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In situ monitoring of tunnel deformation evolutions from auxiliary tunnel in deep mine

Hui Zhou, Cheng-kun Qu, Da-wei Hu *, Chuan-qing Zhang, Muhammad Usman Azhar, Zheng Shen, Jun Chen

State Key Laboratory of Geo-mechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430071, China

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ABSTRACT

Deformation caused by excavation is of great effects on tunnel stability and tunnel support design. Monitoring using instruments that are installed in place within the examined tunnel, cannot record a large amount of surrounding rock deformation that usually takes place ahead and close to the tunnel face. For this important reason, the overall deformation process was observed using instruments installed prior to excavation from auxiliary tunnel in a 900 m deep coal mine tunnel. Two monitoring methods, i.e. multipoint extensometers and wave velocity tomography were used at two monitoring sections with different rock lithology. The results showed that a large amount of deformation at both monitoring sections had already been occurred when the excavation face passed the monitoring sections at a very small distance. The size of the plastic zone at monitoring section 1 is identified as 1.8 m (0.36 D, D denotes the diameter of the examined tunnel) and the velocities within this zone decreased from 4.5 km/s to 2 km/s. The primary deformation was generated in a distance from −0.8 D (ahead the excavation face) to 2–3 D (behind the excavation face). The induced deformation was also observed after the primary deformation period, and some additional deformation was still occurred in the plastic zone although the size of plastic zone remains constant. The displacements and p-wave velocities at the two monitoring sections showed little differences.

1. Introduction

Tunnel excavations in deep rock formations cause re-arrangement of geostatic stresses and consequently generate large deformation in surrounding rocks (Brox and Hagedorn, 1999; Goel et al., 1995; Kaiser, 1994; Kontogianni and Stiros, 2002). In the case of using drill and blast excavation method, the mechanical properties of surrounding rocks are considerably changed (Kwon and Cho, 2008; Wassermann et al., 2011; Siren et al., 2015; Perras and Diederichs, 2015). In areas of surrounding rock mass near the sidewalls of tunnel, significant plastic deformation and obvious variation in term of decrease in wave velocity have been observed (Sato et al., 2000; Martino and Chandler, 2004; Yan et al., 2014). In this plastic zone, rock is either irreversibly damaged or disturbed with significant change in physical, mechanical and hydraulic properties (Sato et al., 2000; Bossart et al., 2002; Tsang et al., 2005; Wu et al., 2009; Diederichs et al., 2004; Li and Liu, 2013; Lisjak et al., 2014; Siren et al., 2015), and these irreversible variations are directly related to crack initiation, propagation and coalescence (Li et al., 2012; Perras and Diederichs, 2015).

Different monitoring methods have been applied to investigate the size and shape of the plastic zone change throughout the excavation process (Kavvadas, 2005). Using micro velocity probe and borehole camera, Martino and Chandler (2004) revealed that the plastic zone was influenced by different factors, e.g. stress adjustment, tunnel direction, shape of excavated section, excavation manner, and other affecting factors. The evolutionary process of cracks in an aquifer was analyzed by Williams and Johnson (2004) using acoustic velocity detection and borehole imaging. Blümling et al. (2007) presented the initial formation stage and long-term processes of plastic zones by microfocus X-ray tomography. Rock bursts in the TBM excavation were monitored via acoustic emission by Cheng et al. (2013). Based on numerical simulations, Yan et al. (2014) proposed that the plastic zones were caused by combined action of blasting load, stress redistribution and transient unloading. Zhu et al. (2014) analyzed the effect of dynamic stress redistribution on plastic zones using a two-dimensional mathematical model. Moreover, based on geodetic monitoring data from transportation tunnels and mining galleries, Kontogianni and Stiros (2005) suggested that the deformation is a 3-D effect instead of 2-D effect, there exists an ignored component of deformation along the tunnel axis which is responsible for the propagation of deformation along tens of meters or even more.

In the above studies, the monitoring instruments were mainly installed in place within the examined tunnel as the excavation face advances; and the minimum distance of instrument installation from the tunnel face is around 2–4 m to avoid interference with the construction of the temporary support (sprayed concrete, steel sets, etc.) (Kavvadas, 2005). However, a large amount of surrounding rock deformation takes

* Corresponding author.
E-mail address: dwhu@whrsm.ac.cn (D. Hu).

