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Rock mechanical problems and optimization for the long and deep diversion tunnels at Jinping II hydropower station

Shiyong Wu*, Ge Wang

Ertan Hydropower Development Co., Ltd., Chengdu, 610051, China

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Abstract: According to site-specific environments such as high water pressures, high in-situ stresses and strong rockbursts, the design scheme of the long and deep diversion tunnels at Jinping II hydropower station was optimized to ensure construction safety. New drainage tunnels were considered. Furthermore, lining structures and grouting pressures were modified during the excavation of tunnels. The construction scheme was updated dynamically based on the complex geological conditions. For instances, the diversion tunnels were first excavated by drilling and blasting method at the first stage of construction, and then by the combination method of tunnel boring machine (TBM) and drilling and blasting, and finally by drilling and blasting method. Through optimized scheme and updated construction scheme, the excavation of diversion tunnel #1 was successfully completed in June, 2011. This paper summarizes the key issues in rock mechanics associated with the construction of the long and deep diversion tunnels at Jinping II hydropower station. The experiences of design and construction obtained from this project could provide reference to similar projects.

Key words: Jinping II hydropower station; diversion tunnels; optimized design; construction method; grouting

1 Introduction

Jinping II hydropower station is located on the Yalong River, at the junction of Muli, Yanyuan and Mianning counties, Liangshan Yi Autonomous Prefecture, Sichuan Province. It is an important hydropower station along the Yalong River, with a total installed capacity of 4 800 MW. Electricity is generated through four 16.67 km-long diversion tunnels, which cut the 150 km-long river bend.

The project consists of 7 deep parallel tunnels, i.e. 4 diversion tunnels, 2 auxiliary tunnels, and 1 drainage tunnel. From south to north, there are auxiliary tunnels A and B, drainage tunnel, diversion tunnels #4, #3, #2 and #1. The auxiliary tunnels A and B with a diameter of approximately 6 m were excavated by drilling and blasting method, and were completed in August, 2008. The drainage tunnel with a diameter of 7.2 m was excavated by tunnel boring machine (TBM) from east to west and later by drilling and blasting method from west to east. Four diversion tunnels were excavated from the two ends at the same time. The diversion tunnels #1 and #3 with a diameter of 12.4 m, were excavated by TBM, while the horseshoe-shaped diversion tunnels #2 and #4 with a diameter of 13 m were excavated by drilling and blasting method. The diameters of the diversion tunnels at Jinping II hydropower station are larger than those of Qinling tunnel and Sierra tunnel, which are 8.8 and 5.8 m, respectively. To ensure that the generators in the diversion tunnel #1 will be in operation in time, the diversion tunnel #1 should be excavated firstly, followed by the diversion tunnels #2, #3 and #4 [1, 2].

The axes of diversion tunnels at Jinping II hydropower station are almost orthogonal to the ridge line of Jinping Mountain. The overburden depth of diversion tunnels is basically over 2 000 m, with the maximum of 2 552 m (greater than that of Simplon tunnel, the maximum of 2 135 m), and it is very close to that of diversion tunnel at Sierra hydropower station in French (the maximum of 2 619 m) [1]. For the purpose of timely water drainage during construction, the working face of drainage tunnel should be ahead of those of diversion tunnels.

Restricted by the complex topography, it is impossible to properly arrange adits, inclined and

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*Corresponding author. Tel: +86-28-82907635; E-mail: wushiyong@ehdc.com.cn

vertical shafts to assist in the excavation of diversion tunnels. The design and excavation of the diversion tunnels are key issues for the construction of Jinping II hydropower station. The complex hydrogeological conditions, i.e. the high water pressure, stable water supply, and high in-situ stress over 70 MPa, made the tunnel construction and structure design difficult. The diversion tunnels at Jinping II hydropower station are the largest and the most complicated underground projects so far in the world.

The design scheme has been modified and optimized several times, and the construction method and layout have been revised during the tunnel excavation. The location and layout of the diversion tunnels at Jinping II hydropower station are shown in Fig.1, where *i* represents the base slope of the tunnels.

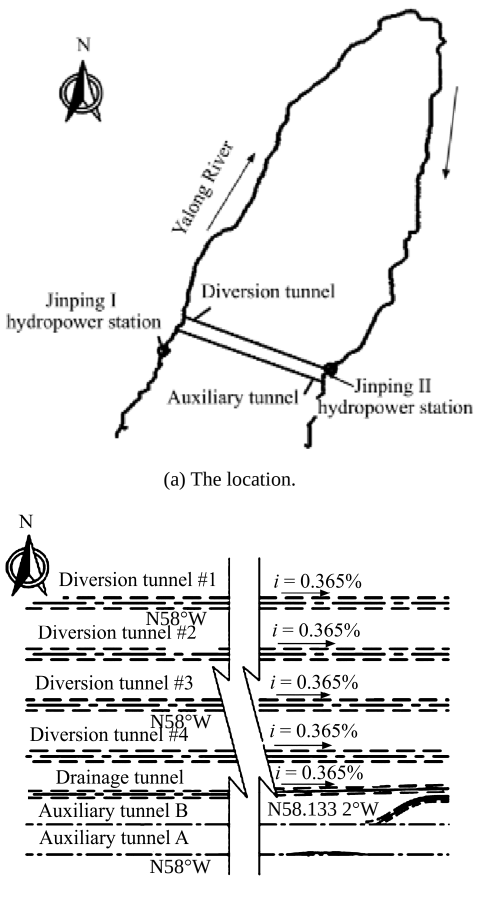


Fig.1 Location and layout of the diversion tunnels at Jinping II hydropower station.

2 Description of geological conditions

2.1 Topography

Jinping Mountain lies in nearly NS direction in the river bend of the Yalong River, where the gullies are deep and steep. Most mountain peaks are over 4 000 m, with the highest of 4 488 m (Santangshan peak). The largest altitude difference is over 3 000 m. The mountain ridges are in SN direction, with an unsymmetrical topography, i.e. wide in east and narrow in west. At mountain foot and the gully, collapsed debris and avalanche debris cone are frequently observed. Alluvial cone can also be observed at the gully mouth. Irregular topography with deep gullies and steep slopes are the basic features in this area.

Most of the prime lateral gullies (level-1) are nearly orthogonal to the Yalong River. These gullies are deeply cut in a form of high and steep slopes, and perennial runoff is observed. Gullies of Mofanggou, Nanmugou, Dashuigou, Mosagou, Meizipinggou, etc., are located in the east, and gullies of Lufanggou, Yangfanggou, Jiefanggou, Pusiluogou, Niuquanping-gou, Mianshagou, Luoshuidonggou, etc., are located in the west. There are also some prime gullies (level-2) that are lack of runoff sometimes, so most level-2 gullies keep dry. Waterfall can be observed sometimes in these gullies.

Carbonate rocks commonly exist in this area. Because of intensive regional metamorphism and sharply crust rise, karst landform is not fully developed. Mountains composed of carbonate rocks are very sharp and steep while mountains composed of clastic rock are thick and flat. There are significant differences between these two kinds of mountains.

