Tunnelling and Underground Space Technology 82 (2018) 325–345

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Cutting force measurement and analyses of shell cutters on a mixshield tunnelling machine

Xing Huang[a], Quangsheng Liu[a,b,*], Lei Chen[a], Yucong Pan[b], Bin Liu[a], Yongshui Kang[a], Xuewei Liu[a]

[a] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430071, China
[b] Key Laboratory of Geotechnical and Structural Engineering Safety of Hubei Province, School of Civil Engineering, Wuhan University, Wuhan, Hubei 430072, China

A R T I C L E I N F O

Keywords:
Shield tunnelling
Cutting forces
Real-time monitoring
Strain gauge
Saddle
Tunnelling parameters

A B S T R A C T

In this study, a real-time measurement method for cutting forces of a mixshield tunnelling machine is proposed. The strain of the cutter saddle is monitored and used to back-calculate the forces acting on the cutter. The normal cutting forces are primarily analyzed in this study. Four resistance strain gauges are placed on the two free side surfaces of the saddle with effective protection, two strain gauges among which are installed in the vertical direction on one free side surface, and individual strain gauge is installed in the vertical and horizontal directions on the other free side surface. Then strain gauges are punched out from the cutter casing and sealed to connect with the data acquisition system. DataTaker DT80G intelligent data logger is employed as the core of the data acquisition system. The data logger is powered by a chargeable battery, and equipped on the back of the cutter-head and rotates with the cutter-head synchronously, which ensures continuous monitoring. The feasibility, durability, and stability of the monitoring system are calibrated and demonstrated. Subsequently, this measurement method has been implemented on the Herrenknecht mixshield machine at the Sanyanglu Tunnel in China. Monitoring was performed from chainage at No. 416 to No. 432 ring segmental lining, which lasted more than 20 days. A complete data set and corresponding tunnelling parameters of the mixshield were acquired. Statistical and trend analyses are carried out, the distribution along the installation radius, as well as the correlations between the cutting force and tunnelling parameters are analyzed. Results show that: (1) the cutting force decreases with increasing installation radius, center cutters experience maximum loading, panel cutters experience relatively equal moderate loads, and edge cutters experience the smallest loads; (2) the cutting force increases with penetration rate following a linear increasing function in general, where the cutting force mainly ranges from 20 to 70 kN; (3) after new cutter replacement, the increasing cutting force is in accordance with the increasing cutter-head thrust forces, however with continuous excavation, the increase in cutting force is slightly lower than the cutter-head thrust force, which may be due to cutter wear and mud cake wrapping; (4) the consistency between the cutting force and the cutter-head thrust force is better than the consistency between the cutting force and the cutter-head torque.

1. Introduction

The shield tunnelling is performed by cutting knives or even disc cutters that equipped on the cutter-head. There are tens of scraper cutters or even some disc cutters equipped on a mixshield machine cutter-head. However cutting forces are generally unequal depending on the installation position, advance parameter changes, cutter wear, and mud cake wrapping conditions, anisotropic features and geological variation of the tunnel face. The imbalance and uneven cutting forces of the cutters may result in serious problems, such as intense cutter-head vibration and serious cutter damage, which can reduce cutting safety and efficiency.

Understanding the distribution of cutting forces provides a basis for shield machine design and tunnelling optimization (Rostami, 2013; Yang et al., 2016a). The distribution of cutting forces contributes to geological conditions prediction, advance parameters adaptive adjustment and TBM/shield machine performance prediction including cutter wear and cutter-head vibration (Yang et al., 2016b, 2018; Huang et al., 2018).

In previous studies, there are some cutting force prediction models

* Corresponding author at: School of Civil Engineering, Wuhan University, Wuhan, Hubei 430072, China.
E-mail address: liuqs@whrsm.ac.cn (Q. Liu).

https://doi.org/10.1016/j.tust.2018.08.052
Received 31 January 2018; Received in revised form 14 June 2018; Accepted 20 August 2018

for disc-cutters of hard rock TBMs (Full Face Tunnel Boring Machine), but for scraper cutters of the EPB (Earth Pressure Balance Shields) or slurry shield TBM, the load on the tools is commonly determined by subtracting cutter-head friction forces and support pressures in the excavation chamber from global thrust, and then dividing by the number of excavation cutters. Such estimation calculated from global thrust forces contains only limited information about the complex excavation processes, i.e. only the variation in mean cutting force. It is therefore necessary to obtain the force on the cutters in real-time, which may provide insight into predicting excessive loading, intense cutter-head vibration and cutters damage.

Apart from the common ground deformation and failure monitoring during tunnelling (Li et al., 2017; Zhou et al., 2017), currently many scholars and TBM manufacturers are making efforts to develop cutter monitoring methods, including monitoring of cutter rotational status, temperature, wear, cutting forces and cutter-head vibration (Burger et al., 2006; Shanahan and Box, 2011; Huo et al., 2015; Edelmann and Himmelsbach, 2013; Lan et al., 2016; Huang et al., 2018). However, most of these methods suffer from a lack of durability or are not able to transmit data reliably. A method for continuous on-line cutter monitoring and measurement is highly desired.