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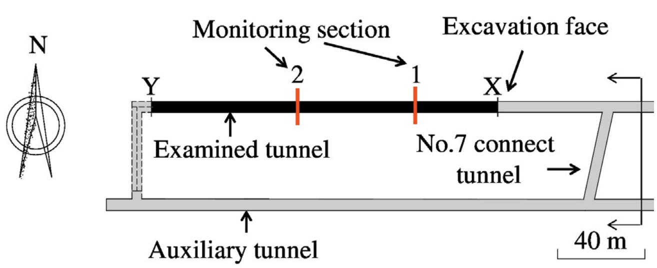
place ahead and close to the tunnel face, from about 1 D ahead of the face up to about 1.5 D behind the face (Hoek, 2001; Kontogianni and Stiros, 2002; Kavvadas, 2005). Therefore, an appreciable portion of the actual deformation occurred prior to instrument installation, cannot be recorded (Kavvadas, 2005). Thus, monitoring using instruments installed from neighboring tunnel prior to excavation of examined tunnel, is highly important for the overall deformation process of plastic zone. Moreover, different from tunnel excavation in hydropower or transportation engineering in the above studies, tunnels excavated in coal mines usually encounters weak clastic rocks (sandstones, claystones, mudstones, and conglomerates) that are characterized by low mechanical strength, high deformability and significant structural anisotropy, which can also influence the development of plastic zone. For this purpose, two monitoring instruments, multi-point extensometer and wave velocity tomography, were installed from the auxiliary tunnel prior to excavation of examined tunnel in a 900 m deep tunnel of coal mine. The overall process of plastic zone was observed at two monitoring sections with different rock lithology.

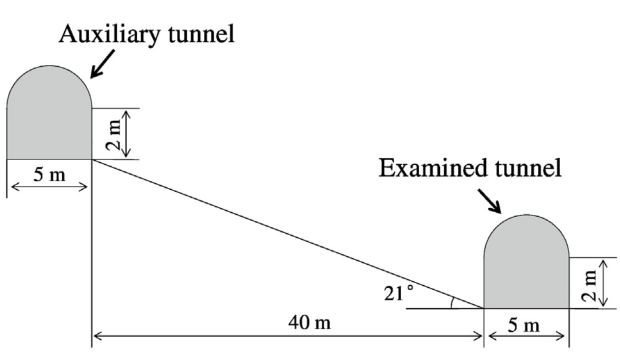
2. Site descriptions and monitoring scheme

2.1. Site descriptions

The monitoring studies were performed in Jining coal mine, located at eastern part of China. The examined tunnel, 5 m in diameter, was excavated at a depth of 900 m using drill and blast excavation method. The examined area is about 160 m long from line X to line Y (see Fig. 1). The support system included shot concrete, steel sets, and occasionally rock bolts. In order to install monitoring instruments prior to the excavation of examined tunnel, an auxiliary tunnel, whose axis is parallel to the examined tunnel axis, was excavated using drill and blast technique in the neighboring rockmass prior to the excavation of examined tunnel. The layout of the two tunnels is presented the in Fig. 1. The distance between the two tunnels is about 40 m, which is 8 D and sufficiently large to avoid the interactions between the two tunnels.



(a) Plan view of two tunnels and monitoring sections



(b) Profile vertical cross section of two tunnels

Fig. 1. Layout of the examined tunnel and auxiliary tunnel.

Fig. 2. Horizontal bedding in the monitoring tunnel.

The principal strata is mainly sandstone of Shanxi Group. The sandstone formation displays an obvious horizontal bedding (see Fig. 2). The elastic modulus and Poisson's ratio of the rock mass near the examined tunnel are approximately 18–35 GPa and 0.24–0.28, respectively. Compressive strength of intact rock determined by laboratory tests is in between 80 and 120 MPa, and the rock quality designation (RQD) value (Deere, 1988) is about 45%–61%.

The in situ stress of rock mass is presented in the Table 1. The three principal stresses are 19.5, 9.5 and 8.4 MPa, respectively. The maximum principal stress σ_1 and intermediate principal stress σ_2 are close to the horizontal direction, and the minimum principal stress σ_3 is at 38° deviated from the vertical direction.

Two monitoring sections (see Fig. 1) were selected in order to analyze the effect of lithological difference on the plastic zone. Monitoring sections 1 and 2 were respectively located in medium-grain sandstone and siltstone, 40 and 100 m ahead of the initial tunnel excavation face along the axis of the examined tunnel. Cylindrical rock samples of the medium grain sandstone and siltstone with dimensions 50 × 100 mm were acquired from the site for laboratory testing. The uniaxial compression test was conducted on an MTS testing machine according to ISRM suggest method (ISRM, 2007) and the typical stress-strain curves obtained are presented in Fig. 3. The strength and elastic modulus of the medium grain sandstone are 120 MPa and 17.1 GPa respectively, which are slightly greater than that (107 MPa and 11.9 MPa) of the siltstone. This difference in deformation characteristics will be considered in evaluating the following monitoring results.

2.2. Monitoring scheme

In this work two different monitoring instruments, i.e., multi-point extensometers and wave velocity tomography, were installed respectively from the auxiliary tunnel prior to the excavation of the examined tunnel. The multi-point extensometers were installed in the boreholes at different pre-selected depths away from the examined tunnel sidewall, and the boreholes were consequently backfilled with cement-bentonite grout. Therefore, the multi-point extensometers measured the relative displacement along the boreholes at discrete intervals from the borehole bottom to the exanimated tunnel sidewall. Generally, the multi-point extensometers have a limit measuring range (i.e. 100–

Table 1
In situ stresses in the monitoring zone.

Principle stress	Value (MPa)	Azimuth angle (°)	Dip angle (°)
σ_1	19.5	116	11.6
σ_2	9.5	201	18.2
σ_3	8.4	156	52