Geological conditions and key rock mechanics issues in the Western Route of South-to-North Water Transfer Project

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Abstract: In terms of special geological conditions of the Western Route of South-to-North Water Transfer Project, the classification method for surrounding rocks is discussed by combining with the construction method of tunnel boring machine (TBM). The classification standard of surrounding rocks is put forward on the basis of physical simulations and engineering practices. Damage, deformation and evolution of surrounding rocks induced by TBM excavation are discussed. Meanwhile, the long-term deformation mechanisms and stability of surrounding rocks are also studied. On this basis, a three-dimensional constitutive model for interbedded sandstone slate and a flat shell-joint element-foundation system for calculating internal forces of segment lining are established. The deformation features of surrounding rocks of deep and steep interbedded sandstone slate and their influences on internal forces of segment lining are presented. Finally, the design methods of segment lining constructed in deep and steep flysch are proposed.

Key words: the Western Route of South-to-North Water Transfer Project; rock mechanics issues; classification of surrounding rocks; stability of surrounding rocks; excavation-induced damage; lining design

1 Introduction

The first stage construction of the Western Route of South-to-North Water Transfer Project (Western Route for short) was designed to divert water from the upper reaches of Yalong River and Dadu River to the upper reaches of the Yellow River. It was planned to be constructed on the Tibetan Plateau. The diversion work consists of diversion junction and long tunnels at large overburden depth. The suggested scheme for water diversion with a volume of $8 \times 10^9$ m$^3$ is composed of 7 dams and 14 tunnels (Fig.1). The overall length of the Western Route is 325.6 km, with 321.1 km of tunnels. The Reba concrete faced rockfill dam (CFRD) in the Yalong River is the highest dam with a height of 192 m. The diversion tunnel plays a very important role in the Western Route. The minimum and maximum diameters of the main diversion tunnel are 7.34 and 9.60 m, respectively. The minimum and maximum natural segment lengths of the tunnel are 3.7 and 72.4 km, respectively. The maximum overburden depth of tunnel is 1 150 m, and the average is approximately 500 m.

The Western Route is located on the first terrace of landform in West China. The natural condition is relatively tough with complicated land surface topography, lithology and regional geological structures. The geological conditions are complicated while the lithology of rocks is rather uniform. The rocks are mainly composed of epizonal metamorphic sandstone and slate of Triassic, which are comparatively uniform layers with large thickness. The rocks are intensively compacted, and the folds are fully developed. The dips of most of strata are relatively large [1–5]. The long tunnel with large overburden depth goes through many engineering geological units, and hydrogeological conditions are complicated, which brings many unexpected difficulties to the tunnel construction. In future construction and operation of the project, numerous difficulties in rock mechanics issues will be encountered.

The geological conditions in the Western Route are suitable for construction using TBM. The advantages of high speed and efficiency of TBM can be well reflected in the construction of long tunnels with large overburden depth. Meanwhile, TBM, which is highly suitable...
mechanized, may be adopted in the Western Route due to the special climate conditions such as coldness and oxygen deficit at the Tibetan Plateau. Therefore, TBM was considered for the main diversion tunnels, and the adits would be constructed by drilling and blasting method according to geological conditions and investment benefits. 24 TBMs with different diameters were selected for the first stage tunnel excavation. The past experiences of tunneling show that, except support, ventilation and drainage techniques that control the construction of long and deep tunnels, various potential geological hazards also should be prevented or treated. Although TBM has the advantages of high speed, high quality, economic merits and security, it is not suitable in unfavorable geological conditions such as tunnel failures, rockbursts, weak rock units, water inrush and swelling rocks. It could impede the process of tunneling if not handled properly.

The issues that may be encountered in the Western Route in terms of rock mechanics, environmental geology and engineering geology have been extensively discussed [6–12]. As for this project, the rock mechanics issues observed in the dam sites (junctions) are usually conventional. But those observed in tunnels are important factors, which may affect the success of the project. The key rock mechanics issues in the Western Route can be approximately reflected in the following 3 aspects. Firstly, the issues considered before TBM operation were preliminary investigations of surrounding rocks. Secondly, the issues concerned during TBM construction were concentrated on the excavated damage and deformation features of surrounding rocks, the interaction of surrounding rocks and segment lining, and the optimized support design. Finally, the issues occurring during project operation concerned mainly the deformation mechanism and long-term stability of diversion tunnels under complicated environments. This paper will discuss the above key rock mechanics issues.