Numerous difficulties are encountered when trying to monitor cutting forces due to the extremely harsh environment of the cutters. Gobetz (1973) placed strain gauges on the roller of the disc-cutter, cutting force data was obtained successfully for an excavation length of 12 feet. Results showed that cutting forces fluctuate severely, and peak forces are much larger than previously thought. Hopkins and Foden (1979) installed wireless transmitting strain gauges on cutters of the raiseborer reaming heads. Samuel and Seow (1984) placed the strain gauges on the roller of the cutters. Cutter loads were monitored for 20 min. Results showed that the forces are dynamic, but frequency-domain analyses showed that the frequencies of the forces are below 10 Hz. Zhang et al. (2003a, 2003b) installed strain gauges on the roller of the cutters to measure and calibrate cutter forces and deformation by Wheatstone bridge. Based on which the characteristics of cutter forces are obtained, a positive correlation between the crack depth and cutting force is presented. Entacher et al. (2012, 2013) placed the strain gauges on the bolts of the saddle that holds the cutters, and cutter forces were calculated by measuring the pre-tightening force variation of the bolts during excavation. The in-situ results proved the feasibility and efficiency of this monitoring method. Chen et al. (2015) placed strain gauges on the sides of the disc cutter cushion block to measure the cutting forces indirectly. Strain gauges installation positions were selected according to numerical simulation results, indicating where the strain gauge is sensitive to loading and insensitive to the load application location. As a result, monitoring accuracy was enhanced.

Previous cutting force measurement methods of disc cutters primarily involved installing strain gauges on the roller of the cutters. However, such an installation pattern affects the cutter changing process and advance rate, which is not suitable for repeated measurements. The measurement methods proposed by Entacher et al. (2012, 2013) and Chen et al. (2015) place the sensors on the bolts of the cutters' saddle and cushion block of the disc cutter respectively, which do not affect the cutter changing process during excavation, and can be used for continued measurement. Such measurement approach has a great deal of significances.

In the monitoring of cutting forces for disc cutters, the cutters roll around the roller, so vibration should be taken into account during measurement. However, scraper or shell cutters are embedded on the saddles tightly. Even though scraper/shell cutters rotate with the cutter-head, scraper/shell cutters and the saddles are relatively static, therefore cutting forces can be analyzed as a static problem if the measurement is performed on the saddles.

Therefore, in this paper a new measurement method for cutting forces of the mixshield shell cutters is developed. Strain gauges are placed on the two free side surfaces of the cutter saddle to measure cutting forces. This method has been implemented on a mixshield machine at the Sanyanglu Tunnel of Wuhan Metro Line 7. The feasibility, durability, and precision of this measurement method are calibrated and demonstrated. Subsequently, the measured forces are analyzed to improve understanding of the cutting force distribution on the cutter-head and the correlations between cutting forces and tunnelling parameters. The presented measurement method and monitoring results help to understand the interaction between the ground and the shield machine, as well as improve performance prediction and operational methods.

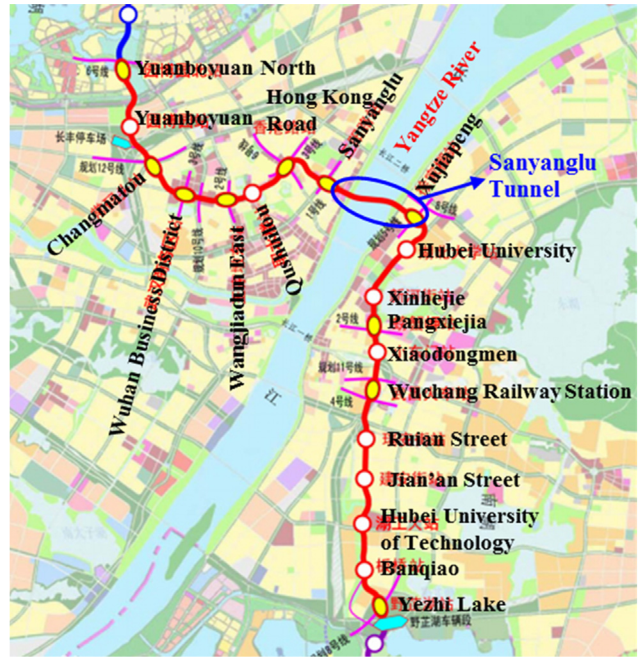

Fig. 1. Map showing the main route of Wuhan Metro Line 7.

2. Project introduction

2.1. Project overview

Sanyanglu tunnel is a mixed-ground metro tunnel advancing through Yangtze River, which is located in China's Wuhan Wuchang District. The Sanyanglu tunnel is one part of the Wuhan Metro line 7, which extends from Yuanboyuan North to Yezhi Lake (Fig. 1) with a total length of 31.3 km. The project is located beneath the Yangtze riverbed and both river banks. The burial depth of Sanyanglu tunnel ranges from 65 m to 228 m, and the average burial depth is 164 m. Sanyanglu tunnel consists of two parallel tunnels. The two tunnels are both about 4650 m long and have a diameter of 15.8 m. The tunnel contains a highway on the upper level and a metro railway on the lower level, as shown in Fig. 2.

The geological profile of the Sanyanglu tunnel is shown in Fig. 3. The overburden is cohesive soil and sandy soil, while the soil surrounding the tunnel is primarily fine sand, silt, and clay. The underlying bedrock is primarily Cretaceous and Tertiary glutenite and silty mudstone. The UCS strength of the glutenite and silty mudstone is approximately 2.3 MPa.

2.2. The used mixshield machine

In order to cope with the mixed-ground, the two tunnels are excavated by two mixshield machines. The used mixshield machines contain advanced conventional slurry technology, developed by Herrenknecht Tunnelling Equipment Co., Ltd. The boring diameter is