2.2 Engineering geological settings

The most common strata exposed in the project area are Devonian-Jurassic strata of neritic-littoral facies and sea-land alternate phase. Triassic stratum covers over 90% of the project area, 70%–80% of which is composed of carbonate rocks.

The rocks along the diversion tunnels are mainly composed of marble, limestone, sandstone and slate of upper and middle Triassic system. The geological profile along the diversion tunnels is shown in Fig.2. It can be seen from Fig.2 that, from east to west, Yantang group (T_{2y}), Baishan group (T_{2b}), the upper Triassic system (T_3), Zagunao group (T_{2z}), and the lower Triassic system (T_1) are distributed along the diversion tunnels in sequence, and they can be described as follows:

(1) Group T_{2y} is mainly observed in Dashuigou gully and Laozhuangzi anticlinal core, which is mainly composed of marble and argillaceous limestone.

(2) T_{2b} marble is mainly observed in the middle area, which forms the main body of Jinping Mountains. It has a stable lithofacies, dense structure and pure

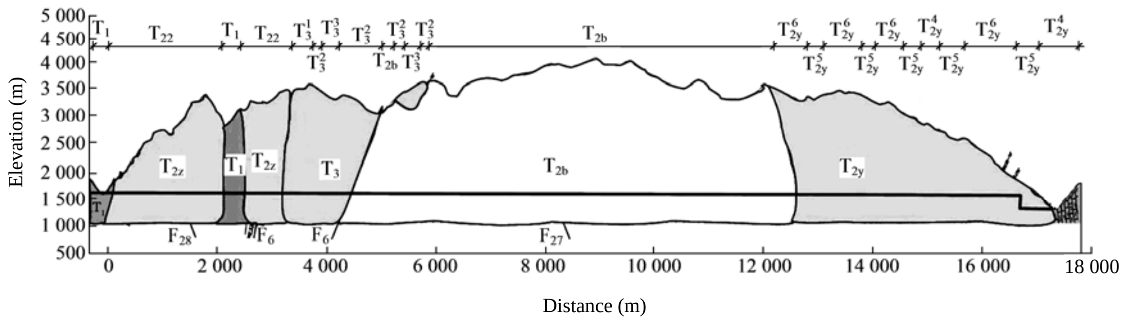


Fig.2 Geological profile along the diversion tunnels.

lithology. The thickness of the T_{2b} marble varies from 750 to 2 270 m.

(3) Group T_{2z} is mainly observed in the west part of the project area. T_{2z} carbonate rocks are characterized with the variations of rock particles and lithology. It consists of white-gray pure marble, occasionally with green schist lenses, thin sandstone, mica schist, etc. The thickness of the T_{2z} varies from 150 to 700 m.

(4) Group T_3 is mainly observed around the ridge area. It mainly consists of sandstone and slate.

(5) Group T_1 is mainly observed in the west part of the project area. This group has a complex lithology, which mainly consists of biotite and chlorite schist, metamorphic fine-grained sandstone and thin layer marble, gravel or stripped marble, etc.

The folds, mainly the SN folds, in project area are extremely developed and very complex, and they generally can be divided into east, middle and west fold belts. The structural planes in the area mainly present thrust properties of NNE faults and bedding extrusion properties. According to different structural features and orientations, the region can be divided into 4 groups: NNE, NNW, NE-NEE and NW-NWW directions. The diversion tunnels cross several main faults such as F_5, F_6, F_{27}, F_{28}, etc. The attitude of fault F_5 is N10°–30°E, NW∠70°, and the influential width is 5–10 m. The attitude of fault F_6 is N20°–50°E, NW or SE∠60°–87°, and the width of the fault is 1–4.2 m and the influential width is 6–37 m. Parts of the faults are located in the marble. The fault is clear in north and tends to converge in south. The attitude of fault in auxiliary tunnel is N45°E, NW∠80°–85°, with the width of 1.6–4.0 m and influential width of 21.4 m. The fault is transpressional and has some water-proof property. Under the influence of structural plane, which is N65°–80°W to the hanging wall, the affected zone may be wider than 100 m. The fault rocks are gray-green sandstone and marble, presenting extremely or fully weathered features with weak lithology. The width of visible fault gouge is 0.2–0.6 m. The rocks in the affected zone are broken, showing that cataclastic rocks are seriously disseminated by Fe and Mn compounds. The attitude of fault F_{27} is N30°–40°W, and the fault is distributed in group T_{2b} and broken by extrusion stress. The attitude of fault F_{28} is N20°E, SE∠70°, and the width of broken extrusion zone is 1–2 m. The rocks are extruded to schistic. The physico-mechanical parameters of rocks in the project area are listed in Table 1.

2.3 Hydrogeological conditions

Jinping Mountains are situated in karst region with bare deep valley, mainly recharged by precipitation. Karst and non-karst strata are in NEE direction. The karst stratum mainly lays in the middle part of Jinping Mountains, while the non-karst stratum in the east and west. Affected by the NNE trending tectonic line and lateral (NWW, NEE) wresting and extending fractures, the network for gathering and draining groundwater in this area between rivers is needed.

Water is abundant in this area, and the valley area is muggy. The existence of 3 levels of planation surfaces indicates that the crustal uplift activity after Cenozoic era was ever stopped for a long period of time, thus providing a suitable geological condition for karst development. However, as the regional metamorphism occurred in this region, the solubility of carbonate rocks decreased. The crust has uplifted rapidly since the Quaternary, and the dissolution velocity is less than the uplifting velocity of the crust. The erosion effect is evident and plays a critical role in this area, thus comprehensive lamellar karst system is not formed. The cold weather of general environment also plays an important role in karst development in this region. CO_2 is rare in cold water and supersaturated in groundwater. This will not be helpful for karst development. Most of karst strata are circled by non-karst strata, which can

Table 1 Physico-mechanical parameters of rocks in project area.

Class	Lithology	Unit weight (kN/m^3)	Uniaxial compressive strength (MPa)		Modulus of deformation (GPa)		Modulus of elasticity (GPa)		Poisson's ratio
			Dry	Wet	Horizontal	Vertical	Horizontal	Vertical	
II	Mid-thick-bedded fine-grained sandstone (T_3)	27.4	104–152	71–114	10–12	11–15	18–25	25–35	0.23–0.27
	Marble of Zagunao group (T_{2z})	27.2	70–90	55–78	8–10	12–14	20–25	30–38	0.22
	Mid-thick-bedded marble (T_{2b})	27.7	90–100	75–85	16–20	15–18	30–40	30–40	0.18
	Stripped mica marble (T_{2y}^4)	28.0	85–90	55–62	13–15	10–12	20–25	15–20	0.21
	Mid-thick-bedded marble (T_{2y}^5)	27.1	70–95	65–85	10–16	9–13	15–35	20–30	0.21–0.22
	Argillaceous limestone (T_{2y}^6)	27.0	70–75	60–70	9–11	8–10	16–17	13–15	0.27
III	Mid-thick-bedded fine-grained sandstone (T_3)	27.1	98–139	71–110	7–9	8–10	15–21	20–25	0.27
	Mutual layered sandstone slate (T_3)	27.6	70–95	42–53	6–9	8–10	10–18	16–21	0.26–0.30
	Marble of Zagunao group (T_{2z})	27.2	65–72	55–65	7–9	9–11	16–20	14–25	0.25
	Chlorite schist (T_1)	26.5	40–50	30–40	6–7	5–6	9–13	8–10	0.28
	Mid-thick-bedded marble (T_{2b})	27.6	75–85	60–70	10–12	9–10	20–25	18–20	0.20
	Stripped mica marble (T_{2y}^4)	27.5	70–85	50–60	8–11	7–10	9–16	8–15	0.23–0.26
	Mid-thick-bedded marble (T_{2y}^5)	26.6	65–90	55–80	6–11	5–10	11–17	7–15	0.23–0.27
	Argillaceous limestone (T_{2y}^6)	26.5	60–70	50–65	6–9	5–8	9–15	6–12	0.28–0.30
IV	Slate (T_3)	26.2	30–40	22–26	2–4	3–5	15–18	8–16	0.31
	Chlorite schist (T_1)	26.1	30–40	20–25	2–4	3–5	10–15	8–10	0.32
	Fault and fracture	—	45–55	40–45	0.6–1.5	0.4–1.0	1.0–1.5	1–2	0.35

