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Modeling of the thrust and torque acting on shield machines during tunneling

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ABSTRACT

The paper analyzes the total load in the shield tunneling process. The cutterhead load is the most complicated component which provides a real-time response to geological conditions and operating states. This study calculates the normal and tangential loads on cutterhead by decoupling the cutterhead-soil system on excavation face. Then a comprehensive consideration is made of the influences of the overburden, the soil cutting, the chamber support, and the friction between the shield and the soil on loads. This study establishes a predicting model for the total load that fully reflects the influences of geological, operating, and structural parameters. The model is applied into two cases. Its effectiveness is verified by comparing the load calculated by the model, measured during tunneling and predicted by the Krause empirical model. The paper provides a reference for load designs and parameter controls during construction.

1. Introduction

Shield construction, a subsurface excavation technique, is widely applied in the construction of underground urban transport systems due to the advantages of safety, efficiency, and low interference with the surrounding environment. Accurately calculating the load in the shield tunneling process provides a theoretical basis for implementing top-down equipment design, as well as controlling and regulating the drive and transmission systems during construction [1–3].

At present, the empirical load model proposed by Krause is still the preferred basis for load determination in shield design and construction areas [4], although studies concerning the problems of shield load have been conducted in recent years. The cutterhead thrust was approximately considered as equivalent to the earth pressure at rest on the excavation face for purposes of analytical load analysis and calculation, creating a linear distribution with the overburden [5]. Wang [6] assumed that the cutterhead load was evenly distributed and calculated through the integration of a concentrated force along the tunneling interface. As for experimental research, Gertsch et al. [7] studied the influences of different geological conditions on shield load by performing rock-breaking experiments; Beaucour et al. [8] analyzed the changing rule of cutterhead friction in shield tunneling through field experiments; and Xue et al. [9] investigated the stress characteristics in the rock breaking process caused by a cutter. Because of the technical and cost constraints of experimental research, numerical simulation technology has been gradually applied in studies on shield load problems. Shen et al. [10] applied an ALE algorithm to analyze the torque variations in the tunneling process; Eberhardt [11] and Kasper and Meschke [12], among others, calculated the stress distribution of soil on the excavation face through a three-dimensional numerical simulation; and Su et al. [13] analyzed the influences of different cutterhead structures on shield tunneling characteristics. At present, the application of numerical simulations in major engineering calculations is still limited by simplified models, complicated calculations, and inadequate soil deformation simulations. Relevant studies based on the analysis and recognition of in-situ data have also been conducted. Jung et al. [14] investigated the fundamental reasons for reduced shield tunneling performance in the Han River riverbed tunnel through a field measurement data analysis. Reza et al. [15] discussed the changing rules of loads based on a multi-factor fuzzy data analysis; Yagiz et al. [16] applied artificial neural networks and non-linear multiple regression to the estimation of tunnel boring machine performance, and [17] also utilized rock mass properties for performance predictions.

Due to its simplicity, the Krause empirical model can be used for preliminary load estimations. However, the estimated load tends to be high and the value range is too broad. A mechanism is clearly required to accurately predict and reasonably describe how these parameters influence loads. During the shield tunneling process, a complex nonlinear coupling system is formed between the cutterhead and the soil on the excavation face; its load provides a real-time response to the geological conditions and the operational states of the equipment [18]. Implementing a decoupling analysis of the system is the foundation for establishing a load predicting model. In existing analytical research, the load distribution on the cutterhead was typically simplified to either an even or linear distribution; with even distribution, the load was approximately calculated through the integration of a

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concentrated force along the tunneling interface, while with linear distribution, the load was approximately calculated through the equivalent of the earth's pressure at rest. The dynamic load components caused by the interaction between the cutterhead and the soil was ignored. While other related research mostly focuses on experiments, numerical simulations and in-situ data, there is still no analytical model for load prediction that fully reflects all of the influences of geological conditions, equipment structures, and operational status on the load.

This paper initially analyzes the interaction characteristics between different parts of the shield tunneling machine and the soil and subsequently determines the composition and core influencing factors of the total excavation load. A predicting model of the total load during the excavation of a shield tunneling machine is established through a decoupling analysis of the coupling nonlinear system between the cutterhead and the soil on the excavation face and a comprehensive consideration of the loads on other parts. In addition, the model is applied to the prediction of the total load in two metro engineering scenarios. The effectiveness of the model is verified and discussed through a comparison of the calculated load and the in-situ data.

