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Development and application of the integrated sealant test apparatus for sealing gaskets in tunnel segmental joints

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ABSTRACT

An innovative apparatus has been developed in this study to investigate the coupled leakage and mechanical behaviors of gasketed segmental joints, subjected to the field loading conditions during the construction and operation stages. The basic principles and detailed configurations of this newly developed test setup are presented in detail. The test apparatus can be used to accurately monitor the water leakage pressure of segmental joints under various combinations of joint openings and offsets. A series of test sets, based on different characteristics of sealing gaskets used in segmental joints, were subsequently conducted to evaluate the functionality of the test setup. Testing apparatus was designed to evaluate the waterproof capacity of the three types of segmental joints (i.e., longitudinal/circumferential joint and T-joint (intersection of longitudinal and circumferential joints)) in the Nanjing Weisan Rd. Tunnel. The tested segments were cast with the identical gasket groove details and flanks to the practical tunnel segments. The correlation between gasket contact stress and supplied water pressure was analyzed. Comparison of the gasket sealant and mechanical behavior showed that there existed a "correlated zone". The results showed that gasket-gasket interface, gasket-concrete gasket groove interface, damaged zones, and frame corners were the potential places of leakage in segmental joints. Finally, the results demonstrated that local concrete damages around the groove flank could serve as a water leakage channel and reduced the sealant performance of gasket.

1. Introduction

The shield-driven tunnelling technology has been widely applied in various infrastructure constructions, e.g. metro, traffic, municipal, and mining tunnels, due to the advantages such as safety, high efficiency, little environmental disturbance and reduced labor. To optimize the design and obtain the maximum safety with the minimal costs, the one-pass segmental lining of bolted precast concrete segments is the common practical choice, benefitting from its reliable performance and good quality. The single-pass lining system must fulfill the sealant and the supporting capacity requirement, in both the construction and operation stage.

Unfortunately, there have been some literatures reporting the adverse effects induced by water and methane leakage in tunnelling process. A disastrous sinkhole accompanied by the uncontrolled groundwater leakage occurred in the reception area of a shield tunnel machine during the construction of a metro tunnel in Kaohsiung, Taiwan, China (Lee and Ishihara, 2010). Several segmental lining structures were totally disrupted by the sudden water and silt ingress through the longitudinal joints, in a drainage tunnel for a power plant (Wang et al. 2016). Water and gas inrush is among the technical challenges which must be considered for the future application of tunnel boring machine (TBM) in mining (Zheng et al., 2016). Furthermore, serious water leakage issues are also discovered for the operated tunnels. Several typical leakage cases are highlighted as below. Wu et al. (2014) presented the field leakage behavior of 4 shield road tunnels under the Huangpu River in Shanghai. Wang et al. (2014) discussed the correlation between the water leakage and uneven longitudinal settlement, based on the field monitoring data and leakage phenomena in Shanghai Metro Line 1. Shen et al. (2014) analyzed the groundwater infiltration locations in the operated Shanghai metro shield tunnel. The leakage at joints accounted for 85% of the total water ingress. Chen et al. (2016b) has reported a significant amount of

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leakage was observed in the drainage TBM tunnel in Jinping-I arc dam. Severe underwater leakage through the joints in tunnel segmental rings was induced by the accidental surcharge (Huang et al., 2016). Leakage induced by the adjacent large excavation was found in the operated tunnel in the Ningbo Metro Line 1 (Chen et al., 2016a). It is, thus, of great necessarity to consider how to control, prevent and mitigate the leakage issue seriously for shield tunnels, especially for those constructed in sandy stratum with high permeation coefficients.

With the increasing concern on the water ingress and leakage problems, the International Tunnelling and Underground Space Association (ITA) has published some technical reports and accredited materials to provide the comprehensive guidance on the groundwater prevention into the tunnel structures (ITA, 1991; Yuan et al., 2012). Meanwhile, a suite of researches have been conducted from the academia as well. Quite often, special efforts have been paid to proposed more and more sophisticated analytical models to calculate the stress and strain state of the tunnel lining based on elastic solutions (Bobet, 2003) and elasto-plastic solutions (Fahimifar and Zareifard, 2009; Shin et al., 2011; Fahimifar and Zareifard, 2014). Complicated analytical methods are also developed to estimate the water inflow to tunnels on the basis of the steady state (El Tani, 2003; Hwang and Lu, 2007; Kolymbas and Wagner, 2007) and non-steady state (Joo and Shin, 2014). All these abovementioned solutions are in 2D form and simplified as continuous ring.

Considering the complex hydrogeological conditions, numerical methods can be a powerful tool to investigate the short-term (Zhang et al., 2015a, 2015b; Zhou et al., 2015; Yoo, 2016) and long-term (Shin et al., 2002; Shin et al., 2012; Wongsaroj et al., 2013) responses of shield tunnel lining structures and ground movements, considering the hydraulic-mechanical coupling. In these studies, the non-linear finite element method (FEM) was adopted in both 2D and 3D.