also hamper the development of karst strata. Those kinds of special geographic environments and regional geological environments cause the evolution particularity of hydrogeological environments, thus karst development in the project area is not sufficient and number of the typical karst morphology is small. The karst fissures are the main morphology around the tunnels. There are few karst caves, and the size is small. However, karst water is abundant with high pressure. The maximum water pressure reaches 10.22 MPa according to the observation of a long exploration adit. During the construction of a 5 km-long exploration adit, large-scale water inrush incidents occurred several times. The water inrush points are characterized by high pressure and large flow rate. The concentrated flow of single water inrush point in 5 km-long exploration adit reaches 4.91 m^3/s, and the stable one is 2–3 m^3/s. As predicted, the stable flux may be 8.48 m^3/s in the diversion tunnels during the rainy season if no grouting treatment is considered. Thus, the flow of 5–7 m^3/s at a single point is reasonable for design and construction processes. During the construction of auxiliary tunnels, the water pressure and flow are 0.6–4.7 MPa and 0.15–15.6 m^3/s, respectively.

3 Key issues in rock mechanics for the diversion tunnels

Due to the effect of site-specific rock mass strength, high in-situ stress and water inrush, the construction of long and deep diversion tunnels of Jinping II hydropower station is very challenging. Selections of reasonable construction scheme and excavation and support methods are the key steps to ensure the safety, cost saving and rapid construction of the long and deep tunnels. The construction condition of Jinping II hydropower station is signigicantly different from that of normal tunnels. The large overburden depth greatly impacts the construction scheme, efficiency, duration and cost.

3.1 High in-situ stress and rockburst

The diversion tunnels are located in high in-situ stress region in Southwest China. The actually measured results indicate that in-situ stress increases with the overburden depth, and the principal stress changes from horizontal to vertical direction. The measured maximum principal stress is 42.11 MPa, but the regression analyses show that the maximum principal stress along the tunnel will reach 70 MPa [2], which belongs to high in-situ stress. Surrounding rocks around the region where rockburst occurred should be classified into class I–II. However, the surrounding rocks around the region where the moderate, strong and intensive rockbursts occurred are classified into classes III_b, IV_b, V_b, respectively. The stability of surrounding rocks decreases sharply due to the rockburst. In groups T_{2y}^5 and T_{2b} where rocks are intact with high strength, the rocks of classes II and III account for 89.1% and 73.6%, respectively. Meanwhile, in groups T_1, T_{2y}^4 and T_{2y}^6 where rocks have relatively incomplete structure and low strength, rocks of classes II and III account for more than 95%. The uniaxial compressive strength of intact rocks is 55–114 MPa. The modulus of elasticity is 25–40 GPa. The modulus of deformation is 8–16 GPa. The intensity of rockburst is classified into 4 grades, i.e. slight, moderate, strong and intensive, which are described as follows:

(1) Slight rockburst

There is no evident noise near the surface of surrounding rocks, or the noise is not easy to be observed. The split blocks fall down randomly with small blocks. The rock pit of rockburst is basically shallow. The type is spalling.

(2) Moderate rockburst

For moderate rockburst, the split blocks will burst with severe peeling. Blocks and debris are ejected to free spaces with crisp rockburst noise. The rock pits are distributed continuously, and the pit diameter of rockburst may be several meters with pit depth less than 2 m.

(3) Strong rockburst

During strong rockburst, loud noises will be captured, and rock blocks are cast out rapidly. The rock pits are distributed continuously, and the pit depth is larger than 2 m. Large areas of surrounding rocks fall off because of cracking, which will threaten the safety of staff and construction equipments.

(4) Intensive rockburst

Explosive sounds will be observed during intensive rockburst. The rockburst suddenly occurs and spreads to the deeper surrounding rocks. The depth of influential zone is larger than 2 m. The damage to surrounding rocks is very severe, which may even destroy the project.

Rockburst could occur as a result of stress release during excavation. In brittle rocks, when the uniaxial compressive strength of fresh rocks is less than 5 times of the maximum in-situ stress that is equal to overburden pressure, rockburst along joint and bedding will occur. As the in-situ stress increases, the intensity of rockburst will also increase, and the rock blocks would be popped up rather than peeled off.

3.2 High-pressure water inrush

The treatment of high-pressure groundwater with large flow is a key issue in the construction of Jinping II hydropower station. During the excavation of 5 km-long exploration tunnel and auxiliary tunnels, several water inrush events happened, which greatly impacted the safety of construction procedure. Sometimes, the working face has to be stopped to deal with the gushing water. During the construction of diversion tunnels, although the auxiliary tunnels could act as geological advanced exploration tunnels, the position and water-rich regularity of corrosion fissures are difficult to be predicted by using conventional hydrogeological exploration only for the presence of concealment of the fissures, invisible abnormal structures and randomly distributed structures.

Groundwater in the diversion tunnels is characterized by high-pressure and outburst. A strong impact force or collapsing force will be induced when the runoff reaches a critical state. The force could adversely impact the safety of construction. During the construction of the diversion tunnels, adverse slope should be considered. As the drainage capacity is limited, it is possible that the working face would submerge by large quantity of water. Moreover, when the temperature of surrounding rocks is high, the gushing water will shift from the excess heat to tunnel space, thus evaporation will be strengthened because of high temperature and humidity. This may also affect the safety of construction. High-pressure water inrush will further decrease the stability of surrounding rocks, which could increase the difficulty in construction.

3.3 Construction ventilation and treatment in unfavorable geological area in deep diversion tunnels

Some harmful substances such as harmful gas, dust and smoke exist in the diversion tunnels, which could make the construction condition worse. The construction ventilation can offer fresh air for the tunnels to dilute and remove the harmful gas, smoke and dust. Ventilation is important in construction of diversion tunnels, which should meet the requirements of the construction. Thus, the operative condition is improved. However, due to the limitation of ventilation techniques, ventilation will in turn affect the organizational design of construction, and sometimes such influence is significant. Therefore, the feasibility and cost of construction ventilation should be considered when determining the construction method and construction progress as well as construction equipments.