2. Analysis and modeling of the total load in the shield tunneling process

2.1. Krause empirical model

The Krause empirical load model is widely used in shield design and construction. In 1987, Krause collected and analyzed the construction load data from 397 sets of slurry shield tunneling machines made in Japan and 12 sets made in Germany. He proposed the empirical load model shown in Eqs. (1) and (2) [19,20]:

$$F = \beta D^2, \tag{1}$$

$$T = \alpha D^3, \tag{2}$$

where F (kN) represents the total thrust, T (kN m) represents the total torque, D (m) represents the shield diameter, and β (kN/m^2) and α (kN/m^2) represent the empirical values for the normal and tangential loads on the unit excavating area that are related to the geological condition, the equipment operating state, and the equipment structure. Their ranges, determined by the statistical analysis of in-situ data and widely used in current engineering, are $\alpha = 9$–23 and $\beta = 500$–1200, as shown in Fig. 1. The model may be used for a rough estimation of the load range. A comprehensive and accurately predictive load model is still necessary for the design and real-time control of the drive and transmission systems in a tunneling process.

2.2. Analysis of the total load in the shield tunneling process

Based on the interactions between different parts of the equipment and the soil, the total load in an excavation process can be divided into the cutterhead load, the shield load, and the subsequent equipment load, as shown in Fig. 2. The cutterhead is a key component of the shield tunneling machine, primarily consisting of the panel, the opening, and the installed cutters, as shown in Fig. 3. The cutterhead load is the load component with the maximum influencing factors and the most complicated rules.

The paper primarily discusses the earth pressure balance shield. The total thrust and the total torque in the tunneling process consist of the following parts, as shown in Eqs. (3) and (4):

$$F_{total} = F_1 + F_2 + F_3 + F_4 + F_5, \tag{3}$$

$$T_{total} = T_1 + T_2 + T_3 + T_4. \tag{4}$$

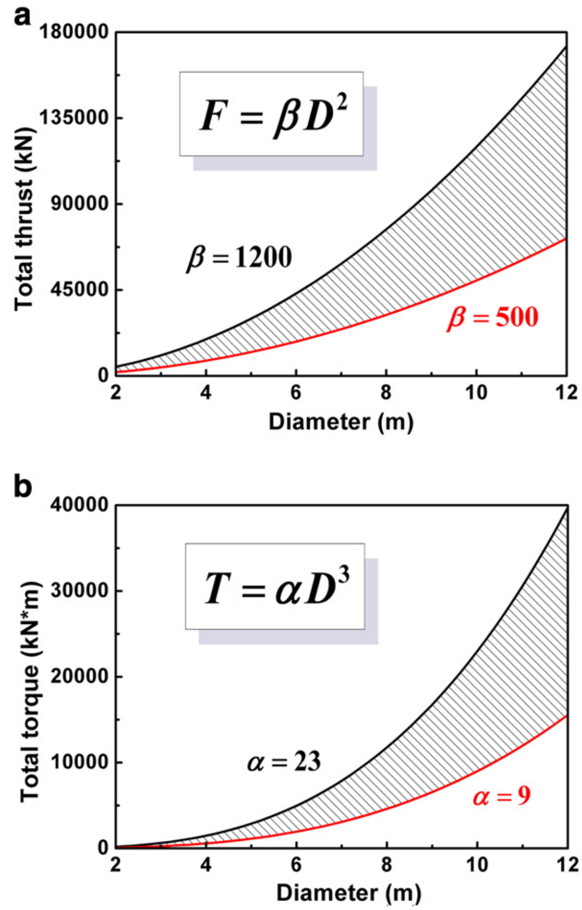

Fig. 1. Load ranges of the Krause empirical model.

F_1, F_2 and F_3 belong to the cutterhead thrust. F_1 represents the cutterhead extrusion force caused by excavation; F_2 represents the earth pressure at rest on the excavation face caused by the overburden; F_3 represents the support pressure from the chamber that maintains the stability of the excavation face; F_4 represents the friction between the shield and the surrounding soil (the shield is used to temporarily support the unlined tunnel); and F_5 represents the subsequent equipment traction.

T_1, T_2, T_3 and T_4 all belong to the cutterhead torque. T_1 represents the friction torque between the cutterhead panel and the soil; T_2 represents the strata resistance torque on the cutters in the soil cutting process; T_3 represents the friction torque between the side of the cutterhead and the surrounding soil; and T_4 represents the mixing torque within the chamber. In addition, the loads also include the friction between the lining segment and the shield, the friction torque of the cutterhead sealing ring, and the friction torque of the speed reducer, etc. However, under normal circumstances, the proportion of the aforementioned load components in the total is less than 5% [21]. Therefore, this paper considers nine load components of F_1–F_5 and T_1–T_4 while calculating the total load.

To analyze the composition of these total loads, the total thrust primarily consists of the cutterhead thrust, the shield thrust and the subsequent equipment thrust, and all of the torque components almost locate on the cutterhead. In general, the shield thrust occupies a large portion of the total thrust but is relatively stable during tunneling. The subsequent equipment thrust is usually a very small part of the total thrust and almost constant while the machine is working. The cutterhead thrust and torque are the fluctuating parts of the total load that are directly influenced by the interaction between the cutterhead and the soil; they provide a real-time response to the