2 Description of geological conditions

2.1 The issues of fault activity

The NW faults are mostly observed in the Western Route, and faults of other directions are few and at a small scale. The fault activities have obvious characteristics of inheritance and small-amplitude, with no active fault developed. The regional active faults are primarily reactivation of faults along the boundaries of tectonic units. The active faults were developed frequently in early and medium Quaternary period, and the range was reduced in the late Pleistocene period. Some faults are not active or only local faults are active. The active faults have an obvious controlling effect on occurrence and magnitude of earthquakes. The earthquakes with magnitudes larger than 6.0 all happened along the Holocene active faults.

According to field investigations and laboratory tests, most of the faults in the vicinity of the project region are not active. Also, there is no distribution of active faults or epicenter at the dam site. No active faults traverses the tunnels. Active faults like Garze-Yushu fault, Sangrima fault and Gande fault, which are 70, 120 and 200 km away from the tunnel, respectively, are distributed within the range of 300 km from the project.
2.2 Features of seismic activity

The Western Route is located within the seismic zones of Xianshui River-eastern Yunnan Province and Bayan Har Mountains. The boundary of the two seismic zones lies in counties of Shiqu, Setar and Danba. Most of diversion tunnels and dam sites are distributed in the zones with low seismic activity, only a small part in the southwest lie in a zone with highly frequent seismic activity.

The strong earthquakes mainly occur in the fault zone at the fold zone edge, where the project is located. The intensity and frequency of seismic activity in the fold zone are reduced significantly. No strong earthquake has been recorded in the near field. Thus, the global earthquake level in the project area is roughly weak. The earthquake distribution is closely related to structures. The epicenter distribution of historically destructive earthquakes presents clearly striping characteristics, primarily along counties of Kangding, Daofu, Luhuo and Garzi.

From the spatial distributions of intermediate strong earthquakes, it can be observed that the earthquakes with magnitudes larger than 4.7 are distributed along the Xianshui River fault zone in the southwest and north parts of the project area. There are few seismic events with magnitude over 4.7 in the central south part. Except for the Dari earthquake with $M_s = 7.75$ in 1947, almost all earthquakes with magnitude larger than 7.0 happened in the Xianshui River fault zone. The intermediate-strong earthquakes in other parts of the project area are relatively dispersed. Besides the earthquake with $M_s = 7.75$ along the Sangrima-Dokog River fault in 1947, some intermediate-strong earthquakes were also observed in the southeast part of the project area and along the Gande-Aba fault.

2.3 Evaluation of regional stability and site selection

The southeast part of Sichuan-Qinghai Plateau is one of earthquake-prone zones in China. Various engineering practices prove that relatively stable places, which are suitable for dam constructions, can be found in this unstable region based on geological investigations. In this paper, the evaluation of site stability was conducted based on Ref.[13], with reference to Engineering Geological Survey Standards (ZBH14003-89). Thus, the instability induced by recent tectonic movement can be taken into considerations. According to the regional map of peak seismic acceleration with 10% probability of exceedance in 50 years [14], the regional stability is classified into 4 groups based on the site-specific geological conditions of the Western Route, i.e. stable, basically stable, approximately unstable, and unstable. The specific indices are listed in Table 1. The layout of corresponding classification of regional tectonic stability for the Western Route is shown in Fig.2. Thus, the project area of the Western Route can be categorized as stable, basically stable and approximately unstable according to relevant investigations, and most areas are basically stable. No unstable area is observed.

- **Table 1** Suggested classification of regional tectonic stability for project area in the Western Route.