The unfavorable geological area mainly consists of soft stratum, fault fracture zone, water inrush zone and rockburst area along the diversion tunnels. The rocks in these areas belong to classes III and IV with weak supporting capacity and short stabilization time. Based on the prediction of classification of surrounding rocks, the length of class IV surrounding rocks is approximately 2.047 km, accounting for about 12.3% of the whole tunnel length. Meanwhile, the length of class V surrounding rocks is about 0.409 km, accounting for about 2.5% of total tunnel length. The tunnels will pass through about 30 fault belts. Several belts among them are wider than 15 m. The attitude of fault F_6 is N20°–50°E, NW or SE∠60°–87°. The width of faults in the project area is 1–4.2 m, and the width of influential belt reaches 6–37 m. Some serious geological problems will be encountered by the combination of the faults and local hydrogeological conditions. Various kinds of temporary supports should be taken to deal with the problems.

3.4 Construction with TBM under high in-situ stress conditions

According to the site-specific conditions in auxiliary tunnels and the self-stability of surrounding rocks in Jinping II hydropower station, TBM may be suitable for this project, but no similar case or experience can provide a reference for such extremely complex conditions. Many challenges and risks will be encountered when using large-diameter TBM at Jinping II hydropower station. The tunneling speed of TBM and its backup systems under large water inflow, high in-situ stress and strong rockburst should be carefully considered.

4 Optimization of design scheme

Great difficulties and big challenges will be encountered in the construction of Jinping II hydraulic tunnels under the complex geological conditions, especially the large-scale underground constructions. The complex hydrogeological conditions include external high water pressure with long-term stable water supply, and high in-situ stress of over 70 MPa, etc. Thus, a series of rock mechanical issues should be addressed for the tunnel construction and structure design. Unfortunately, the actual geological conditions exploited by the excavation are more complex than those in the original design, which makes the construction of long and large tunnels even more difficult. With introduction of dynamic design concept, it is essential to optimize the tunnel structure and effectively guide the construction with modified design scheme based on the actual geological conditions.

4.1 Auxiliary drainage tunnel

In the feasibility study stage, according to actual geological conditions, experiences of excavation and water-plugging of the 5 km-long exploration adit, and the requirements of environmental protection, the design principle of “water plugging first with combination of water drainage” was adopted for water inrush control in the construction of diversion tunnels.

The principle of water inrush control can be described as follows: for the possible amount of gushing water over 20 L/s, water should be predicted and stopped by high-pressure grouting technique before exploitation; for the spots with small water gushing, it can be stopped after the excavation.

Drainage construction design mainly considers the drainage of the rest small amount of groundwater in the tunnels, and possible gushing water in a short period of time.

According to the prepared construction method and scheme, the shotcrete, bolt and concrete lining should be conducted behind the working face during the full-face tunneling. Thus, shotcrete and bolt should be implemented immediately behind the working face, and concrete lining should be taken within 1 000 m behind the working face.

In this way, all the gushing water points should be plugged in the shotcrete and lining section of tunnels, and the drainage design mainly considers the possible water inflow in 1 000 m-long tunnel section. The maximum water inflow may be 700 L/s.

According to this scheme, the drainage system was planned in pairs. In each diversion tunnel, two parallel drainage ditchs were designed. In case of large amount of gushing water, water could be diverted into another diversion tunnel through cross adit, and then it was drained out of the tunnel. In this way, the influences of the gushing water on the tunnel construction can be reduced.

During the actual construction, the water inflow exposed in the auxiliary tunnels was much higher than expected. The maximum amount of gushing water from single point reached 15.6 m^3/s. The long-term average amount reached 6.05 m^3/s in dry season and

8.35 m^3/s in rainy season in the east, and 2.69 m^3/s in dry season and 3.15 m^3/s in rainy season in the west.

The large amount of gushing water caused serious influence on the construction of auxiliary tunnels. The gushing water control became a key challenge for successful tunnel construction. Considering the feasibility study results and the actual construction conditions of the auxiliary tunnels, it is necessary to arrange a drainage tunnel for the high-pressure gushing water in order to relieve the pressure of the gushing water, and to reduce the construction difficulties of concrete pavement and grouting in the auxiliary tunnels. Meanwhile, it was decided to arrange a drainage tunnel between the auxiliary tunnel B and the diversion tunnel #4. It was helpful for the regular excavation of concrete lining and grouting of the 4 large-diameter diversion tunnels to reduce the construction difficulties of the concrete lining and consolidation grouting of surrounding rocks in the diversion tunnels.

The drainage tunnel in three-centered arch section is parallel to the diversion tunnels, with the dimensions of 16.73 m in length, 8 m in width and 7 m in height. The bottom of the drainage tunnel is 1.5 m lower than that of the diversion tunnels, and 1.137 m lower than that of the auxiliary tunnels. For classes II and III rocks, the shotcrete and rock bolts were adopted as the permanent support, and the excavation sizes were kept at 8.2 m in width and 7.1 m in height. Considering TBM, the drainage tunnel was adjusted to circular cross-section of 7.2 m in diameter, with the maximum drainage capacity close to 32.5 m^3/s.

Auxiliary tunnels can satisfy the requirements of drainage of auxiliary tunnels and diversion tunnels. The drainage demand of the east part of auxiliary tunnels will be satisfied firstly to ensure the excavation speed as the commissioning of auxiliary tunnel will satisfy the demand of construction traffic, which is increasingly urgent along with the construction of Jinping I and II projects. A reasonable and safe distance between the additional drainage tunnel and adjacent tunnels should be adopted to ensure the safety and stability of surrounding rocks in tunnels. According to Specification for Design of Hydraulic Tunnels (DL/T 5195-2004), the distance between centers of tunnels should be 3 times larger than the excavation diameter. For deep underground caverns, the center distance should be at least 4 times the excavation diameter. In Jinping II project, the center distance between drainage tunnel and auxiliary tunnel B is 35 m, about 4.37 times average diameter of adjacent tunnels. Meanwhile, the center distance between drainage tunnel and diversion tunnel #4 is 45 m, about 4.28 times average diameter of adjacent tunnels. The arrangement of tunnels can meet the requirements of the specification (DL/T5195-2004).

4.2 Optimization of lining design

4.2.1 *Structural design in feasibility study stage*

For class II rock masses, the surrounding rocks of the diversion tunnels after normal excavation have a good self-stability. According to feasibility study, after the completion of primary shotcrete-bolt support, the surrounding and supporting structures can ensure the long-term safety and stability of the diversion tunnels. The main function of secondary lining is to smooth the cavern, decrease the roughness and head loss, and protect the surrounding rocks from washing and scouring by high-pressure gushing water. Thus, the secondary lining can prevent the surrounding rocks from falling. Secondary shotcrete-bolt support is used as a permanent lining structure in 5 km-long section of diversion tunnels. Meanwhile, reinforced concrete lining support is used as a permanent lining structure in 11.7 km-long section.