Most of the previous studies usually assumed the segmental lining as the continuous ring, i.e. neglected the joint effect. However, for the tunnel lining structure fabricated by precast segments, we should bear in mind that one of the most significant factors is the existence of the segmental joints on the overall behavior and response (Wood, 1975; Koyama, 2003). This has been confirmed by the authors' and other fellows' previous studies that the joints serve as the weakest and vulnerable point in the segmental ring, in terms of analytical (Lee and Ge, 2001; Lee et al., 2001), experimental (Ding et al., 2013; Li et al., 2015d, 2015e; Liu et al., 2015; Zhang et al., 2015a, 2015b; Kiani et al., 2016) and computational (Ding et al., 2004; Teachavorasinskun and Chub-uppakarn, 2010; Li et al., 2014, 2015a, 2015b, 2015c) approaches. For a modern underwater tunnel subjected to high water head, the segments are required to cast by the high performance concrete with excellent quality and very low permeability (DAUB, 2013). Hence, the main leakage channel is perceived to be the segmental joint, which has been verified by field experience and case studies (Wang et al., 2011). Based on such assumptions, it may be more valuable to understand how the segmental joints withstand the groundwater ingress, rather than just focus on the global responses of lining structures subjected to water pressure.

In modern shield/TBM tunnels, the standard solution for sealing the joints are the Ethylene-Propylene-Diene Monomer (EPDM) elastomeric rubber gaskets arranged circumferentially on the end faces of the segment. In view of this circumstance, special attention should be paid to the sealant behavior of the EPDM sealing gaskets, to evaluate the waterproofing of the segmental joints. Furthermore, a time-dependent constitutive model of EPDM rubber used in tunnel segmental joints, has been recently proposed to assess the long-term waterproof performance (Shi et al., 2015). The mechanical behavior of the EPDM gaskets, is found to be close related with the sealant behavior in this article. Therefore, any investigations concerning these two objectives should be greatly welcomed, especially based on the experimental approach. Karl Von Terzaghi, the father of soil mechanics, encourages the geotechnical scholars to "observation and learning from experience" (Einstein, 1991). However, at this moment, quite few experimental studies on the coupled waterproof and mechanical performance of the tunnel sealing gaskets are available.

Thus, this paper presents a detailed experimental methodology focusing on the integrated sealant and mechanical behavior of the sealing gaskets used in shield tunnel joints. A newly developed test apparatus allows measuring the water leakage pressure of different types of segmental joints (i.e., longitudinal joint, circumferential joint, and T-joint) in practical tunnel lining structures, subjected to various joint opening and offset conditions. Furthermore, it can be adapted to evaluate mechanical properties of EPDM gaskets used as sealing materials in segmental joints. The continuous measurement obtained with the new test apparatus allows the determination of the accurate water leakage pressure at different joint opening and offset combinations. Based on the abovementioned test data, the sealant and mechanical behavior of sealing EPDM gaskets are studied individually. The correlation between the waterproofing and compression force is subsequently identified. Finally, locations of leakage are discussed to reveal the sealant mechanism of EPDM gaskets, in order to provide some valuable information to practical tunnel engineering.

Before introducing details of the new test apparatus, it is of necessarity to review the current practices of monitoring the waterproof pressure and compression force of sealing EPDM gaskets. As a consequence, this new test method can be compared with conventional ones.

2. Literature review

2.1. Joint waterproof tests

Sealing gasket, adopted in the segmental joint, must be watertight against the groundwater in various combinations of joint openings and offsets during the construction and operation stages (DAUB, 2013). Despite this apparently simple principle, very limited test standards or guidelines, concerning the joint watertightness evaluation, are publically available. The Research Association for Underground Transportation Facilities (STUVA) in Germany was the first to publish a testing recommendation on sealing gaskets in shield tunnel segmental linings (STUVA, 2005). It should be noted that this recommendation just summarized an overall requirement and lacked necessary explanations and detailed experimental procedures. Prior to the official testing document, explorative investigations have been conducted from the academia based on practical tunnel cases in a more concrete way. Professor Emeritus Stanley L. Paul and his colleagues from University of Illinois at Urbana-Champaign (UIUC) were among the initial researchers to experimentally study the gasket sealant performance, on the basis of a steel picture frame device (Shalabi et al., 2007). It was observed that T-joint was the place that most leakage took place. Also using the steel form test rig, Girnau (1978) performed the short-term water leakage tests on rib gaskets. The results showed that the T-joint was the most potential leakage place. Ohtsuka et al. (2000) proposed a waterproofing design method for water-swelling gaskets in Japan shield tunnels. Lu et al. (2008) studied the sealant performance of EPDM gaskets used in Shanghai Yangtze River Tunnel. It should be noted that all these tests were conducted using the simplified steel picture frame device, which cannot simulate the real contact characteristics between the gasket and the groove in practical concrete seg-