<table>
<thead>
<tr>
<th>Classification of stability</th>
<th>Earthquake intensity I</th>
<th>Acceleration (g)</th>
<th>Active fault</th>
<th>Magnitude of earthquake</th>
<th>Regional gravity and magnetic anomaly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable</td>
<td>≤VI</td>
<td>&lt;0.05</td>
<td>No active fault within 5 km</td>
<td>$M_s&lt;5.00$</td>
<td>None</td>
</tr>
<tr>
<td>Basically stable</td>
<td>VII</td>
<td>0.1–0.15</td>
<td>Active fault longer than 10 km existing within 5 km</td>
<td>$5.00 ≤ M_s &lt; 6.00$</td>
<td>Less</td>
</tr>
<tr>
<td>Approximately unstable</td>
<td>VIII</td>
<td>0.2–0.3</td>
<td>Active fault longer than 6.00 ≤ $M_s &lt; 7.00$ (or no more than one seismic event with $M_s ≥ 7.00$)</td>
<td>Strong</td>
<td></td>
</tr>
<tr>
<td>Unstable</td>
<td>≥IX</td>
<td>≥0.4</td>
<td>Active fault longer than 10 km and seismic structure of $M_s ≥ 5$ existing within 5 km</td>
<td>$M_s ≥ 7.00$</td>
<td>Intensive</td>
</tr>
</tbody>
</table>

The Western Route is a water-diversion project, so the main requirement of the planning is to transfer more water with less cost. Therefore, the appropriate researches and the minimum engineering cost are the key factors. The overall project layout of the Western Route is the prerequisite for the selection of the dam sites. Based on the practical techniques and project budget limitations, the dam sites might or might not be the ones with most favorable geological conditions.

2.4 Classification of surrounding rocks

This paper mainly adopts the classification methods introduced in Ref.[15]. The results of rock mass classification indicate that the surrounding rocks in the project area primarily belong to classes II–III, with a smaller part with classes IV–V. Class II rocks account for 27%, class III rocks about 64%, and classes IV–V rocks around 9%. The overall stability conditions of surrounding rocks are good, but part of them is poor. The geological investigations and support requirements for classes IV–V rocks need to be strengthened.
Fig. 2 Layout of classification of regional tectonic stability for project area in the Western Route.

Classes IV–V rocks are mainly distributed at the entrances, outlets, shallow sections, fracture zones, and so on. As for the classes II and III rocks with large overburden depths, possible large deformation should be controlled and relevant measures should be taken beforehand. For the shallow rocks, because of the unfavorable combination of steep and multiple sets of joints, the wedge blocks may fail, which can lead to collapse. More attention should be paid to the construction of entrances and outlets.

2.5 Stability of surrounding rocks

The lithologic combination is uniform and most of rock strata are steep. The hardness of sandstones and slates is intermediate. Except some fracture zones, the surrounding rocks of tunnels are basically intact. The strike of rock strata is mainly NW. Besides, the direction of the Western Route mostly intersects at large angles or near perpendicular to the strike of structural lineament, which is helpful for the stability of surrounding rocks in underground caverns and tunnels.

Calculation results show that during excavation, deformation will be observed in surrounding rocks of the tunnels, which are mainly composed of slates. At large overburden depth, the plastic deformation and failure may occur in surrounding rocks during excavation. The strength softening coefficient of slates ranges from 0.5 to 0.7. Water absorption rate of slates after full immersion is relatively small. Failures may tend to happen along the bedding planes after immersion [16], and temporal factors have a great effect on creep behaviors of slates [17]. Therefore, the effective methods to prevent large deformation of the slates during construction are to strengthen the supports timely and take effective water-proof measures.

For the tunnels embedded in the interbedded sandstone slate strata, plastic deformation and failure of slates under high in-situ stress may occur in local positions. Rockburst is not likely to occur. Under high in-situ stress at greater depth, large deformation or rheological plastic deformation may occur in structural fracture zones and argillite sections, which is controlled by the geological structures. Under the effect of groundwater coupling, water inrush and mud outburst may happen, which may last for a long period of time and lead to the difficulties in tunnel construction.