According to the results of geological investigation in feasibility study, most of surrounding rocks along diversion tunnels are of classes III and II, 53.6% and 29.1% of rock strata, respectively. Parts of the surrounding rocks are of classes IV and V, about 17.3% of rock strata. Among them, about 4.6% of surrounding rocks belong to the fault belt, and others belong to the rockburst region caused by high in-situ stress. In order to shorten the construction period and speed up the project progress, the shotcrete-bolt support is applied as the permanent lining structure in regions where surrounding rocks belong to class II and the in-situ stress is not such high. In addition, concrete is used to protect the tunnel floor. Considering the differences between the rock mass class and the rockburst intensity, the support method could be adopted by 8–10 cm long steel fiber sprayed concrete, suspended net shotcrete, channel steel, arch rib construction to prestressed or normal hollow grouting anchor. The thicknesses of secondary reinforcement concrete support in classes III, IV and V rocks, whose strength was decreased by high in-situ stress, are 45–60, 80–100, 45–60 cm, respectively. Therefore, each diversion tunnel has about 4 836 m-long region, which could use shotcrete-bolt support as permanent lining structure, and other regions should consider whole cross-sectional concrete lining structure.

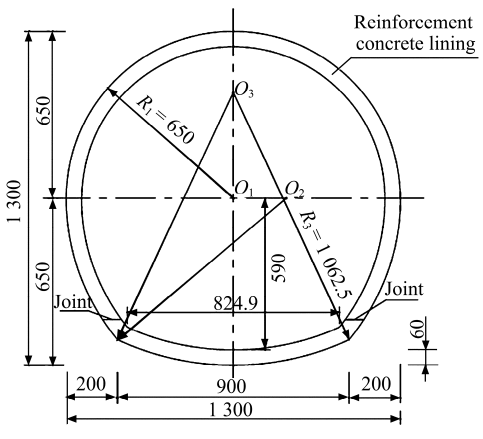
4.2.2 *Structural design in bidding design stage*

In the bidding design stage, further optimization scheme of tunnel lining is performed to simplify construction and speed up the construction. The geological conditions and surrounding rock classification along the diversion tunnels are timely revised combining with the exposed geological conditions of auxiliary tunnels. Some preconditions should be considered before scheme optimization. Firstly, the stability of surrounding rocks should be ensured. Then, the total water head loss of the diversion system should be reasonable. Thus, we use suspended net shotcrete support as the permanent lining structure in the middle part of the tunnel where the surrounding rocks belong to class II or III and rockburst is slight (class II_b rocks). The total length of the tunnel using this kind of support method may be approximately 8 km. The other part of tunnel, which includes local region excavated by drilling and blasting method in the east and west ends, the middle part of tunnel where the rock mass is class IV and rockburst is strong (classes III_b, IV_b, V_b rocks), should be supported at whole cross-section as permanent lining structure. The total length of the tunnel using this kind of support method is 8.65 km.

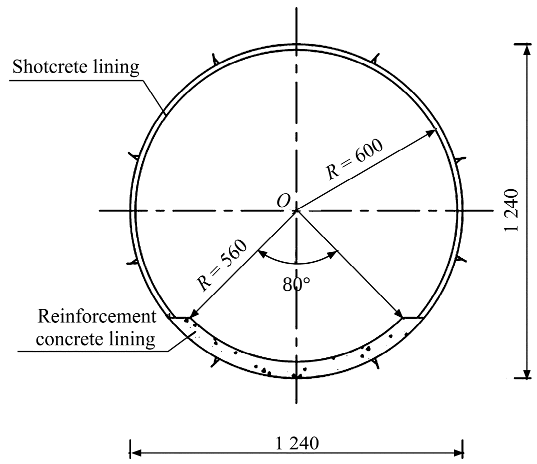
The middle part of diversion tunnels #1 and #3 with circular permanent water-carrying cross-section is constructed by TBM. The east and west ends of the 4 diversion tunnels, where TBM cannot enter the construction site, should be excavated by the drilling and blasting method. The form of cross-section in this part adopts its original design, using horseshoe-shaped cross-section as its excavation cross-section and four-center circle horseshoe-shaped cross-section as the permanent water-carrying cross-section. The typical cross-sections are shown in Fig.3.

4.2.3 *Optimization in construction stage*

(1) Analysis of monitoring data in excavated area of diversion tunnels



(a) Four-center circle horseshoe-shape cross-section.



(b) Circular cross-section.

Fig.3 Typical cross-sections (unit: cm).

Safety monitoring is very important during the construction of deep tunnels in Jinping II hydropower station. The monitoring data not only are the direct foundation to evaluate the effectiveness of construction support method, but also can provide the basic data for adjusting support parameters dynamically through feedback analysis. Through analyzing the damage of surrounding rocks and responses to excavation during construction, the actual situation could be tracked, and the best solution could be obtained.

(i) Arrangement of main monitoring equipments

139 groups of multi-point extensometers, 172 groups of bolt stress meters and 6 anchor dynamometers were installed in the east and west ends in June 2010. The diversion tunnels are horizontally arranged in sequence. Thus, several groups of multi-point extensometers and bolt stress meters under different geological conditions were arranged, of which the multi-point extensometers were installed in advance in horizontal boreholes from diversion tunnels #2 and #4 to diversion tunnels #1 and #3.

(ii) Analysis of relevant monitoring data

According to the monitoring data, the deformation in diversion tunnels is not significant except for chlorite schist area in west end. About 90% of multi-point extensometers show that the monitoring deformations are less than 10 mm, only 15 monitoring points show the values are larger than 20 mm, accounting for about 3.6% of total points. The maximum deformation of surrounding rocks in the east part of diversion tunnels occurred at the transition region from the diversion tunnel #4 to the diversion tunnel #3. The deformation is stable at present. The maximum tensile stress is 217.8 MPa in diversion tunnel #4, which occurred in the position apart from northern sidewall (2 m away from stake No.16+250) with overburden depth of 592 m. The rocks in the west end of diversion tunnel belong to Zagunao group marble. The monitoring deformations are relatively small. The tunneling conditions around the area are good. The drilling footage in sandy slate area is relatively small. The monitoring data show that the region is under stress redistribution stage, and the changes in stress are relatively large due to initial deformation.

(iii) General analysis of monitoring results

Monitoring data show that the deformation of surrounding rocks is not the dominant factor. However, the tiny fracture in surrounding rocks and delayed fracture caused by damage may propagate with time. The damaged area may occur and extend. Therefore, these results should be taken into account when selecting the permanent support structures.

(2) Analysis of geophysical prospecting results in excavated area of diversion tunnels

The geophysical prospecting results are used for estimating the quality of surrounding rocks and investigating the temporal effect of structural evolution in rocks. The prospecting cross-sections around the loose circle of surrounding rocks are arranged according to the site-specific geological conditions along the diversion tunnels. The purpose is to understand the damage and relaxation degree of surrounding rocks induced by excavation. Thus, the information can be used for stability analysis of surrounding rocks and dynamic design of support method. The damage and relaxation degree of surrounding rocks can be captured by acoustic wave test.

