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ORIGINAL PAPER

TBM tunneling in marble rock masses with high in situ stress and large groundwater inflow: a case study in China

Q. M. Gong · L. J. Yin · Q. R. She

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Abstract Two of four headrace tunnels in the Jinping II hydropower project were constructed using tunnel boring machines (TMBs). The geology along the tunnel alignment is dominantly massive to highly fractured marble and the maximum overburden depth is 2,525 m. The paper discusses the problems encountered during the TBM tunneling, including instability of the tunnel wall and face induced by high in situ stresses, high-pressure groundwater inflows and excessive cutter and cutterhead damage. Measures taken to overcome these problems involved modifications to both the machines and the mode of operation as well as changes to the support parameters.

Keywords Tunnel boring machine (TBM) · In situ stress · Groundwater inflow · Marble · TBM optimization

Résumé Deux des quatretunnelsd'amenée du projethydroélectriqueJinping IIontétécreusés en utilisantdes tunneliers. La géologiele long dutracé du tunnelestprincipalementconstituée de marbres massifs à fortementfracturés, avec un recouvrementatteignant au maximum 2,525 m de hauteur. L'articlediscute des problèmesrencontrés pendant le creusement au tunnelier, avec des instabilités de paroi et du front de taille du tunnelrésultant des fortes contraintes in situ, des venues d'eau sous forte pression, des hors profils et des dommages aux boucliers des tunneliers. Les mesuresprises poursurmontercesproblèmesontcomporté des modificationsà la fois desmachines et du mode opératoireainsique des changementsdans le dimensionnement du soutènement.

Mots clés Tunnelier (TBM) · Contraintes in situ · Venues d'eau · Marbre · Optimisationdes tunneliers

Q. M. Gong (✉) · Q. R. She
Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China
e-mail: gongqiuming@bjut.edu.cn

L. J. Yin
Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory for Rock Mechanics (LMR), 1015 Lausanne, Switzerland

Introduction

Excavation by tunnel boring machine (TBM) is becoming common in the tunneling industry, not least because of its performance advantages, particularly in favorable geological conditions where they can result in a reduction in overall construction time and cost (Laughton and Nelson 1996; Bruland 1998; Barla 2000; Barla and Pelizza 2000; Barton 2000; Zhao et al. 2007; Johannessen 1998; Skjeggedal and Holter 1998). However, in adverse geological conditions, such as high in situ stresses, fractured rock masses and high groundwater pressures, they can result in low advance rates, increased down-time and cost over-runs (Barla and Pelizza 2000; Della Valle 2001; Herrenknecht et al. 2004; Centis and Giacomin 2004).

In the 21st century, more and more mountain tunnels are planned and constructed at great depth where problems associated with high in situ stresses, groundwater inflow and fractured rock masses have to be overcome. When the in situ stress is high, stress-induced slabbing and spalling, raveling, face over-break and ground squeezing may occur (Phien-wej and Cording 1990; Myrvang, Blindheim and Johansen 1998). For example, the Lotschberg tunnel (Aeschbach 2002; Markus 2002), the Gotthard Tunnel (Ehrbar 2008) in Switzerland, and the tunnels at Jinping II hydropower station in China (Wu et al. 2010), all encountered the problems induced by high in situ stresses during TBM excavation.

For the Jinping II Hydropower Project, the general overburden along the headrace tunnels was high; >1,500 m of overburden over some 70 % of the tunnel, with a maximum of 2,525 m. In this project, two headrace tunnels were excavated by TBM in very complex geological conditions. Monitoring of the TBM tunneling progress in the Jinping project for 2 years produced a large amount of operational data as well as tunnel face and wall mapping, such that advance curves could be prepared. Based on these data, this paper discusses the influence of tunnel face and wall instability (induced by high in situ stresses and water inflow) on the TBM excavation, and the measures proposed to overcome these problems.

Jinping II hydropower project headrace tunnels 1 and 3

The Jinping II hydropower plant is located at Xichang City, Sichuan Province, China. It is mainly composed of an intake structure, four long headrace tunnels and a powerhouse. The four parallel headrace tunnels have an average length of about 17 km, as shown in Fig. 1; the maximum overburden along the tunnel alignment is 2,525 m. To conveniently drain the inflow water, headrace tunnels 1 and 3 were excavated from east to the west using two 12.4 m diameter hard rock TBMs (Tables 1, 2).

The geological structure in this region is controlled by a WNW ∼ ESE stress field and is characterized by a series of complex folds with very steeply inclined beds and near vertical faults (ECIDI, 2009).