2.6 Features of rockburst

In the region of the Western Route, the in-situ stress field is mainly composed of tectonic stresses. The direction of the maximum principal stress is NE–NEE (NE65°–75°), which intersects the tunnel axis at a large angle. When the overburden depth of tunnel is 500–800 m, the corresponding magnitude of the maximum principal stress is 21.75–31.05 MPa. At the maximum overburden depth of 1 100 m, the magnitude of the maximum principal stress is approximately 40 MPa. The rocks in the Western Route are fractured layered sandstone and slates, and the natural rock strength generally ranges from 50 to 70 MPa. In consideration of the operative conditions of TBM, the probability of rockburst in the tunnels of the Western Route is small and the intensity of rockburst is low. For the tunnel in sandstones, when the overburden depth is less than 400 m, the probability of rockburst is small; for overburden depth of 500–800 m, rockburst may
happen; for overburden depth above 800 m, intensive rockburst is more likely to occur. The actual rockburst intensity may be lower under the effect of fissured water.

2.7 Permeability of rock mass

The groundwater in the surrounding rocks of the Western Route basically flows through bedrock fissures. For the sandstones, slates or interbedded sandstone slates, the permeability in the direction vertical to the bedding planes is larger than that in the direction parallel to bedding planes. Although bedding has certain influences on the permeability of rock mass, the global influence is small. The results in Ref.[18] indicate that, at the depth of less than 100 m, the influence of weathered fracture on the rock mass is small. The permeability of sandstone intercalated with slates and interbedded sandstone slates are 6 and 3.50 Lu, respectively. It is indicated in Ref.[19] that permeability tends to decrease at depth, and the permeability coefficient tends to decrease as the in-situ stress increases.

Hydrogeological analysis and prediction of water inflow in the diversion tunnels in this paper show that the sections, where severe seepage or water inflow may happen, are mainly located at shallow depth, or water-rich section formed by broken rocks at or near the synclinal fold cores and fault fractured zones. As a whole, these sections are distributed on tectonic combination belts listed as follows: (1) Runiange formations along Yalong River-Yanong in Daqu-Maiyunong-Zhake and Daqu-Niqu, (2) the fault zone on Setar hilly plateau along Niqu-Duke River, (3) Duke River fault zone along Dokog River-Markog River, Huona diversion adit, and (4) Geike hilly plateau along Ake River-Yellow River, etc.

In summary, from the above-mentioned site investigations, most sites in the Western Route region are basically stable from the geo-hydro-mechanical perspectives, considering regional seismicity, rockburst, fault activity, tunnel-fault interactions, surrounding rock types and their strength-deformation-flow characteristics, suitability of using TBM, water inflow into the tunnels and its possible consequences, and variations of geological and hydro-mechanical conditions with depth.

3 Advances in rock mechanics issues in the Western Route

There exist different ideas on the issues such as failure mechanism of surrounding rocks in complicated situations, the changes of mechanical properties caused by the damage to surrounding rocks by different excavation methods, the rheological properties of jointed rocks, and the lining-rock interaction mechanism under complicated conditions.

At present, the conventional methods in lining design, such as load-structure method, ground-structure method and experiential analogism, etc., have some shortcomings. Meanwhile, the long-term stability of tunnels under high in-situ stress is a complicated issue. Under the long-term high in-situ stresses, ductility of hard brittle rocks increases. When immersed in water, rocks will be softened, leading to large deformations. The large deformation of rocks will provide pressure on the concrete lining, causing concrete lining to be cracked or even tunnel failure. The Western Route covers a lot of engineering geological units. The deformation features and failure modes at different sections are diverse under different geological conditions, and the influential factors on engineering structures are also varied.

3.1 Classification issues of surrounding rocks

The key technical issue in the Western Route is how to construct the super-long tunnels with TBM, and the basic task is to correctly evaluate and characterize the surrounding rocks. The efficiency of tunnel construction is closely related to the geological features of surrounding rocks [20–23], which can be estimated from two aspects: (1) whether TBM can be adopted when considering the overall geological conditions of the whole region in the Western Route; and (2) whether rock hardness and strength can meet the requirements of TBM construction. The influence of geological features is attributed to the classification of surrounding rocks based on TBM construction.