The acoustic wave tests on about 50 groups of single holes and 2 groups of cross holes had been carried out along the east and west ends of the 4 diversion tunnels at the end of June, 2010. Meanwhile, lots of acoustic wave tests for quality and relaxation depth of surrounding rocks had been conducted. The relaxation depth is 1–3 m in good rock area where rock masses belong to classes III and II, and the rockburst is slight. Among them, the minimum relaxation depth is 0.6 m. However, the relaxation depth is relatively large in surrounding rocks where rocks belong to class IV due to the unfavorable geological conditions, and the maximum relaxation depth is 6.4 m. The tunneling conditions along the diversion tunnels are good. The damage of surrounding rocks around chlorite schist area is large deformation of soft rock, which can be distinguished from failure mechanism of marble. It is noted that the number of downstream holes where relaxation depth is greater than 3 m is more than the number of upstream holes. This phenomenon indicates that the marble in the diversion tunnels has the delaying damage characteristics. The results also show that the relaxation depth increases with increasing overburden depth, which indicates that the damage of surrounding rocks is much more severe in large overburden areas due to high in-situ stress.

According to the long-term observation results, the obvious temporal effect exists in large underground cavities under large overburden depth, even were observed in the whole rock structure. The relaxation depth increases with time. However, more long-term monitoring results are needed to determine whether the relaxation depth will converge to a relatively stable value or not. It is noted that the temporal effect will be greater when the overburden depth is over 2 000 m and full-section excavation is carried out. Close attention must be paid to the effect analysis.

(3) Analysis of long-term deformation and damage of surrounding rocks in diversion tunnels

The high-stress damage is obvious due to the large overburden depth and high in-situ stress in the area where the diversion tunnels are constructed. The delaying damage effect induced by high in-situ stress in surrounding rocks is very easy to be observed. Fracture development and stress relaxation normally last for several months, even several years after excavation completion. The phenomenon of temporal effect mentioned above is the performance of this delaying damage effect. The engineering practice shows that the fracture and relaxation region will propagate in a long period of time if the support is not effective under high in-situ stress conditions. The mechanical properties of surrounding rocks will decrease due to accumulation of fracture and damage. Therefore, the stability of surrounding rocks may become worse continuously, accelerating the damage progress. In operating period, the boundary conditions of surrounding rocks will greatly change because the external water pressure will be recovered and internal water will permeate. This change is generally harmful to stability of surrounding rocks. Therefore, high-level requirements are put forward to ensure the long-term stability in operating period.

(4) Change of lining type in diversion tunnels

According to the excavation information feedback and monitoring data, the stability of surrounding rocks in construction period is good. The deformation is not large and tunneling conditions are relatively good except for chlorite schist area in west end. However, because of the site-specific engineering conditions such as great overburden depth, high-span cave and brittle marble, the relaxation, fracture and spalling often occur around the surrounding rocks. The long-term relaxation cannot be ignored, which will influence the long-term stability of the structure in operating period. Some rock bolt systems may fail under high in-situ stress and high osmotic pressure conditions. The strength of surrounding rocks in wet condition may be lower than that in dry condition. Furthermore, constructing bolt system at this moment may not be reasonable, which may cause certain risks in operating period if the shotcrete support is only used in construction period. Thus, it is necessary to carry out secondary reinforcement concrete support to ensure the long-term stability of surrounding rocks and improve the safety level.

Many factors should be considered when selecting lining types for a long tunnel at high water pressure. These factors include stability conditions of surrounding rocks, structural conditions of permanent lining, hydraulic conditions, construction investment and progress. According to the foregoing analysis, the lining types of the diversion tunnels are changed with reinforced concrete support all along the tunnel. The thickness of the lining varies as the geological condition changes.

The long-term stability can be ensured by using reinforced concrete support, and water head loss of the system can be decreased. It may affect the transient process condition from hydraulic part to mechanical part in power generation system. With many engineering measures taken, the influence may be controlled within the design value, but the engineering quantity and project investment will increase, which will exert greater pressure on the whole project. After changing the lining structure, it is necessary to increase the construction resources for the purpose of speeding up excavation, lining and grouting, and timely groundwater plugging to ensure the construction progress.

5 Optimization of construction scheme

5.1 Construction scheme in feasibility study stage

In different construction stages in terms of different geological conditions, the construction scheme of the diversion tunnels has been dynamically modified. At the first stage of construction, the drilling and blasting method was adopted to excavate the diversion tunnels. Then, TBM was used in combination with drilling and blasting method. At last, all the diversion tunnels were excavated by drilling and blasting method. These optimizations, which increase the direct investment of the project, play a very important role in ensuring the safety and progress of the project, making it possible to generate electricity a year in advance. The economic and social benefits, produced by power generation in advance, surpass the additional direct investment greatly. These benefits strongly prove that the adjustments are successful and effective.

Due to the topographical constraints, it is impossible to arrange adits and inclined shafts in the middle of the diversion tunnels to shorten the construction period. The excavation can only start from both ends of tunnels. The advanced construction of the auxiliary tunnels greatly contributes to the construction of the diversion tunnels. On one hand, the geological conditions and groundwater exposed by excavation of the auxiliary tunnels can be fully utilized and pretreated. On the other hand, the auxiliary tunnels are helpful to widen the working face and dig the long tunnel step by step.

Based on the construction conditions and progress, the diversion tunnels are divided into three segments, i.e. the east segment, the middle segment and the west segment. The track transportation is used in 6.5 km-long east segment and 4 km-long middle segment, while the trackless transportation is used in 5.5 km-long west segment. At the beginning of construction, the excavation of the downstream drift of diversion tunnels #3 and #4 was completed with the help of the auxiliary tunnels and adit #2 in the east end. It provides passageways for the middle segment construction and contacts the west working face directly, decreasing the difficulty of inverse slope drainage in a long distance.

5.2 Constrution scheme in bidding stage

5.2.1 *General construction scheme of the west segment*

The diversion tunnels were excavated by drilling and blasting method with trackless transportation in this segment. The water in water-rich area is plugged by grouting in advance, and other water-rich areas are treated immediately when a safe blasting distance from the tunnel working face is guaranteed. At the same time, backfill and consolidation grouting are arranged timely as soon as the strength of lining concrete meets the design requirement. To meet construction safety requirements, the diversion tunnels #2 and #4 should be constructed side by side, followed by tunnels #1 and #3 (50–100 m apart from each other), where multi-process operation in parallel arrangement can be implemented. As grouting construction largely affects the concrete hardening, the concrete construction should be lagged 500 m behind the working face, leaving enough space for the construction.

5.2.2 *General construction scheme of the east segment*

In July 2006, the construction was arrested by great amount of water inrush and intensive rockburst caused by high in-situ stress. Considering the urgent need of external transport, the construction scheme of the diversion tunnels is modified to lower construction risk and ensure the construction period as scheduled. From the experiences achieved in site, it is observed that the drilling and blasting method has advantages of high mobility, flexibility and adaptability, while TBM has advantages of high efficiency, small perturbation, less engineering quantity of support, safety and simplification of ventilation arrangement. Therefore, in order to ensure the construction safety and speed up the construction progress, TBM is adopted for the diversion tunnels #1 and #3 in the east end, drilling and blasting method for diversion tunnels #2 and #4.

