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Squeezing failure of tunnels: A case study

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ABSTRACT

The Laodongshan Tunnel, as a part of Guangtong-Kunming railway in China is one of the most important connections in the whole railway line. The large deformation and failure of primary support occurred in the early tunneling stage, and deformation characteristics and failure causes of primary support were obtained by means of field investigation and analysis. There have been many factors that result in the occurrence of squeezing failure of tunnel during construction, such as high in situ stress, soft-weak rock, groundwater seepage, weak support, delay closure of primary support, etc. The lessons to be learned is that for tunnels construction in weak rock mass under high in situ stress, the controlling principle of tunnel deformation ought to be based on combination of stress releasing and support resistance. The support type and method during tunnel excavation needed to be adjusted dynamically based on the pre-excavation geological forecast (e.g. tunnel seismic prediction (TSP), ground penetration radar (GPR), and horizontal pre-boreholes, etc.). Besides, many countermeasures were proposed during construction, including strengthened pre-support, improvement of support stiffness, grouting reinforcement, installing additional supports, closing the tunnel ring early, and timely installation of secondary lining. Finally, from feedbacks of monitoring results, squeezing failure of Laodongshan tunnel was effectively controlled. Thus these countermeasures can guarantee safety construction in weak rock mass under high in situ stress was achieved.

1. Introduction

In recent years, with the rapid development of tunnel construction in China, tunnels under construction gradually present such characteristics as long length, large section and deep depth. However, during tunneling in these tunnels complicated and difficult situations often have to be encountered such as high in situ stress, poor ground conditions, abundant groundwater, etc. During tunneling in the difficult ground, the problems may be occurred such as tunneling-induced large deformation (Steiner, 1996; Dalgıc, 2002; Zhang et al., 2012), tunnel squeezing (Hoek, 2001; Feng and Jimenez, 2015), tunnel floor heave (Tang and Tang, 2012), tunnel instability (Anagnostou and Kovari, 1996; Oreste and Dias, 2012; Perazzelli et al., 2014; Shi et al., 2016, 2017), large-scale failure caused by high in situ stress (Zhang et al., 2014; Lin et al., 2016), etc. Moreover, high in situ stress is a major issue for tunneling, especially in soft and weak rock, which has obvious effect on tunnel construction and may cause large deformation (e.g., Hoek and Marinos, 2000; Meguid and Rowe, 2006). Collapse will occur easily in case large deformation cannot be effectively controlled during tunneling, seriously endangering the safety of builders and construction equipment in the tunnels. Thus, how to control large deformation in case of instability and collapse becomes a critical subject during tunnel construction in soft and weak rock mass.

Many studies have been conducted to investigate those problems mentioned above during tunneling excavation. Brox and Hagedorn (1999) introduced an example of extreme deformation and damage during tunneling in weak rock mass, and summarized the causes of excessive deformation in the case. Song et al. (2016) analyzed the characteristics and mechanisms of rock mass deformation during the excavation of Jinping I hydropower station, and also proposed measures for controlling large deformations of underground caverns under high in-situ stress condition. Zhang et al. (2014) illustrated outstanding issues in excavation of deep and long rock tunnels, and presented key technologies and experiences for large deformations under high in situ stress. Kaya et al. (2011) and Kaya and Bulut (2013) investigated tunnels excavation and support requirements for a tunnel portal in weak rock mass using empirical and numerical methods. Hoek (2009) described extreme squeezing problems encountered during the construction of the Yacambu-Quibor tunnel. Li and Zhao (2016) and Li et al. (2016) systematically studied ground displacement characteristics and performance of tunnels excavated in loess ground based numerical modeling and field monitoring. Feng and Jimenez (2015) agreed that tunnel squeezing or time-dependent large deformations are common in tunnels constructed in weak rock masses at large depth or subjected to

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Table 1
Statistical case histories of large deformation induced by tunneling excavation.

