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Void-induced liner deformation and stress redistribution

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ABSTRACT

Voids behind the liner may be created during or after construction of the tunnel liner because of insufficient backfilling, poor workmanship, water erosion or gravity. Survey on a number of tunnels that suffered collapse while in service showed that voids behind the liner were the main factors for the failure. The paper provides a better understanding of the stress redistribution that occurs in the rock mass around a void and quantifies the stresses induced in the liner due to the voids. The effects of cavities or voids due to different size, location and depth are explored numerically through an elasto-plastic finite element analyses. Other factors such as lining flexibility, in situ stresses and tunnel shape are also investigated. The analyses show that voids can induce a large change of the thrust and bending moment in the liner with respect to the case of a liner without a void. The bending moment can even reverse sign, which may result in cracks in the lining or even failure. The voids also change the distribution of the rock stresses around the tunnel, which may result in progressive failure of the rock and rock falls that can lead to additional damage to the liner. Because the void forms behind the liner, it may not be readily detected until significant damage to the liner has been produced, generally in the form of severe cracking, spalling or even failure.

1. Introduction

By the end of 2009 there were 6139 tunnels in China, with a total length of 3942 km, according to the Ministry of Transport of the People's Republic of China (2009). Most of these tunnels have been constructed in mountain areas and have been in service for about 5 years or more. Most of them are starting to show some deterioration and/or reduced performance. There are many reasons for this, the most important ones include cracking of the liner, voids behind the liner, (as illustrated in Fig. 1), water infiltration, lining deterioration, and tunnel deformation (Liu, 2007). To keep these tunnels in good service conditions, significant maintenance is required that at least includes regular inspections and thorough assessment of the structural performance of liner and rock.

Damage to the tunnels caused by voids may be due to natural causes or man-made. These can be classified as follows:

- *Water erosion*. Voids may be created by water effects behind the liner when the surrounding rock consists of soft rock or of rock minerals that are soluble or weather easily.
- *Improper backfilling*. Rock overbreaks and rock collapse are the most common problems encountered during tunnel construction. Ideally the voids left by this phenomena should be backfilled with cement mortar or concrete as soon as possible. In reality this is not always the case and cavities may be improperly backfilled or inadequate fill materials may be used, e.g., rock or timber, often because of economic reasons.
- *Poor construction*. Voids are often the result of poor construction quality. Insufficient concrete thickness, poor concrete quality (which may result in concrete shrinkage and separation between the initial lining and the secondary lining), inadequate framework support (which results in settlement of the lining concrete), and poor workmanship are often the sources of voids behind the liner. In addition, if the concrete at the crown is not properly placed or no re-injection of concrete or grout takes place after construction, a void may be formed.

The negative consequences of voids can appear as minor surface corrosion of tunnel appurtenances, major deterioration of the liner with associated reduced load carrying capacity and even failure of the liner, as the surrounding rock loosens progressively around the void (US Department of Transportation, 2005; Meguid and Dang, 2009; Martini et al., 1997; Tang, 1997; Yuan and Harrison, 2006; Hajiabdolmajid et al., 2002).

Voids behind the liner can lead to settlements of adjacent facilities and/or cause eccentric loading to the liner that can induce undesirable stresses and/or progressive loosening of the surrounding rock. Evidence for such problems can be readily found in the technical literature. For example, Talesnick and Baker (1999)

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Fig. 1. Photographs of voids behind the tunnel lining (Liu, 2007).

reported the failure of a large diameter (1.2 m) concrete-lined steel sewage pipe buried in clayey soils, possibly caused by a gap of approximately 20 mm between the invert and the soil bedding, that was found from field investigation. Severe cracking occurred at the crown and the springline along a 300 m long segment of the pipe. In addition, Asakura and Kojima (2003) reported spalling of concrete linings in the Fukuoka Tunnel and in the Kita-Kyushu Tunnel along the Sanyo Shinkansen (Bullet Train) line and in the Rebunhama Tunnel along the Muroran Main line, where it was found that the spalling was caused by loosened rock originated by insufficient contact between the liner and the rock. Erosion voids in soft ground behind tunnel liners have been investigated by Meguid and Dang (2009), who identified water infiltration into leaky joints, dissolution of Karst limestone and dynamic loading caused by construction as potential sources for void formation.

