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The long-term safety of a deeply buried soft rock tunnel lining under inside-to-outside seepage conditions

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ABSTRACT

For deeply-buried long tunnels, which are constructed in environments with high stress and soft rock, stability is definitely an important engineering problem. In this study, the buried depth of the chlorite schist section of a headrace tunnel in the Jinping II Hydropower Station was between 1550 and 1850 m. In this project, rheological problem, the wetting-induced softening problem and inside-to-outside seepage problem were all prominent, which posed serious threats to the long-term stability of the tunnel lining. This study detailed inspected the engineering geological conditions of the chlorite schist sections, the extrusion deformations of the surrounding rock mass following the excavation, and the surrounding rock support and reinforcement after the expansion excavations. In addition, the characteristics of rheological mechanical and wetting-induced softening for the chlorite schist were determined through laboratory testing and field monitoring. The rheological mechanical characteristics of the chlorite schist were not obvious when the stress was low. However, they were quite obvious when the stress was high. Based on the results, the rheological mechanical behaviors of the chlorite schist were described by a visco-elastoplastic rheological model (CVISC). Then, this study verified the rationality of the existing reinforcement scheme and obtained the final deformation stability time of the surrounding rock through a numerical simulation of the support reinforcement and the secondary lining during the operational period. Furthermore, the safety of the lining structure during the operational period was evaluated. These results may potentially play an important role in the guidance of future engineering designs and construction and may potentially be used as a reference for the support designs of similar deeply buried soft rock projects.

1. Introduction

Soft rock has the features of low strength, large deformations, serious wetting-induced softening, and obvious rheological effects (Liao et al., 2006; Sharifzadeh et al., 2013). In headrace tunnels, being excavated in deeply-buried soft rocks, the problem of deformation during the excavation and installation of supports is quite serious. And these problems along with their controlling factors will undoubtedly pose major threats to long-term safety of the tunnel lining during its operational period. For example: ① The long-term rheological deformation of the surrounding rock, which is under high stress, will constantly increase the lining pressure; ② During its operational period, the long-term inside-to-outside seepage will cause rock softening which can reduce the strength and deformation modulus, and leads to cracking and instability of the lining; ③ The cracking of the lining will speed up the seepage and softening of the surrounding rock (Tang and Tang, 2012; Zhao et al., 2015; Zhang et al., 2016). As a result, a vicious cycle will occur. For example, the chlorite schist of the Jinping II Hydropower Station exhibited the characteristic of a typical soft rock. After the excavation and support of the upper section, extrusion deformations of the surrounding rock appeared within a short time and became worse as further time elapsed. If these problems are not addressed during the construction period, the maintenance cost and power generation loss will become incalculable when cracks and damages occur to the lining due to the extrusion deformations of the surrounding rock. Therefore, stability of tunnels in deeply-buried soft rock and tunnel lining both are key controlling factors in the long-term safety of deep tunnel engineering projects.

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Many researchers have carried out in-depth studies regarding soft rock engineering. By considering mechanical properties of weak rocks, Yoshida et al. (1997) calculated and analyzed the weakening of mudstone due to absorption of water and its influence on mechanical behavior of surrounding rock mass in tunnels. Mechanical response of surrounding rock mass during the excavation of rounded tunnel in viscoelastic media under hydrostatic pressure was studied by Fahimifar et al. (2010). Sulem et al. (1987) calculated and analyzed the rheological mechanical laws of the surrounding rock in rounded soft rock tunnels using an empirical formula. Guan et al. (2008) used Burger-deterioration rheological model to calculate and analyze the surrounding rock deformation in a mountainous tunnel. Pellet et al. (2009) adopted a numerical simulation method to calculate the rheological mechanical behaviors of the damage zones in surrounding rock mass following the excavations of underground galleries. By considering support in soft rock tunnels, Sakurai (1978) deeply examined stresses and support structures during the excavation of tunnels. Carranza and Diederichs (2009) calculated and analyzed the mechanical behavior of wire mesh and shotcrete composite lining in rounded tunnels. Creep characteristics of galleries in soft surrounding rock mass with bolt-grout supports were studied by Lian et al. (2008) by numerical simulation. Pellet (2009) studied the contacts between the tunnel lining in viscoelastic media and the surrounding rock within easily damaged areas. He et al. (2015) applied the material point method to evaluate the safety of excessive deformations in tunnels.

In deeply-buried soft rock tunnel engineering, it is necessary to consider following three factors: rheology of the rock mass, inside-to-outside seepage (Zarei et al., 2012, 2013) and wetting induced softening. These factors play a vital role in the safety of tunnels in deeply-buried soft rock masses because of the complex physical and mechanical properties of soft rocks, unfavorable geological environment and engineering conditions. The lining structure stresses, which arise from the rheological and elastic-plastic deformations of the surrounding rock mass, are the loading conditions that require consideration during the analysis of lining design and safety. The combined action of these factors is quite complicated because these are interconnected with each other. Therefore, research conducted on only a single factor cannot possibly meet the necessary requirements.

