Tunnelling and Underground Space Technology 60 (2016) 80–95

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

The effect of external water pressure on the liner behavior of large cross-section tunnels

Yong Fang [a,*], Jianning Guo [a], Jacob Grasmick [b], Mike Mooney [b]

[a] Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, Southwest Jiaotong University, Chengdu 610031, China
[b] Center for Underground Construction & Tunneling, Colorado School of Mines, Golden, CO 80401, USA

ARTICLE INFO

Article history:
Received 13 November 2015
Received in revised form 14 June 2016
Accepted 15 July 2016

Keywords:
External water pressure
Scaled model test
Liner behavior
Fracturing

ABSTRACT

Recent extreme weather with heavy rainfall has brought new challenges to the operation of a karst tunnel as a large amount of groundwater flowing toward the tunnel in a short time exceeded the drainage capacity and caused high external water pressure. By evacuating the air in the inner space of the tunnel structure, an apparatus was developed to simulate the external water pressure on the tunnel structure. It was also employed to study the behavior of a highway tunnel structure with a large cross section considering cavities behind the liner. The results showed that the bending moment of the liner increased with the external water pressure, which helps to decrease the nonuniform distribution of the thrust force, and the maximum bending moment and eccentricity were generally located at the knees or side walls. Lower external water pressure contributed to reducing the eccentricity of the liner while higher external water pressure does not further reduce the eccentricity. Under external water pressure, fractures appeared first at the knee, then at the invert and finally at the vault. The air tightness tests under external water pressure also showed that the cavity decreased the bearing capacity of the liner and significantly aggravated the fractures in the liner nearby. The results help to estimate the bearing capacity of the liner under external water pressure, and the method of simulating external water pressure can also be used to study tunnels with different cross section geometries.

1. Introduction

Groundwater is one of the main challenges associated with stability and safety issues in the construction of mountain tunnels. Groundwater assessment and control during both construction and operation of the mountain tunnels are typically the biggest problems faced by the designer and contractors. In mature karst formations, the risk of tunnel construction is much higher due to interference with ground cavities that are either empty, auriferous or filled with erodible materials (Casagrande et al., 2005; Parise et al., 2008; Waele et al., 2011; Alija et al., 2013; Gao et al., 2014). However, some mountain tunnels have to be constructed in mature karstic systems as they are widely distributed in areas such as the southwest China provinces of Chongqing, Yunnan, Guizhou, Sichuan and Hubei, and many long karst tunnels have been constructed successfully in China.

In general, there are three methods for dealing with groundwater: full sealing, full drainage and blocking with limited drainage. Full sealing is used in tunnels with small cover depth or low groundwater level where the liner takes on the entire groundwater pressure. Blocking with limited drainage is used in mountain tunnels with high groundwater levels, like the Yuanliangshan railway tunnel (Cheng et al., 2014), and underwater tunnels with difficulties in drainage, like the Jiaozhouwan undersea tunnel in Qindao (Qiu et al., 2014) and the Xiang-an undersea tunnel in Xiamen (Zhang et al., 2014), China. The contractor must always be focused on stability and safety during the excavation (Zhang et al., 1993; Li et al., 2013; Li and Li, 2014). Many grouting and consolidating techniques have been applied successfully in the treatment to decrease the pressure and inflow of groundwater (Tseng et al., 2001; Aksoy, 2008; Zhang et al., 2014; Yesilnacar, 2003). The liner of the tunnel takes on reduced groundwater pressure which is determined by the seepage parameters of the grouting annulus (Dahlo et al., 2003). Based on the estimation of water inflow and reasonable drainage scheme (Li et al., 2009; Hwang and Lu, 2007; Wang et al., 2008), full drainage is generally used whether the grouting consolidation is carried out or not (Yang et al., 2016). The liner with enough drainage capacity is designed for most mountain tunnels while the external water pressure on the structure is neglected (Fu et al., 2007).

* Corresponding author.
E-mail address: fy980220@swjtu.cn (Y. Fang).

http://dx.doi.org/10.1016/j.tust.2016.07.009
0886-7798/

In recent years, extreme weather with heavy rainfall has become frequent and has brought new challenges to karst tunnel operation that were not considered in the design. In this case a large amount of rainwater can flow toward the tunnel in a short time from the ground surface through the interconnected passages in the karst formation. If the groundwater flowing to the tunnel exceeds the drainage capacity, it will accumulate behind the liner and cause high external water pressure which can lead to the failure of the liner as shown in Fig. 1.

