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Development and in-situ application of a real-time monitoring system for the interaction between TBM and surrounding rock

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ABSTRACT

In this study, a real-time monitoring system for the interaction between TBM (Tunnel Boring Machine) and surrounding rock is developed, in which the focus is on the cutter-head vibration, and the interaction between the surrounding rock and the shield. The monitoring system consists of sensors, data acquisition subsystem, remote data transmission-storage subsystem and data analysis subsystem. A program is developed to carry out unattended operation of the monitoring software. Further, it can transmit the data synchronously from inside the tunnel to the system outside the tunnel, as well as give feedback information of any operation error to the users automatically. The feasibility, stability, durability of the developed monitoring method has been validated. Subsequently, the time-domain and spectral frequent-domain analysis methods for the accelerated velocity of cutter-head vibration are put forward. Further, the back-calculation analyses method for the surrounding rock pressures acting on the shield and shield jamming warning approach is also developed. Then, the developed monitoring method has been implemented on the double-shield TBM in China's Lanzhou Water Resource Project. Many evolution rules have been obtained. Firstly, the cutter-head vibration monitoring results show that: (a) the cutter-head vibration is significantly correlated with the TBM advance parameters and the geological conditions; (b) the cutter-head vibrates intensely during TBM restarting after a stoppage or entrapment; (c) the cutter-head vibration intensity increases with the increasing cutter-head rotational speed and penetration rate. Secondly, in-situ monitoring of the surrounding rock pressures acting on the shield manifests that: (a) the surrounding rock pressures acting on the shield is non-uniform, which increase with the growing distance from the tunnel face; (b) the contact scope enlarges from the front shield to the rear shield gradually with time, and the surrounding rock loads acting on the shield increases simultaneously; (c) the squeezing pressures acting on the shield decrease and then return to the relatively small pressures after the relief countermeasures were conducted on the trapped TBM. The measured data give insights on the intense cutter-head vibration warning and shield jamming prediction. Furthermore, the verifications, significances, advantages, weaknesses and future improvements of the monitoring system are discussed.

1. Introduction

With the growing development of TBM (Tunnel Boring Machine) tunnelling technologies, TBMs often need to advance through complex and difficult grounds, such as high overburden, mixed-grounds, faults or even highly fractured zones (Barton, 2000; Barla et al., 2014; Avunduk et al., 2012). Many previous studies and historical cases showed that the geological disasters and construction accidents were essentially caused by the interactions between the TBM and the ground (Barton, 2000; Liu et al., 2016; Gong et al., 2016a, 2016b). For instance, shield jamming is the results of the contact-frictional interaction between the surrounding rock convergence and the shield in essence (Ramoni and Anagnostou, 2010; 2011). When the convergence that produced by the dilatancy and fracturing behavior of soft or weak ground zones reaches the overcut gap between the surrounding rock and the shield (Huang et al., 2017a), then the surrounding rock gets in contact with the shield and subsequently produce frictional resistance on the shield. If the total thrust force is insufficient to overcome the

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Nomenclature

List of symbols

ε	strain
b	temperature correction coefficient of the strain gauge
di	circumferential distance between two adjacent measurement points of the same cross section
dj	longitudinal distance between two adjacent monitoring cross sections
f	frictional coefficient
f_0	initial frequency of the strain gauge
f_i	measured frequency of the strain gauge
F_b	thrust force used for TBM boring
F_I	rated thrust provided by the TBM propulsion system
K	calibration coefficient of the strain gauge
P_{ij}	surrounding rock pressure acting on the shield
R_f	total frictional resistance
T_0	initial temperature of the strain gauge
T_i	temperature of the strain gauge
W	TBM self-weight

frictional resistance on the shield surface, then shield jamming occurs. Regarding to cutter-head vibration, it is generated due to the imbalance cutting forces when the cutters cut the inhomogeneous rocks at the tunnel face (Huo et al., 2015). In essence, the cutter-head vibration is caused by the interaction between the cutter-head and the rocks at the tunnel face.