No.	Tunnel	Country/ region	Maximum cover depth (m)	Length (km)	Cross-section area (m^2)	Rock mass type	Maximum deformation	
							Crown settlement (cm)	Horizontal convergence (cm)
1	Enasan (Kimura et al., 1985)	Japan	450	8.635	100	Weathered granite	93	112
2	Tauern (Leitner, 2001)	Austria	1000	6.4	90–105	Sericite phyllite	120	–
3	Arlberg (John, 1980a,b)	Austria	740	13.98	90–103	Phyllite, gneiss	35	70
4	Muzha (Cai, 2001)	Taiwan	140	1.875	150	Shale, siltstone, sandstone	150	70
5	Jiazhuqing (Zhang et al., 2004)	China	400	4.99	82.5	Limestone, sandstone, mudstone, basalt	240	160
6	Wushaoling (Lei et al., 2008)	China	1100	20.05	84.3	Slate, phyllite, fault gouge, breccia	105.3	103.4
7	Muzhailing (Liu, 2011)	China	728	19.095	46.5	Slate, carbonaceous slate	181	240.3
8	Maoyushan (Li, 2011)	China	700	8.503	177	Carbonaceous slate	54	120
9	Xinshuhe (Ge and Zhang, 2009)	China	200	8.989	87.4	Carbonaceous schist	190	225
10	Yanmenguan (Lin et al., 2016)	China	820	14.085	52.5	Gneiss	41.25	30.66
11	Baozhen (Tian, 2013)	China	630	11.595	–	Clastic rock, marlstone	51.09	99.29
12	Tianpingshan (Fu et al., 2011)	China	775	14	180	Sandstone, carbonaceous shale	25.28	16.52
13	Liangshui (Xia et al., 2015)	China	346	4.945	176	Carbonaceous phyllite	76.19	54.37
14	Dujiashan (Wang et al., 2012)	China	194	3.727	93	Phyllite	–	90
15	Jiubao (Li and Liu, 2014)	China	493	9.585	138	Granulite, gneiss	46.7	188.4

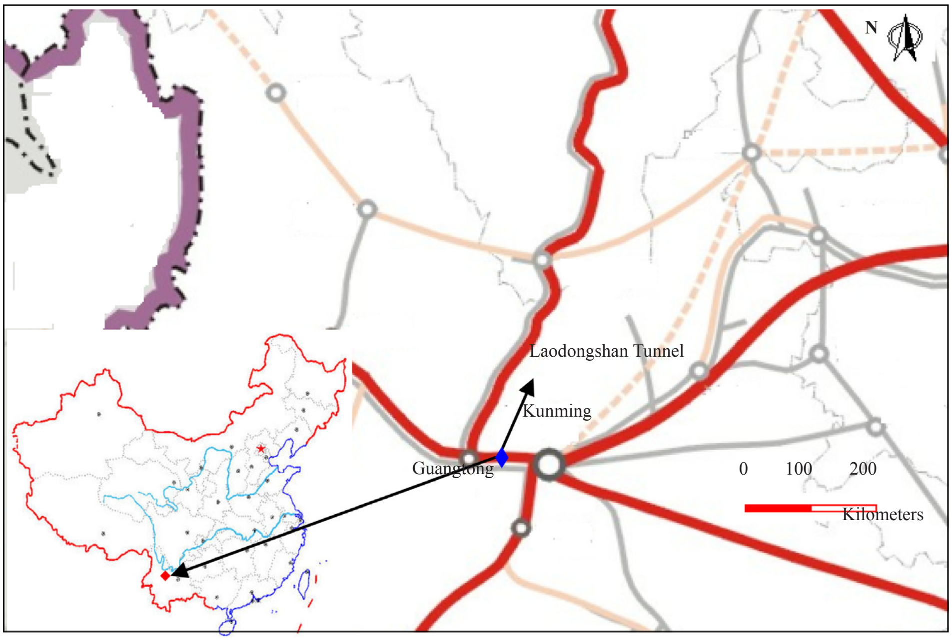

Fig. 1. The location and plane layout of Laodongshan Tunnel.

high horizontal in situ stresses in tectonically active regions. To predict tunnel squeezing, a novel application of Bayesian networks (BNs) was presented in his research. Tang and Tang (2012) used numerical modeling analyze time-dependent behaviour of floor heave of tunnel under the high humid condition. Xie et al. (2016) investigated blasting-induced damage evolution mechanisms of rock in deep tunnels subjected to high in situ stress by the mean of numerical modeling. Wang et al. (2015) proposed the dynamic failure constitutive model and implemented it to study the rock mass deformation and failure mechanism of deep mining tunnel. Lin et al. (2016) discussed the deformation and failure of a tunnel in the restraining bend of a strike–slip fault zone. To promote understanding of deformation and failure of tunnels, some laboratory model tests also have been conducted. Lin et al. (2015) conducted the geomechanical model tests to investigate failure behaviour of the “large, deep, long and in-group” tunnels under high in-situ stresses. Huang et al. (2013) explored the effect of weak interlayer on failure pattern of rock mass around tunnel based on both physical model tests. He et al. (2010) conducted physical modeling of deep ground excavation in geologically horizontal strata based on infrared thermograph. Zhu et al. (2010) investigated the spalling and failure mechanism of the caverns in a hydropower station under high in situ stresses. Furthermore, so far there also have been many well-known tunnel engineering examples, during the construction of which serious large deformation occurred, such as Enasan highway tunnel in Japan,