According to engineering features of deep super-long tunnels in the Western Route, various geological factors, which would affect the safety, speed and economy of TBM construction, should be considered. Based on rock breaking mechanism of TBM, this paper presents researches using laboratory tests, numerical simulations and other methods to study the factors influencing the classification of surrounding rocks. The generalized model of TBM cutter as the wedge-shaped knives is used in physical simulations to cut the mortar samples and to simulate failure process under different operative conditions. In this way, the influences of various factors on rock masses failure are determined. 3DEC program is used
to build different 3D rock breaking models for TBM construction [24]. The advance rates of TBM, which are calculated with different rock mechanical parameters and constant mechanical parameters of TBM, are compared.

The research results indicate that uniaxial compressive strength (UCS), petrofabric features, properties of structural plane, etc., have great influences on the efficiency of TBM construction. In Ref.[25], quartz content was adopted as an important index in classification of surrounding rocks, and it is closely related to abrasion resistance of rocks. Though the quartz content of sandstone in the Western Route is 50%–87.5%, the granularity of quartz is mainly fine. The quartz mainly contains siliceous debris and single crystal quartz, and little polycrystal quartz whose crystallinity is high. The quartz content in slate is basically less than 5%, and most of it is siliceous debris whose crystallinity is low. As a whole, the quartz content in the rocks of project area is not high, which has little influence on the efficiency of TBM construction. Rock hardness and abrasion resistance related to quartz content also have little influence on the efficiency of TBM construction. According to the surrounding rock features in the Western Route, the quartz content and abrasion resistance will not be considered as classification factors in this paper.

The relationship between rock strength and advance rate is not linear. On the basis of physical simulations and engineering practices of rock breaking, the surrounding rocks in the Western Route can be classified into 5 types according to rock strengths (Table 2).

**Table 2** Strength classification of surrounding rocks based on TBM construction.

<table>
<thead>
<tr>
<th>Types of surrounding rocks</th>
<th>Uniaxial compression strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>30–60</td>
</tr>
<tr>
<td>II</td>
<td>60–100</td>
</tr>
<tr>
<td>III</td>
<td>15–30</td>
</tr>
<tr>
<td>IV</td>
<td>&gt;100</td>
</tr>
<tr>
<td>V</td>
<td>&lt;15</td>
</tr>
</tbody>
</table>

Among the parameters of structural planes, inclination of structural planes can be considered as a correction factor for rock mass classification. In this paper, the simulation results of joint inclination and rock breaking efficiency show that rock breaking force changes remarkably with joint inclination and joint angel has a great influence on rock breaking force of the cutter. Larger inclination may cause larger rock breaking forces needed. When joint inclination is 40°–60°, the breaking force is the minimum; when joint inclination is more than 60°, the rock breaking force is the maximum. When the joint inclination is less than 30°, the rock breaking force is relatively small. But when the joint inclination is larger than 50°, the advance depth will increase rapidly. When the joint inclination is larger than 60°, the advance rate will increase slowly. With large inclinations, the coalescence of fractures and joints is difficult. The load imposed on the cutter needs to be increased, thus the invasion degree of cutter becomes greater.

Meanwhile, the strikes of structural planes and the advance direction of TBM (direction of tunnel axis) are important factors influencing TBM construction efficiency. The simulation results indicate that when the angle between the joint direction and tunnel axis is 50°–60°, the advance rate is the optimum. The advance rates will decrease gradually with the joint-tunnel intersecting angle (from high to low): 60°–80°, >80°, 30°–50°, and <30°, respectively.

Basically, when the integrity of rock mass is comparatively low and spacing between structural planes is small, the weak interfaces developed locally in the rock mass will be helpful for cutting, thus the advance rate of TBM will increase. However, when the structural planes are fully developed or not developed, it is not helpful for the advance rate of TBM.

Considering the results of physical and numerical simulations, the properties of structural planes and rock mass structures, the surrounding rocks in the Western Route can be classified into 5 types (Table 3), in which rock grading standard (GB50218-94) is referred to.