After the assembly of TBM, the diversion tunnels #1 and #3 were excavated first. The excavation of the diversion tunnels #1 and #3 started in November and October 2008, respectively. The diversion tunnels #2 and #4 constructed by drilling and blasting method use the bench method for excavation, trackless transportation for dregs, wet shotcrete for support, rig 353E for drilling anchor holes, and hydraulic steel trolley for lining construction. In September 2007, the drilling and blasting method was adopted at the east and west ends of diversion tunnels #2 and #4. After the installation of fixed belt conveyer outside the hole, the mobile crusher was adopted to crush gravel. Then, the crushed gravel is transported to the continuous belt conveyer in the diversion tunnels #1 and #3 through cross holes. TBM and drilling and blasting method can coordinate well with each other. When some positions are not suitable for TBM construction, the reverse construction in the back of TBM can be conducted by drilling and blasting method by increasing an additional adit. When TBM successfully passes through the working face of drilling and blasting method within a certain distance, enough working space for drilling and blasting method can be provided through the branch holes and thus the construction progress can be accelerated.

5.3 Gradual optimization of constrcution scheme

The construction of tunnel group in Jinping II hydropower station is one of the key issues in construction. A series of key technical issues, such as rockburst caused by high in-situ stress, sudden gushing water, construction ventilation, transportation of dregs in long distance, material transportation, have to be addressed. The construction of main part of the diversion tunnels started in July 2007, and other tunnels were excavated by the drilling and blasting method when assembling TBM simultaneously. For further construction, the construction schedule should be optimized to meet construction period and power generation timely. Of course, difficulties in construction and pressures on construction schedule have to be properly solved.

5.3.1 *Construction scheme in 2008*

The auxiliary tunnels, diversion tunnels and drainage tunnel were excavated simultaneously, and the auxiliary tunnels were completed on August 8, 2008. Two TBMs started to work in April and May 2008, respectively. In September 2008, the assembly was accomplished and some excavation tests were conducted. In November 2008, the TBM passed the acceptance test and was readily to be applied in field officially.

5.3.2 *Construction scheme in 2009*

TBM in the east diversion tunnels #1 and #3 was time-consuming as unexpected, which was mainly exhausted in equipment debugging, modification, defects improvement and trial tunneling. In the process of trial tunneling, three problems were observed, i.e. equipment, geology and organization management. Adaptability alteration of equipment to geological conditions of surrounding rocks, detailed research of reasonable support and frequent staff turnover should be fully considered, which will lead to unfavorable drilling footage throughout the year. The excavation of drainage tunnel progressed slowly in some regions for very strong rockburst. Moreover, an intensive rockburst occurred on November 28, 2009, which led to the snap of TBM girder, complete damage of the machine, and life loss.

5.3.3 *Construction scheme in 2010*

A length of 8.7 km of the diversion tunnel #1 was completed, which was more than the sum of the length of excavation in 2007–2009. The diversion tunnels and the drainage tunnel were accomplished approximately 27.7 km in a year. The TBM construction created a record of driving footage more than 680 m in a month. In order to ensure the successful completion within contract period, more working faces are needed for the existing channels. After in-depth and detailed evaluation, it was decided that auxiliary diversion adits #1, #2 and #3 and auxiliary drainage adits #1 and #2 were raised. On the premise of ensuring safety, it was decided to accelerate the construction progress of auxiliary diversion adits and auxiliary drainage adits, which can serve the construction of tunnels as soon as possible and improve controllability of construction period. The additional layout of auxiliary diversion adits and auxiliary drainage adits is a systematic project, including the number of tunnels, location, alignment selection, drainage and pumping standard, water storage layout, equipment configuration and so on. Through careful planning, good results have been achieved in this project.

Meanwhile, as TBM gradually advanced to strong rockburst area, the construction scheme should be modified. For the feasibility study of TBM application to the tunnels under high in-situ stress, the pilot tunnel was excavated as trail test, and then TBM was adopted. This scheme has some positive effects on rockburst prevention during construction. But whether TBM can be applied in high in-situ stress area is still uncertain, where adaptability of TBM is somewhat confusing. To achieve the rapid construction of tunnel, the TBM #1 was stopped in October 2010, replaced by drilling and blasting method.

5.3.4 *Construction scheme in 2011*

In 2011, the diversion tunnels #1 and #2 and the drainage tunnel will be completed, but the issue of strong rockburst should be properly addressed. Auxiliary diversion adits and auxiliary drainage adits can create enough working faces so as to accelerate construction progress and lay the foundation for power generation in 2012.

Through unremitting hard work, the diversion tunnel #1 was completed successfully on June 6, 2011. Because 15% of length of the diversion tunnel #1 belongs to strong rockburst area, different support methods were applied considering different rockburst intensities, where detailed improvements were put forward. During excavation, many new materials, techniques and methods were used to ensure safety and speed of construction, such as advance blasting stress relieving method, water swelling anchors and nano-material injection. Moreover, micro-seismic monitoring technology was used for the tunnel construction of large-scale hydropower station, and a new micro-seismic monitoring system was built. With this system, we can monitor and analyze the micro-seismic activity of rocks continuously, which is helpful for rockburst forecast.

6 Discussions

6.1 Selection of TBM

The selection of TMB largely depends on the geological and hydrological conditions. For example, the grade of rock fissures, uniaxial compressive strength and toughness of surrounding rocks will determine the excavation speed and construction cost. The overburden depth of the tunnel, class of surrounding rocks, water inrush and other issues will affect the methods, forms and types of support after excavation. For those reasons, TBM used in Jinping II hydropower station is an open-type with shield extended top, which is equipped with an expanding excavation function in order to deal with the stuck problem caused by rock deformation. According to the requirements of hydraulic tunnels and geological conditions, TBM was equipped with backup system. TBM was also improved in the design in terms of host and backup system. At the bottom of the host, a high flow water-proof gate was placed. An opening-and-closing controllable anti-rockburst ceiling and steel tiles preventing high-pressure groundwater were installed in area L1. In order to reserve adequate drainage channels, transportation tracks and backup system were both laid over head. Emergency rescue stations were placed on the backup system to decrease the influence of high-pressure water inrush on staff and equipments.

In the actual construction procedure, water inrush is no longer the main factor affecting TBM construction, but high in-situ stress and rockburst directly determine the construction efficiency of TBM. For deep tunnels in karst strata, groundwater, high in-situ stress, rockburst, rock strengh and other factors should be considered when deciding whether to use TBM [3–5].

6.2 Groundwater treatment

In the early process of water inrush treatment in auxiliary tunnels, the principle of “forecast ahead and water plugging in combination with water drainage” should be held to prevent sudden water inrush in the project construction. But it is very difficult to accurately forecast groundwater in practice. When plugging the high-pressure gushing water, groundwater leakage in some cracked faces and gushing holes at the rear of the water inrush points will occur because underground karst pipes are closely connected with each other, thus it is extremely difficult to increase grouting pressure when it reaches a certain value.