A lot of empirical, analytical and numerical methods have been used to analyze the interaction between surrounding rock and TBM (Huang et al., 2017b). Sugimoto and Sramoon (2002) proposed a theoretical model for the interaction between TBM-shield and surrounding rock/soil. Ramoni and Anagnostou (2010; 2011) studied the interaction between shield, ground and tunnel support, and the pressures on the shield in TBM tunnelling through squeezing ground using the finite element code 'HYDMEC'. When TBMs are tunnelling in jointed or soft rock mass, Vergara and Saroglou (2017) gave the TBM performance prediction in mixed ground conditions; Zhang et al. (2017a, 2017b, 2018) analyzed the geometrical and mechanical behavior of rock blocks considering the TBM-block interaction which is further divided into the cutter-head-block interaction and the shield-block interaction based on the block theory. The identification algorithms for influenced blocks and three types of contacting blocks were presented. With this approach, the contact forces between the cutter-head and rock blocks, and the rock forces between the surrounding rock and the shield can be identified. These methods provide powerful tools for evaluating the excavation efficiency and tunnelling safety. However, the analytical and numerical methods simplify the surrounding rock conditions, their results may differ from the field situations. Hence, it is useful to carry out real-time monitoring for the interaction between the TBM cutter-head and the tunnel face, and the interaction between the TBM shield and the surrounding rock, so that the state of the TBM operation and the state of the surrounding rock can be assessed. The state of the TBM operation includes the cutting forces, cutters abrasion, cutter-head vibration and shield jamming, etc. The state of the surrounding rock includes the convergence and rock properties. The measured data can be used to verify and supplement the theoretical and numerical analyses. Moreover, as the TBM advances at a rapid rate, the data measurement is more meaningful only when it is carried out in real-time. The measured data can then be transmitted and analyzed in real-time, so that the results are more useful for intelligent tunnelling and disasters prediction. Otherwise, only passive measures can be carried out after the accidents happened. Further, the measured data can even be uploaded to a cloud platform. It can then be shared among the owners, constructors, design engineers, manufacturers and researchers. The massive measured data can also be mined (Zhang et al., 2013; Festa et al., 2012), so that the models which capture the interaction between the TBM and the ground can be developed. These models can be used for intelligent tunnelling control and geological hazards prediction.

At present, there are in situ monitoring technologies in TBM tunnelling. They are mainly about the surrounding rock stability (Song et al., 2009; Chen et al., 2010; Li et al., 2011, 2012), the segmental lining deformation and cracks evolution (Gue et al., 2015), and even the advance geology forecast (Li et al., 2017, 2018). For example, using a digital panoramic borehole camera during a TBM tunnelling, Li et al. (2012) carried out in-situ monitoring of the fractures evolution in the excavation damaged zone (EDZ) during TBM tunnelling. These previous measurement approaches were successful. However, most of them have difficulties to monitor the entire tunnelling process all the time. They also have difficulty to ensure the stability and durability of the operation in the rugged environmental conditions of TBM tunnelling (Entacher et al., 2012). They may even need to use manual operation. Although there are many sensors can be equipped on the TBMs to measure the operational parameters (Sun et al., 2018), most of the measured data are not about the interaction between the surrounding rock and TBM. The biggest problem of the above measurement methods is that they are difficult to carry out real-time monitoring under TBM tunnelling conditons. Consequently, the measurement efficiency is low, and only limited measured data are collected.

In order to know the TBM operation state and predict possible geohazards better, many TBM manufacturers and researchers started to develop and implement some on-line monitoring technologies based on the wireless transmission technologies (Wan et al., 2012) and the fiber grating technologies (Ye et al., 2017) etc. As to the cutter-head/cutters, there are some continuous measurements of rotational speed, temperature, cutting forces, wear of a cutter and cutter-head vibration (Shanahan and Box, 2011). For example, the Mobydic project (part of Tunconstruct) monitored disk-cutters health by measuring cutting forces, temperature and rotation (Beer, 2009). Entacher et al. (2012, 2013) installed the strain gauges on the bolts of the cutter's saddle, and calculated cutter forces by measuring the pre-tightening force variation of the bolts. Huo et al. (2015) used the acceleration sensors to measure the vibration of the TBM equipment (such as the main girder and main bearing). Based on an eddy current sensor, Lan et al. (2016) developed an on-line rotational speed monitoring system for the TBM disc-cutters. Huo et al. (2017) put forward a dynamic stress calculation method of a TBM cutter-head by measuring its strain using a wireless testing system. These measurement approaches have a great deal of significances. However, they may influence the cutter changes and construction process easily during monitoring, and usually lack of real-time measurement platforms. It is still difficult to measure the interaction between cutter-head/cutters and tunnel face because of the difficulties in sensors installation, protection and transmission of the signals in the narrow shielding space.

Regarding the monitoring in the shield area, measurements such as surrounding rock convergence, EDZ evolution, supporting loads and failure in gripper TBM tunnelling are relatively more. For instance, based on the laser collimation approach, Song et al. (2009) developed a convergence measurement method in gripper TBM tunnelling; Zhou et al. (2017) used multipoint extensometers and wave velocity tomography to investigate the deformation evolutions during tunnelling in different rock lithology from an auxiliary tunnel; load cells, strain gauges and crack gauges are used to measure the supports deformation or failure (Hoult and Soga, 2014), but back-calculation for the surrounding rock pressures acting on the supports is still difficult. However, in shield TBM tunnelling, because of the narrow space for sensors