A chlorite schist formation was found during the excavation of a headrace tunnel at the Jinping II Hydropower Station. The formation had a total length of approximately 400 m, a burial depth of about 1550–1850 m, and gravity stress of approximately 42–50 MPa (Liu et al., 2013). After the tunnel excavation and initial support, the extrusion deformation became serious. The rheological effect was prominent, the wetting-induced softening effect was strong, and inside-to-outside seepage problem was existed. The aims of this study were to analyze and evaluate the lining structure safety during the operational period, based on a detailed inspection of the geological conditions, excavation method, initial support, and support reinforcement for the chlorite schist section. The processes of actual tunnel construction and tunnel operational conditions were analyzed using visco-elastic rheological model. The rheology mechanical behavior of the rock mass and the wetting-induced softening effect were also considered in this analysis. The fluid-solid coupling method was applied in this analysis. Then, several indexes, including the rheological deformation, stress, FAI (Failure Approach Index (Zhang et al., 2011), which is an index for the strain assessment) and plastic zone, were introduced to evaluate the safety of the surrounding rock mass and lining structure. Fig. 1 illustrates the flow chart of the research work in this paper.

2. Engineering situations of the chlorite schist section in the Jinping II Hydropower Station

2.1. Engineering geological characteristics of the chlorite schist section

The headrace tunnel of the Jinping II Hydropower Station consisted of four parallel headrace tunnels, with a total length between 16.658 and 16.675 km, maximum burial depth 2525 m, and average burial depth approximately 1610 m. The chlorite schist of the Jinping II Hydropower Station was mainly distributed in K1 + 537 to K1 + 800 of the #1 headrace tunnel, and K1 + 613 to K1 + 755 of the #2 headrace tunnel. It had a burial depth ranging from 1550 m to 1850 m and gravity stress value approximately 41–50 MPa. The majority of the surrounding rocks were grade-IV (Ministry of Water Resources of the People's Republic of China, 2008), as shown in Fig. 2.

The strata, which were exposed during the excavation of the west end of the headrace tunnels, mainly consist of lower Triassic green schist (T_1), middle Triassic Zagunao Formation marble (T_{2z}), and lower Triassic sand slate (T_3). The T_1 was interbedded and consisted of green sandstone, chlorite schist, and gray white/light fresh pink marble with each layer thickness between 20 cm and 60 cm. The attitude change of the chlorite schist was quite large, with a strike of NS SN to N 20° E, an inclination direction of W/NW, and an inclination angle of ∠75° to 85°. The chlorite schist stratum constitute the core of an anticline with T_{2Z} in conformal contact on both sides as shown in Fig. 2. For the lithology boundary, the strike is N28° to N45°, the inclination direction is W/NE, and the inclination angle is 55°. The attitude of the strata in the K1 + 200 to K1 + 900 m section was found to be very complex, and changed from NE (intersected with the tunnel axis at a large angle) to NW (parallel to the tunnel axis). There were many complex folds observed in this section due to which the rocks were strongly extruded, distorted, and crumpled. After the extrusion of chlorite schist from the tunnel, the surrounding rocks became so weak and loose that they can be broken off by hand. There was no big adverse structural plane through the chlorite schist section. The gaps between the small structural planes were filled with rock flour and thereby the small structural planes were smooth. The chlorite schist formation acted as a water-resistant layer which ceases the further growth of karst and movement of underground water. Therefore, the external water action could be neglected during the design of the lining structure.

2.2. Excavation support of the chlorite schist section

In accordance with the lithology classification and surrounding rock quality, the tunnel diameters and support parameters during the initial excavation were shown in Tables 1 and 2. In this project, rock mass basic quality [BQ] system (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2015) was applied for evaluation of rock mass quality. It is the engineering rock mass classification standard of China (GB/T50218-2014), in which rock mass quality could be divided into five grades by the [BQ] value ($[BQ] \in [550, +\infty]$, Grade I; $[BQ] \in [550, 451]$, Grade II; $[BQ] \in [450, 351]$, Grade III; $[BQ] \in [350, 251]$, Grade IV; $[BQ] \in (-\infty, 250]$, Grade V). For the chlorite schist in the Jinping II hydropower station, the [BQ] value was 286 and the quality of chlorite schist belongs to grade IV. The design tunnel diameter was between 13.4 and 13.8 m. Top heading and benching method was used to excavate the tunnel with upper bench height was 8.5 m and lower bench height was between 4.9 m and 5.3 m. The excavation was divided into left and right parts, and a steel arch grid was erected following the excavation of the upper bench. Soon after, anchor bolts were installed and shotcreting was done as initial support for the tunnel. In addition, steel fiber-reinforced siliceous concrete with outstanding bending resistance was adopted. The majority of the anchor bolts were full-length common mortar anchor bolts.

Support parameters listed in Tables 1 and 2 are:

- *S4-n:* The tunnel diameter was 13.4 m; diameters of the systematic bolts in the full-section were 28–32 mm; the lengths of the anchor bolts were 6–9 m, which were alternatively arranged with 1-m spacing; the thickness of the steel fiber-reinforced siliceous concrete was 20 cm; the spacing between the grid steel arch was 1.0 m;