The Shuangbei twin tunnels, constructed in 2014 and each with length of 4373 m and three lanes, carries an expressway in Chongqing City, China. They are NATM tunnels. The reports of site investigation show that the lithology of the surrounding rocks along the tunnel includes mainly muddy limestone and sandstone. In the limestone formation, karst can easily develop along the tunnel. The length of the karstic zone is about 2127 m, which accounts for nearly half of the tunnel length. The cover depth of the tunnel in the karstic zone ranges from 150 m to 200 m. Groundwater is also widely distributed and has a complex relationship to the ground surface. The evaluated classes of surrounding rocks along the tunnel route range from Grade III–V according to the Chinese Code for Design of Road Tunnel (JTG D70-2004). The initial ground stress was also reported to be comprised of primarily gravity stress; tectonic stress was not apparent. During the construction, grouting with a cement and sodium silicate solution was used to block the groundwater and to fill cavities to ensure the stability and safety of the tunnel liner. The drainage system was designed to drain out the residual groundwater, completely overlooking the external water pressure on the liner. Typical cross sections of the liner for Grade IV are shown in Fig. 2.

During tunnel operation, new interconnected passages in the ground or cavities behind the liner might have formed considering the erosion of the strata due to water. In occasional cases such as extreme heavy rain on the mountain area above the tunnel, high external water pressure develops behind the liner if the groundwater flowing towards the tunnel is beyond the capacity of the drainage system, a case generally not encountered during construction. It is of interest to assess how much external water pressure is allowable and to identify zones of weakness in the liner cross section when cavities are present. This paper describes the development of a new method of applying external water pressure to model tunnels. The method was employed to model tests to characterize the behavior of the liner for the Shuangbei tunnel. The study concentrated on the loads on the liner and ignored the process of excavation in the ground with initial stress. This method can also be used to investigate the behavior of tunnels with waterproofing liner.

(a) (b)

Fig. 1. Liner failure under high external water pressure in Chongqing, China (a) failure at the side wall, (b) failure at the knee.

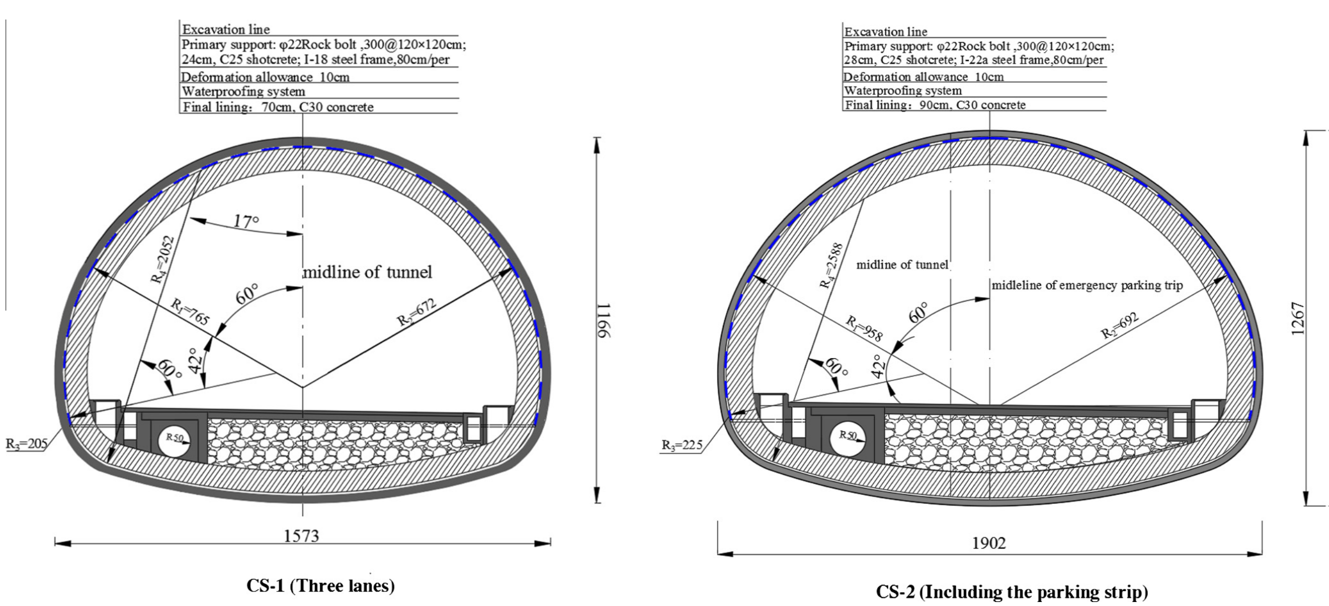

Fig. 2. Cross section of Shuangbei tunnel (Grade IV, unit: cm).