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Analysis of mechanical behavior of soft rocks and stability control in deep tunnels

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ABSTRACT

Due to the weakness in mechanical properties of chlorite schist and the high in situ stress in Jinping II hydropower station, the rock mass surrounding the diversion tunnels located in chlorite schist was observed with extremely large deformations. This may significantly increase the risk of tunnel instability during excavation. In order to assess the stability of the diversion tunnels laboratory tests were carried out in association with the petrophysical properties, mechanical behaviors and water-weakening properties of chlorite schist. The continuous deformation of surrounding rock mass, the destruction of the support structure and a large-scale collapse induced by the weak chlorite schist and high in situ stress were analyzed. The distributions of compressive deformation in the excavation zone with large deformations were also studied. In this regard, two reinforcement schemes for the excavation of diversion tunnel bottom section were proposed accordingly. This study could offer theoretical basis for deep tunnel construction in similar geological conditions.

1. Introduction

The West ends of diversion (high pressure) tunnels #1 and #2 of Jinping II hydropower station were located in the chlorite schist stratum with the length of about 400 m. This stratum is characterized with complex geological conditions, e.g. high in situ stress, and large overburden depth. The main characteristics of chlorite schist are related to the weakness in the mechanical properties, water-weakening effects and significant creep strain of rocks. Extremely large deformation was observed during construction due to the inadequate support measures, such as delayed support and low-strength support, after excavating the top section of tunnels. The significant interference of primary support with original lining section contributed to the continuously increasing deformation of rocks. This considerably increases the risk of instability of surrounding rock mass when excavating the bottom section of tunnels, resulting to a problem in the power generation capacity due to reduction of the tunnel cross-section.

Many definitions and/or concepts regarding soft rocks have been proposed (Fan, 1995; Guo, 1996; Lin, 1999). According to the work of Sciotti (1990), soft rocks, i.e. sandstone (Nickmann et al., 2006) and mudstone (Yoshinaka et al., 1997), have the main characteristics such as large deformability, strong dependence of resistance on degree of saturation or temperature, and susceptibility to alteration. For simplicity, soft rocks have been classified into two sets (Clerici, 1992; Russo, 1994): geological soft rock and engineering soft rock. The set of the geological soft rock has the intrinsic properties of weakness, looseness and expansibility, while the engineering soft rock generates significant plastic strain and creep strain subjected to engineered effect. The chlorite schist of Jinping II hydropower station can be viewed as a geological soft rock due to its weakness in mechanical properties, but also as the engineering soft rock due to high in situ stress at depth of approximately 1500 m.

Excavating tunnel in soft rock stratum usually will cause accident due to the complex geological conditions and mechanical behaviors of soft rocks. Many methods of support techniques have been proposed consequently. For example, the New Austrian Tunneling Method (NATM) (Han, 1987) which is also known as sequential excavation method (SEM) is a popular method in modern tunnel design and construction. Salamon (1970) studied the support system in terms of energy. The support structure and

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surrounding rock simultaneously generate compatible deformation and the support structure can absorb part of dispersed energy from surrounding rock mass. The combined support method (Feng, 1990) proposed that increasing the thickness of support was not the optimum method for tunneling in soft rocks, and the method of pre-flexibility and post-stiff was of priority. He (1994) suggested that the support technique for deep tunneling should be carried out in two steps: first flexible support and a coupling support followed for the critical parts. Dong et al. (1994) also proposed support theory for the loose circle in surrounding rock mass.

The support system for tunneling in soft rock is still a challenging issue due to the special mechanical behaviors of soft rocks. Therefore, the stability of the diversion tunnels passing through the chlorite schist stratum of Jinping II hydropower station should be analyzed. Based on this, laboratory tests were conducted to study the petrophysical properties, mechanical behaviors and water-weakening properties of chlorite schist. In addition, the creep deformation of surrounding rock mass, destruction of support structure and large-scale collapse induced by high in situ stress associated with mechanical properties of chlorite schist were analyzed. Accordingly, the excavation and reinforcement schemes for the diversion tunnels construction were proposed.

