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Cracking mechanism of secondary lining for a shallow and asymmetrically-loaded tunnel in loose deposits

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ABSTRACT

Tunnels constructed in loose deposits with low strength and complex composition are usually subjected to asymmetrical stresses at the entrance and exit. The secondary tunnel lining is prone to excessive deformation, cracking, or even collapse, seriously affecting the safety of tunnel construction and operation. In this paper, a large shallow highway tunnel in loose deposits is used as an example to study the cracking mechanism of secondary lining. Triaxial consolidated-drained shear tests are carried out on large remolded specimens to obtain the mechanical parameters of the surrounding soil. Three-dimensional numerical modeling is conducted based on the field monitoring data to simulate the process of tunnel construction and to analyze the mechanical mechanism of cracking in the secondary lining. It is shown that even with the 30 m advance pipe roof at the tunnel entrance, the apparent difference in stiffness between the retaining wall and the surrounding soil results in an obvious stress concentration at the spring of the secondary lining near the end of the retaining wall, due to the effect of highly asymmetrical stresses. In addition, loose deposits are very sensitive to construction disturbances. Large horizontal deformation towards the lower topography occurs during tunnel construction. With increasing overburden depth, the stress concentration at the spring level and the horizontal deformation in the secondary lining increases, which are the main reasons for cracking in the secondary lining. These findings can be useful for tunnel design and construction in the similar type of loose deposits.

1. Introduction

Over the last few decades, with the rapid development of transportation construction in China, soft rocks or soils have been encountered in many tunnels built through poor geological conditions. Because of poor mechanical properties, rapid deformation and large range of disturbances, soft rocks and soils have great impact on the stability of underground structures (Sharifzadeh et al., 2013). Excessive deformation is likely to occur in the tunnel secondary lining during construction, and sometimes, cracking or even collapse occurs. Soft surrounding rock have aroused great attention in the construction of traffic projects (Gonzalez and Sagaseta, 2001; Jeng et al., 2002; Ozsan and Basarir, 2003; Mestat et al., 2004; Lee and Schubert, 2008; Shahrour et al., 2010; Weng et al., 2010; Wang et al., 2012; Zhu et al., 2013). Especially during construction of shallow and asymmetrically-loaded tunnels in loose deposits with poorer mechanical properties and complex composition, the disturbance effect on loose deposits slope due to excavation of the tunnel entrance and exit sections is even more pronounced. Large stress and displacement occur, directly affecting the stress and deformation of underground structures (Inokuma and Inano, 1996; Wang, 2010), leading to damage, cracking or even collapse of the tunnel secondary lining and subsequently affecting the tunnel construction safety. A number of researches have been conducted on loading and cracking of concrete lining in tunnels (For example, Asakura and Kojima, 2003; Zhu et al., 2003; Kim and Eisenstein, 2006; Chiaia et al., 2009). Moreover, during construction of the tunnel entrance and exit sections under asymmetrical loading, a variety of measures including retaining wall, long pipe roof and rational construction scheme can be adopted to ensure construction safety (Yoo and Shin, 2003; Hisatake and Ohno, 2008). However, how these measures would affect the

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secondary lining of tunnels in soft rocks and soils, especially at the tunnel entrance and exit sections in loose deposits with extremely asymmetrical topography, whether these measures can ensure the safety of secondary lining have direct impacts on tunnel construction and operation safety. Therefore, an in-depth study on stress and deformation in secondary lining and its cracking mechanism is necessary for shallow and asymmetrically-loaded tunnels in loose deposits. The study will have important practical significance to the current rapid development of highway tunnels.

In this paper, a large shallow highway tunnel in loose deposits is taken as an example to study the cracking mechanism of secondary lining, Triaxial consolidated-drained shear tests are carried out on large remolded specimens to obtain the mechanical parameters of the loose deposits. Based on the field monitoring data, three-dimensional numerical modeling is conducted to simulate the process of tunnel construction. The cracking mechanism of the secondary lining is discussed.

2. Project overview

The left tunnel is 470 m long, and the right line is 500 m, passing through a large-scale loose deposits massif (Fig. 1). The asymmetrical topography causes serious asymmetrical loading on the left tunnel entrance (Fig. 2). The loose deposits are of diluvium formation and the lithological composition is mainly silt clay with gravels and cobbles (Fig. 3). The tunnel intersects the long tongue-shaped diluvium slope at a large angle. A few shallow landslides were observed in the slope above the tunnel entrance, where the soil stability is poor and the geological condition is complex.

During construction of the left tunnel entrance, collapses, cracking of primary support and subsidence etc. were encountered. After installation of secondary lining, cracks with a total length of about 53 m appeared at the spring level at section ZK106+940~ZK106+993, the main crack is parallel to the tunnel axis (Fig. 4).

3. Mechanical tests on loose deposits and calculation parameters

Triaxial consolidated-drained shear tests were carried out on large remolded specimens to obtain the mechanical parameters. Due to the practical difficulties to acquire large undisturbed soil samples of the deposits, remolded cylindrical samples were used. The density of remolded samples was in accordance with the result of field density tests. The dry density of the two groups of samples was 1.65×10^3 kg/m^3 and 1.50×10^3 kg/m^3 respectively. The maximum particle size of soil samples was 60 mm and the particle size distribution curve is shown in Fig. 5. The sample was prepared in 5 layers, with a diameter of 300 mm, and the total height of 700 mm and saturated by using the vacuum and water saturation method.

Fig. 1. The mountain composed of loose deposits.

Fig. 2. The slope above the left tunnel entrance.

Fig. 3. Composition of loose deposits.

The consolidation time was 24 h, and the rate of shear was 0.122 mm/min. The stress–strain curves of the tests are shown in Fig. 6. The strength parameters and non-linear modeling parameters of loose deposits are shown in Table 1.

The initial tangent elastic modulus and Poisson's ratio of the Duncan–Chang model under different confining pressures are obtained on the basis of the actual stress state of the loose deposits, and approximated as elastic modulus E and Poisson ratio μ of numerical simulation. As the initial tangent elastic modulus is lower than the actual value, and the initial tangent Poisson's ratio is larger than the actual value, this approximation may lead to larger deformation, but the results are on the safe side.

The relationship between the initial tangent modulus and confining pressure of the Duncan–Chang model is given by:

$$E_i = KP_a\left(\frac{\sigma_3}{P_a}\right)^n \tag{1}$$

The relationship between the initial tangent Poisson's ratio and confining pressure is given by:

$$\mu_i = G - F\ \lg\left(\frac{\sigma_3}{P_a}\right) \tag{2}$$

where K, n and G are test parameters; P_a is atmospheric pressure in kPa. The overburden depth of the tunnel under study is about 35–70 m, with an average depth of 48 m. The static lateral pressure coefficient of the loose deposits is 0.45, and the natural density is 1.70×10^3 kg/m^3. After substituting the above parameters and K, n, G, F from tests into Eqs. (1) and (2), the elastic modulus E and Poisson's ratio μ of the Mohr–Coulomb model can be obtained. Since the deposits are loose, considering the test condition, the Poisson's ratio is adjusted to 0.38, the cohesion to 30 kPa, and the friction angle to 20°.