [6,7]. The process of determining the optimal thrust force of an EPB shield machine with even driving systems under different conditions has been discussed in detail [8]. Various predicted models for TBM performance have also been presented [9].

Main structure of an EPB shield machine is shown in Fig. 1. During the tunnel excavation, the rotating cutters fixed on the cutter head cut off soil and rocks, which pass through a pressurized head chamber where muck pressure is equal to the earth pressure of the tunnel face. Then, the entire machine is pushed forward by hydraulic cylinders of the thrust system that apply pressure on rear lined segments [10,11]. The thrust system not only pushes the entire machine forward during tunneling but also adjusts the pose of the main machine to make sure that the machine will move along the planned trajectory [12].

When all of the jacks apply a force on the rear segments, the lining segments provide the equivalent counter pressure to the driving system. Cracks may develop in segments when the thrusts of all the hydraulic cylinders reach the crown of the tunneling anti-load segment. In particular, the anisotropy of the excavated interface rocks and the inconsistencies of the resistance surrounding the machine, along with its own weight, may create a complicated working condition. Consequently, offset load may be easily generated on segments under the aforementioned condition. The eccentricity of the spatial force ellipse in a thrust system has been discovered and used to scale the performance of force transmission in homogeneous ground [13]. As commonly known, no single ground exists in engineering applications. Concurrently, some studies have suggested that a significantly large eccentricity of the

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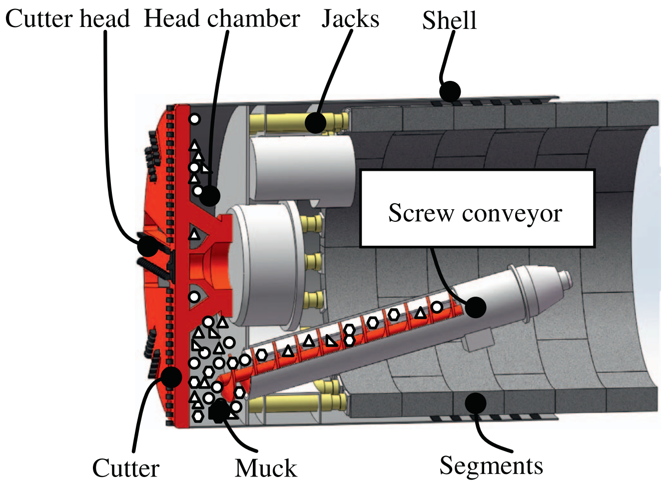

Fig. 1. Schematic structure of an EPB tunneling machine.

spatial ellipse rapidly reaches the limitation of 1 in various kinds of shield machines with diameters ranging from 1 m to 14.5 m [14]. Therefore, eccentricities cannot be distinguished efficiently among driving systems with spatial ellipse eccentricities that are all near 1. And a new way to evaluate force transmission for driving system would be discussed in the article.

In general, all the hydraulic cylinders of the thrust system for shield machines are arranged equidistantly along the circumference inside the shell, and the number of jacks completely depends on tunnel diameter and geological conditions. However, certain complex load conditions must be considered when design a non-equidistant driving system, including non-homogeneous oil, drastic changes in the load direction on the machine body, and an overweight cutter head. Many researchers have indicated that various deformation characteristics and natural frequencies may exist in different driving system configurations with the same number of hydraulic cylinders in a single stratum [15,16]. The characteristics of spatial force ellipse transmission have been researched [13]. Although the deformation characteristics of the driving system in mixed ground have been discussed [17] and the carrying capacity of the propelling system [18] has been investigated on the basis of the Ref [19] only a few studies have been conducted to investigate the adaptability characteristics of a thrust system under various arrangements in mixed ground.

The mechanical model for a pushing system in a tunneling machine has been presented in this study. Then, using the eccentricity of the relative thrust coefficient to measure the uniformity degree of force transmission, eccentricity on the conical surface has been discovered. Eventually, the performance of force transmission under different types of driving system layout has been discussed by considering a conical surface in the propelling system as an engineering application. The results can provide a theoretical basis and support for designing a new driving system for shield tunneling machines under special conditions.