Typically, tunnel design does not consider the presence of voids behind the liner because they are often associated with either poor construction techniques or with unusual or unforeseen phenomena. The reality is that the contact between the liner and the surrounding rock may not be perfect because of cavities created during construction or during service of the tunnel through time-dependent processes such as rock dissolution, weathering or softening. As the contact between the rock and the liner deteriorates, the load transfer mechanism from the rock to the liner changes, leading to a stress increase in the rock, which then accelerates the deterioration of the contact causing a stress rise in the liner.

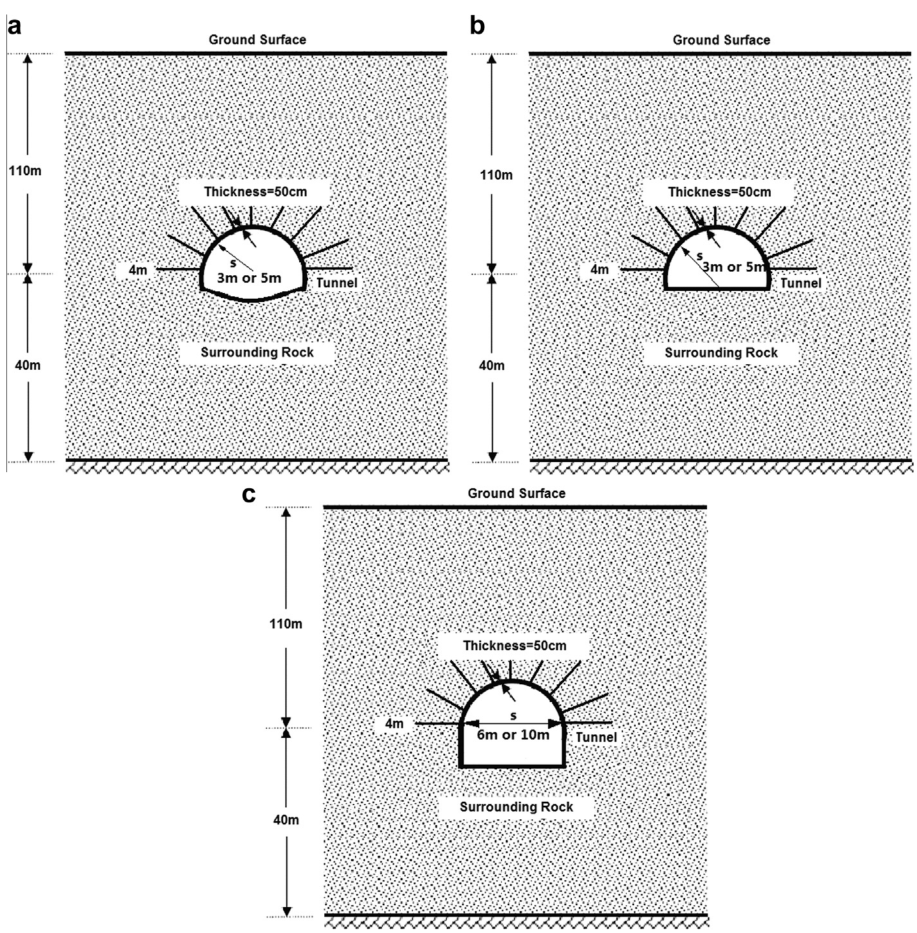

Fig. 2. Tunnel geometry used in numerical simulations. (a) Section 1: semicircular tunnel with invert; (b) Section 2: semicircular tunnel without invert; (c) Section 3: horseshoe tunnel.