**Table 3** Classification of surrounding rocks in the Western Route based on structural plane.

<table>
<thead>
<tr>
<th>Class</th>
<th>Spacing between structural planes (m)</th>
<th>Angle between structural plane and tunnel axis (°)</th>
<th>Inclination of structural plane (°)</th>
<th>Structure type</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.2–0.4</td>
<td>50–60</td>
<td>40–60</td>
<td>Medium-thin interbedded or fractured</td>
</tr>
<tr>
<td>II</td>
<td>0.4–1.0</td>
<td>60–80</td>
<td>20–40</td>
<td>Medium-thick interbedded structure</td>
</tr>
<tr>
<td>III</td>
<td>&gt;1.0</td>
<td>&gt;80</td>
<td>&lt;20</td>
<td>Extremely thick layer</td>
</tr>
<tr>
<td>IV</td>
<td>≤0.2</td>
<td>30–50</td>
<td>60–80</td>
<td>Fractured structure</td>
</tr>
<tr>
<td>V</td>
<td>Extremely fractured</td>
<td>&lt;30</td>
<td>&gt;80</td>
<td>Granular structure</td>
</tr>
</tbody>
</table>
From Tables 2 and 3, rock mass classification can be determined with the rock strength and five parameters of structural planes.

### 3.2 Mechanism and prediction method of water inflow and water inrush in deep fractured sandstone slates

97% of the tunnels of the Western Route traverses epizonal metamorphic sandstone slate region of Triassic. The basic features of hydrogeological conditions include superimposed fold zones, low or very low permeability of rock mass, high groundwater runoff modulus, deep fracture groundwater, and high salinity of deep circulating water in fractured zones. The quality of groundwater in shallow layer or weathered layer is good.

The excavation of long and deep tunnels, in the sandstone slate strata of high mountainous area in the vicinity of high plateau, will encounter the issues of local water inrush and water inflow, which are different from those in shallow strata. A research was performed on the influence of high in-situ stress and high water pressure on water inrush and water inflow during tunnel construction. The software PFC³D, based on discrete element method, was adopted to study the mechanism of water inrush. Taking advantages of discrete element method in analyzing large deformation and particle element in simulating particle flow with different sizes, the mechanism of water inrush and mud outburst were studied by building particle element models for fractured rock mass and fractured zones [26–28]. Based on a fracture water controlling model, a comprehensive multi-factor analytical method for estimating water inrush amount was proposed. The multi-factor correction method using a 3D hydrogeological model of fracture water controlling was put forward to predict water inrush in deep long tunnels. In addition, the ideas and methods employed in the model of fracture water controlling, which can evaluate water inflow in deep long tunnels in non-karst areas, were also proposed. The water inrush of deep long tunnels in non-karst areas comes directly from groundwater network of fractures in the surrounding rocks. The results suggest that 90% of water inrush of deep long tunnels is from fault zones. Therefore, the permeability coefficient of intact rock mass should be determined from the macroscopic view, and more attention should be paid to stability evaluation of fault structures.

### 3.3 Simulations of excavation-induced damage of surrounding rocks in long and deep TBM tunnels

Under different advance rates, tunnel overburden depths, lithologies of surrounding rocks, joint inclinations and other conditions, the surrounding rocks of the tunnels have different features of excavation-induced damage. Rocks can be classified into large-variation, small-variation and stable areas in terms of excavation-induced deformation. Using stresses, rocks can be classified into strong-, rapid- and slight-disturbance areas. The excavation damaged zone (EDZ) of surrounding rocks is frustum-shaped. With the increase in advance depth, the EDZ expands in circumferential direction of tunnel and extends with the advancing working face. The distribution ranges of strong-disturbance zone and EDZ are almost the same, indicating that EDZ has a drastic change in deformation, strong stress perturbation and stress release. The analytical results based on one set of joints indicate that the existences of joints and other unfavorable geological bodies are the main factors for excavation-induced damage of rocks.

Results in Refs.[29, 30] show that the overburden depth of tunnel, advance rate, lithology of surrounding rocks and inclination of joint sets are the main factors that control excavation-induced deformation and damage. Excavation-induced deformation and damage zones in the maximum influential range around a tunnel increase with the increase in overburden depth of the tunnel, but decrease with the increase in advance rate. Under favorable geological conditions, the proper advance rate can decrease excavation-induced damage of surrounding rocks effectively. The excavation-induced deformation and damage of various surrounding rocks have different influences on the maximum influential range. As for slate and sandstone, the difference can reach 40%. The inclination of joint sets has a remarkable influence on the shapes of excavation-induced deformation and distribution ranges of damage zones. Excavation-induced deformation reaches its peak value when the inclination of joint sets is 60°, and the maximum influential range of damage zone around a tunnel reaches its peak value when the inclination of joint sets is 45°.