Meanwhile, after plugging parts of the high-pressure water inrush points, water pressure in the front of the excavation face is still extremely high. Therefore, plugging kept to the exposed high-pressure water is needed. After excavation, the risk of high-pressure water inrush, a serious threat to the construction staff and equipments, will emerge. This will in turn cause serious constraints on the construction schedule. With the further understanding of groundwater treatment and experiences gained during construction, groundwater treatment in auxiliary tunnels was adjusted according to the principle of "forecast ahead, rapid excavation, and water plugging in the best time", considering the requirements of social environment of project area and rapid excavation. For different types, flows, pressures and locations of groundwater, different measures were taken [5–10].

Experiences in the treatments of groundwater in auxiliary tunnels show that it is extremely important to drain groundwater during construction. Groundwater interconnects with various rock fractures, thus it should be handled in a proper way according to the practical situation.

6.3 Significance of micro-seismic monitoring for rockburst prevention

The seismic monitoring system was adopted to predict rockbursts during drainage tunnel construction in Jinping II hydropower station. The principle of the seismic monitoring technology is to monitor the micro-ruptures in damage process of solid materials. The time, space and intensity of released energy during the internal rupture of rock masses can be directly predicted. Besides, related sensors can be arranged in the area far away from the damaged rock masses, thus the monitoring system cannot be destroyed for a long period of time. Analyses of monitoring data can help to predict rockburst by tracking the location and the damage trend of the seismic events before rock masses fail. Practical application of seismic monitoring in the construction of drainage adit of Jinping II hydropower station has made certain achievements in rockburst forecast. Combined with empirical methods, the approximate scope of rockburst occurrence could be located. However, several key issues still need to be addressed when applying seismic monitoring, e.g. continuous wave velocity should be reset all the time due to the changes of lithology and structure in the drainage tunnels excavated by TBM. TBM's unexpected tunneling time, uncertain tunneling speed and the disturbance to the rocks cannot be precisely determined, making it difficult to accurately predict the occurrence of rockbursts. Prediction experiences need to be obtained in the future research on those issues [11–16].

Accurate prediction of rockbursts is always difficult for underground engineering. At present, the methods to accurately predict the location and time are not available. However, with large amounts of construction data, it is possible to identify the potential location of rockburst. Micro-seismic monitoring, a new means to prevent rockburst, should be applied more frequently.

6.4 Modification of grouting pressure

The diversion tunnels of Jinping project cross Jinping Mountain with features of large overburden depth, high in-situ stress, and high external water pressure. Preliminary observations suggest that external water pressure in the middle of diversion tunnels can reach 10 MPa. It is difficult to withstand the great external pressure relying solely on conventional reinforced concrete lining. Therefore, shotcrete-bolt, secondary lining, high-pressure consolidation grouting and other measures were taken to reinforce the surrounding rocks in the design of anti-seepage support structure, which was applied to be the main bearing and anti-seepage structure. The grouting ring of the diversion tunnels ensures the permanent stability of surrounding rocks. With support system, the grouting ring also acts as the important structure withstanding external water pressure and rock stress. At the same time, it plays an important role in keeping long-term seepage stability and preventing water leakage.

Groundwater levels were getting lower because of the drainage of auxiliary adits, providing a good hydrogeological boundary condition for consolidation grouting of anti-seepage. Detailed research based on grouting tests indicates that reducing the number of filling holes and grouting pressures is practicable. At present, the grouting pressure is reduced to 6 MPa at most of gushing points, while the pressure in some segments with lower groundwater level is reduced to 4 MPa. The drilling quantity of grouting holes is 1/3 lower than that in the stage of bidding design, and 50% lower than that in the stage of feasibility study design. Under the conditions of sharp decreases in grouting pressure and grouting quantity, we decided to combine consolidation grouting with water-plugging grouting to speed up construction and improve cost-effective grouting quantity. According to the actual construction of the tunnel sections and the plugging schemes of groundwater, we also implemented uncovered grouting before the construction of concrete lining and accomplished deep consolidation grouting and shallow water-plugging grouting. When the concrete lining is completed, the shallow anti-seepage and consolidation grouting can be further conducted.

6.5 Construction measures for fault controlling

Geological investigation, geophysical methods and drilling methods should be carefully considered to determine how to detect and control faults. Firstly, the survey data of the project area should be carefully analyzed, and a comprehensive analysis of the extension and controlling conditions of the unfavorable geological conditions should be made. The geological survey outside the tunnel should be extended, and the occurrence, performance and distribution of the unfavorable geological conditions should be carefully analyzed. The geophysical methods, especially land sonar detection and geological advance prediction system TSP203, can detect relatively large areas and obviously abnormal areas easily. But the judgments still depend on personnel experiences. The geological predictions of the auxiliary tunnels in the west and the diversion tunnels prove that mistakes at this link are often made.

In fault fracture zone, excavation should be carried out carefully with short footage by weak blasting. Controlling the loop footage within 1.5–2 m, making the surrounding borehole spacing dense and reducing the amount of charge in a single hole are helpful for smooth blasting and reducing the disturbance of the surrounding rocks drastically. The principle of “advanced management, strict grouting, short footage, weak blasting, strong support, early closure, and frequent measuring” should be carried out strictly in the construction across unfavorable faults. In order to ensure that construction can be successfully performed in sections with defective geological bodies, site-specific designs are needed, where the strict construction organization, advanced geological prediction, adequate planning and experiences in the construction are also absolutely required. With these measures, these unfavorable geological sections can be passed through safely, fastly and smoothly.

7 Conclusions

The diversion tunnels of Jinping II hydropower station are the largest hydraulic tunnels in the world at present. The engineering construction difficulty is a great challenge for the project tunneling. The project will attribute to the development of underground engineering technology. A series of achievements will be gained in the process of construction, including hydrogeological analysis of karst structure around hydropower station, design methods for long and large tunnels, optimization of construction scheme, proper prediction methods and forecast methods, and treatment of high-pressure groundwater. The diversion tunnel #1 was completed through continuously reconnaissance survey and scientific study in the past 40 years and construction experiences in the past 4 years. Most of the geological conditions are clearly surveyed at present, thus the main technical issues have been properly addressed.

(1) The followed lining and grouting workloads of diversion tunnel #1 are considerately huge. The construction speed under complex interaction conditions should be controlled strictly.

(2) Plugging the groundwater turns up to be the key step during the lining process of tunnels. Some experiences have been gained in the construction of auxiliary tunnels. However, the plugging effect is not perfect, and there is no other available experience to be followed in plugging the high-pressure groundwater. Thus, further study should focus on the high-pressure groundwater plugging.

(3) Excavation of the diversion tunnels #2, #3 and #4 has been advanced to the areas with high in-situ stress and strong rockbursts. Realizing fast construction with safety of the project and applying micro-seismic monitoring methods to later construction region are big challenges. Prediction and treatment strategies for rockburst under special geological conditions are needed.

(4) TBM was designed to be evacuated in its dismantling chambers after excavation completion of all the tunnels in original scheme. However, the construction method was totally changed. TBMs in the diversion tunnels #1 and #3 are being dismantled according to the new scheme. Dismantling TBMs and evacuating them out of the tunnels, which absolutely do not disturb the fast construction at the present stage, are also challenging problems.

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