2. Project overview

Jinping II hydropower station is located at the Yalong River, Sichuan Province, China. The Jinping II hydropower station is well known as a super-large hydropower project due to the ultra-long, deep-buried and large-scale tunnel section. The four parallel diversion tunnels of Jinping II hydropower station are 16.7 km in length and the spacing between two adjacent tunnels is about 60 m. The tunnels 2 and 4 were excavated by drilling-and-blasting method in two steps, while tunnels #1 and #3 by TBMs. Full-section reinforced concrete tunnel support structure with thickness of 50–140 cm was used. The overburden depth along the tunnel is basically 1500–2000 m and the maximum depth is 2525 m.

The West ends of the diversion tunnels #1 and #2 were located in chlorite schist stratum in the stakes of (1) 1 + 537 and (2) 1 + 613 at the depth of about 1500 m (see Fig. 1). The chlorite schist is complex for geological conditions and frequent changes in lithology can be observed. The rocks are mainly green sandstone, green sandstone–marble interbedding, chlorite schist–marble interbedding and chlorite schist. The accumulated lengths of chlorite schist–marble interbedding and chlorite schist in the diversion tunnels #1 and #2 are 264 m and 314 m, respectively. The existence of chlorite schist–marble interbedding and chlorite schist strata caused the major collapse and destruction of primary support due to large deformation of surrounding rock mass in large area. Moreover, large deformation of surrounding rock mass in a large area was also observed in the second excavation (enlarged) and some local large deformation once again caused the destruction of support structure.

3. Physical properties of chlorite schist

Creep deformation, destruction of support structure and large-scale collapse were observed during excavation due to the weakness of mechanical properties of chlorite schist and high in situ field stress. These problems should be addressed in order to maintain the progress of project construction. Therefore, related petrophysical tests were carried out to analyze the physical properties and mineral compositions of chlorite schist, which could be helpful to investigate the mechanical behavior and the stability assessment of the diversion tunnels. All the samples are from the stake of (1) 1 + 760.

3.1. Mineral composition

Four typical samples of chlorite schist were used to identify the mineral composition and the results are shown in Table 1. It clearly shows that the main mineral component is chlorite, which has an evident property of water-argillization. This property is one of the most important factors that cause water-weakening and large deformation of soft rocks. The second main component is amphibole, whose Mohs mineral hardness is twice of the one of chlorite. Some talc is found in all the four samples. Talc has the minimum Mohs mineral hardness among all the mineral components; the sample with the maximum composition of talc thus has the minimum elastic modulus and strength. Moreover, small quantity of calcite is also observed in the sample of IRSM #1. The sample of IRSM #4 contains a little more calcite and some dolomite. This phenomenon can be explicated by the inclusion of marble in the samples of chlorite schist.

3.2. Microstructures of rock samples

Scanning electron microscopy (SEM) was used to observe the microstructures of the four samples in order to study the deformation mechanism of chlorite schist and the results are shown in Fig. 2. Except for the sample of IRSM #3, the other three samples have similar mineral arrangement and porous structure. The mineral grains are arranged in orientated layered sheet, resulting in tight porosity structure and low porosity. The sample of IRSM #3 presents disordered mineral arrangement and its porosity is formed by the connection of mineral grains in a dense type. The microstructure of chlorite schist revealed by SEM shows that the samples have low porosity and low permeability.

3.3. Expansibility

The mineral composition in Table 1 shows that no hydrophilic expansion mineral is observed in the samples; the expansibility of chlorite schist is thus not significantly different from the first estimation. The following expansion tests were performed to investigate the free expansion ratio, axial expansion ratio with lateral restraint and expansion pressure. The results are shown in

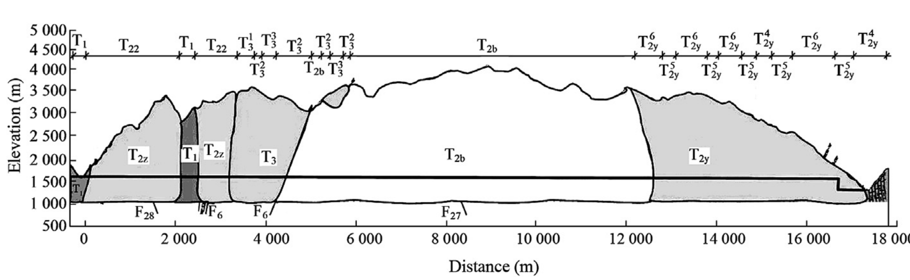

Fig. 1. Geological profile along diversion tunnel of Jinping II hydropower station. T_1: chlorite schist, T_{2z}: marble, T_3: sandy slate, T_{2b}: marble, T_{2y}: marble.