### 3.4 Deformation mechanism and long-term stability of diversion tunnels under complicated environments

One of the basic issues in stability analysis of the Western Route tunnels is to understand the
deformation, damage process and strength of the deep surrounding rocks. On this basis, a rheological constitutive model for the Western Route rocks is established.

To understand rock behaviors of the Western Route and long-term stability of diversion tunnels, hydro-mechanical (HM) coupling effects was considered in a rheological experiment according to the water-rich and high in-situ stress features of the Western Route tunnels. Thus, a non-stationary viscoelasto-plastic rheological model was built to study the long-term mechanical behaviors of the Western Route rocks [31–33].

The results of cyclic loading-unloading tests show that the peak cohesion of the Western Route rocks is significantly larger than residual cohesion, and internal friction angle is smaller than residual internal friction angle. It was observed that confining pressure for brittle-ductile critical transition was approximately 46 MPa. Meanwhile, the relationship between fracture angle and confining pressure $\sigma_3$ was established. Based on the results, the influences are confirmed with existence of different mechanisms and their conversions on the damage of rocks at great overburden depth.

In the creep experiments considering HM coupling, a triaxial servo-controlled device was employed to conduct triaxial creep test on Western Route rocks. The isochronic curves, deformation rates, influence of creep on deformation and damage mechanism were further analyzed, providing important information and reference for building rheological constitutive models under HM coupling.

For analysis of rheological model and long-term stability of diversion tunnels, the non-stationary viscoelasto-plastic rheological model under HM coupling was put forward and the finite difference equations were derived. This model can analyze long-term mechanical behaviors of soft and hard rocks in diversion tunnels at various overburden depths (500, 1000 and 1500 m). It can also provide theoretical support for TBM construction and optimum support design of the Western Route tunnels.

3.5 Design principle and support technology of deep tunnels under complicated geological conditions

A 3D constitutive model for interbedded sand slate and a flat shell-joint element-foundation system for calculating internal forces of segment lining were established. The deformation features of surrounding rocks of deep and steep interbedded sandstone slates and the influence of internal forces on segment lining were studied, providing technical support for the structural design of segment lining in the Western Route of South-to-North Water Transfer Project [34, 35].

4 Conclusions

The geological conditions of the Western Route of South-to-North Water Transfer Project are very complicated. The key rock mechanics issues can be properly addressed under current economic and technological conditions. Most diversion tunnels almost intersect at large angles or near perpendicular to the strike of structural lineament. Main structural fractured zones traverse tunnels in short distance, which is helpful for the stability of underground caverns. In addition, the seismic performance of deep tunnel is good, which is scarcely influenced by frozen soil, landslide, debris flow and other geological hazards. The surrounding rocks are mainly composed of sandstones and slates. The rock hardness ranges from intermediate to hard. The surrounding rocks are mainly class III, followed by classes II and IV. From the classification of surrounding rocks and calculation results of rock deformations, it can be concluded that TBM construction is practical.

According to the geological conditions of deep long tunnels in the Western Route, boreability of the rock masses, and rock breaking mechanism of TBM, the influences of rock strength, properties of structural planes and other factors on TBM’s efficiency were taken into account. On this basis, the classification method of surrounding rocks was proposed. It provided an effective way to evaluate TBM’s efficiency at different sections and a reference for customization of TBM.

The calculation methods of rock pressures in deep and steep flysch and flat shell-joint element-foundation system, incorporated into the model of internal force analysis of segment lining, were studied. On the basis of deformation mechanism and failure mode, the range of EDZ of surrounding rocks induced by TBM construction and its evolution behaviors under different environments (stress, seepage, earthquake, and so on) were proposed. The optimized design methods of segment lining in deep and steep flysch can offer...
technical support for the tunnels in the Western Route of South-to-North Water Transfer Project.

References