2. Construction of an eccentricity surface model for a driving system in heterogeneous ground

According to [12], the mechanical model for the thrust system and the Lagrange partial differential equations can be obtained as follows:

$$\sum_{i=1}^{N} F_i - F_z = 0, \tag{1}$$

$$\sum_{i=1}^{N} F_i x_i + M_y = 0, \tag{2}$$

$$\sum_{i=1}^{N} F_i y_i - M_x = 0, \tag{3}$$

$$F_i - \overline{F} + \lambda_1 + \lambda_2 x_i + \lambda_3 y_i = 0, \tag{4}$$

where $\bar{F}$ can be expressed as

$$\bar{F} = \frac{1}{N}\sum_{i=1}^{N} F_i = \frac{1}{N}F_z, \tag{5}$$

where (x_i, y_i) represents the layout coordinates of ith hydraulic cylinder in the pushing system; F_i $(i = 1, 2, \ldots, N)$ is the thrust force of the i jack in a propelling system; N is the number of driving systems; F_z is the resultant resistance in the direction of shield machine tunneling; M_x and M_y are the drags in the horizontal and vertical directions, respectively; and λ1, λ2, and λ3 are the Lagrange's coefficients for Eqs. (1)–(3), respectively.

By simultaneously solving Eqs. (1)–(4), the forces Fi of all the hydraulic cylinders are determined to consist of a spatial ellipse, and the eccentricity of the force ellipse is used to scale the uniform degree of thrusts for the jacks in a single ground [13]. However, no pure single stratum exists in engineering applications, and resistance Fz, as well as moments Mx and My, which can be deduced from the given geological parameters, should be changed frequently within the ranges. Therefore, the following relative thrust coefficient dri is proposed in this study to scale the even degree of thrusts in a fixed ground:

$$d_{ri} = (F_i - \overline{F})/\overline{F} \tag{6}$$

By introducing Eq. (6) into Eq. (4), the following equation can be obtained:

$$\overline{F} d_{ri} + \lambda_1 + \lambda_2 x_i + \lambda_3 y_i = 0 \tag{7}$$

Given the uniform distribution of the hydraulic cylinders in the thrust system, the following equation can be obtained:

$$x_i^2 + y_i^2 = r^2, \tag{8}$$

where r is the radius of the arrangement of all jacks.

As shown in Fig. 2, plane α can be expressed using Eq. (7), and cylindrical surface β with radius r can be determined using Eq. (8). The spatial points (x_i, y_i, d_{ri}) should be in a closed spatial ellipse curve line, which is the intersection of plane α with an angle of γ between planes o-xy and α. d_{ri} is the value of the relative thrust coefficient of the ith hydraulic cylinder at point coordinates (x_i, y_i). Then, the eccentricity of the relative thrust coefficient of the ellipse demonstrates the uniformity

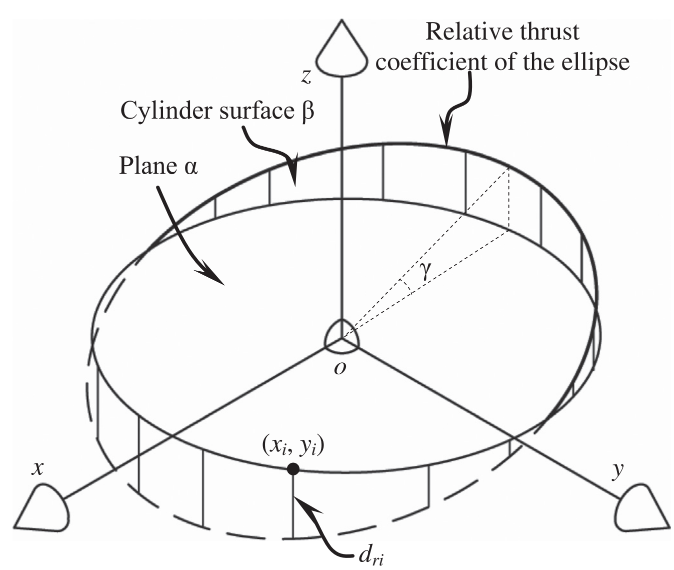

Fig. 2. Relative thrust coefficient of the spatial ellipse in the thrust system.