As can be seen from the cross-section in Fig. 2, the geology consists of

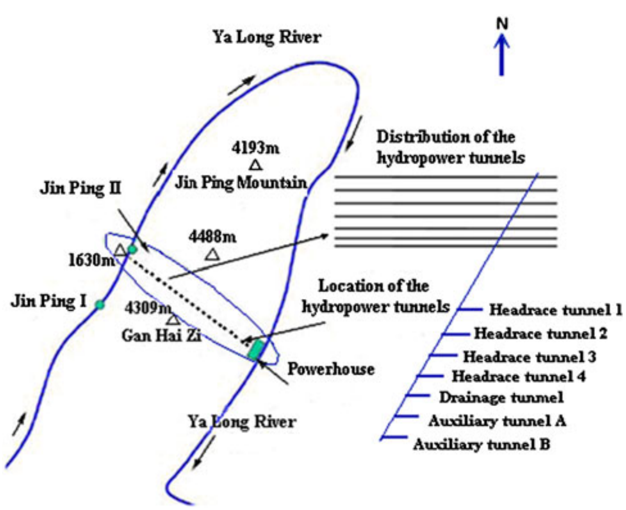

Fig. 1 Jinping II hydropower station project layout

(1) The Lower Triassic (T_1): epidote, chlorite and biotite schists, metasandstones and metamudrocks and conglomeratic marble. These beds occur mainly in the western part of the tunnel.

(2) The Middle Triassic (T_2): over 10 km of carbonate rocks, locally interbedded dolomitic marble with some interbedded clay bands (0.5–2 cm thick) which reduce the quality of the rock mass. These rocks are located mainly in the middle part of the tunnel where some of the marble horizons are up to 5 m thick, sometimes with schist interbeds.

(3) The Upper Triassic (T_3): mainly composed of sandstone and slate. Marls can be found locally in the west of the tunnel.

Samples were taken from along the alignment of headrace tunnels 1 and 3; the physical and mechanical properties of the rock are listed in Table 3. Cerchar tests undertaken to assess abrasivity for the TBM excavation section (Table 4) indicated low-abrasion or non-abrasive rock according to Bruland's (1998) classification.

Water was encountered during the construction of the 5 km long trial tunnel. The stable flow rate was 2–3 m^3/s, but the maximum inflow at a single point was 4.91 m^3/s. Higher levels of external water pressure/water inflow were expected with depth (Zhang et al. 2009).

In situ stress measurements in the project region show stress not only increases with burial depth (to a maximum of 42 MPa) but changes from horizontal to vertical from 600 to 3,000 m depth. The maximum in situ stress obtained from the survey reached 42.11 MPa. The regression curve of in situ stress along the auxiliary tunnel alignment is shown in the Fig. 3.

The geological investigations indicated the main problems would be related to high in situ stresses, groundwater inflow and fractured rock masses.

TBM advance

Headrace tunnels 1 and 3 were excavated from the east to the west with a small slope to allow gravity drainage of inflowing water. The advance curves for headrace tunnels 1 and 3 are plotted in Fig. 4, based on the recorded TBM operational data. Compared with the normal advance curve, the learning period of the two curves is very long—almost 11 months for headrace tunnel 1 and 6 months for headrace tunnel 3. In complex geological conditions, a significant amount of time needs to be spent on adjusting and modifying the TBM to improve its performance.

During the learning stage, the TBM in headrace tunnel 1 was modified twice: firstly to adjust the conveyor belt systems and secondly to place additional muck removal

Table 1 TBM specifications for headrace tunnel 1

Items	Content	Performance index
TBM manufacturer	Robbins	
Whole equipment	Diameter	With the newly mounted cutter: 12,430 mm, With the limited wear cutter: 12,400 mm
Cutters	Number of cutters	Center cutter: 8 (432 mm) face cutter/gauge cutter: 70 (483 mm) over-cutter: (2,483 mm)
	Cutting spacing	89 mm
	Maximum thrust force	267 kN
Cutterhead	Rated torque	16,519 kNm (2.4 RPM)
	Maximum torque	24,778 kNm
	Rotation direction	Left/right direction, single-track muck transport
	Maximum rotation speed	5.6 RPM
	Recommended thrust force	22,703 kN
	Maximum tolerable thrust force	24,260 kN
Thrust cylinder	Stroke	1,820 mm
Gripper system	Maximum operation pressure	345 bar

Table 2 TBM specifications for headrace tunnel 3

Items	Content	Performance index
TBM manufacturer	HERRENKNECHT	
Whole equipment	Diameter	With the newly mounted cutters: 12,440 mm, With the limited wear cutter: 12,400 mm
Cutters	Cutter diameter	483 mm
	Maximum thrust force	315 kN
	Cutter number	81
	Cutting spacing	78.7 mm
Cutterhead	Drive power	4,900 kw
	Rated torque	13,167 kNm (3.2 RPM)
	Maximum torque	21,067 kNm
	Rotation direction	Left/right rotation, single-track muck transport
	Maximum rotation rate	5RPM
	Recommended thrust force	24,885 kN
	Maximum tolerable thrust force	35,625 kN, 310 bar
Thrust cylinder	Maximum thrust force	39,584 kN/350 bar
	Stroke	1,850 mm
	Maximum penetrate rate	75 mm/min
Gripper system	Maximum operation pressure	350 bar/109,956 kN

equipment immediately behind the cutterhead to clear the rock blocks from the invert of the tunnel. Between 2nd August and 23rd September 2009, the contact area between the rock mass and the gripper pads was enlarged, and the finger shape shield tail was reinforced. In addition, the support system at L1 was modified and protected with steel shells.

The TBM in headrace tunnel 3 was also modified to prevent large rock blocks entering the muck bucket and damaging the conveyor system.

After the modifications the performance improved considerably such that by October 2010, the average

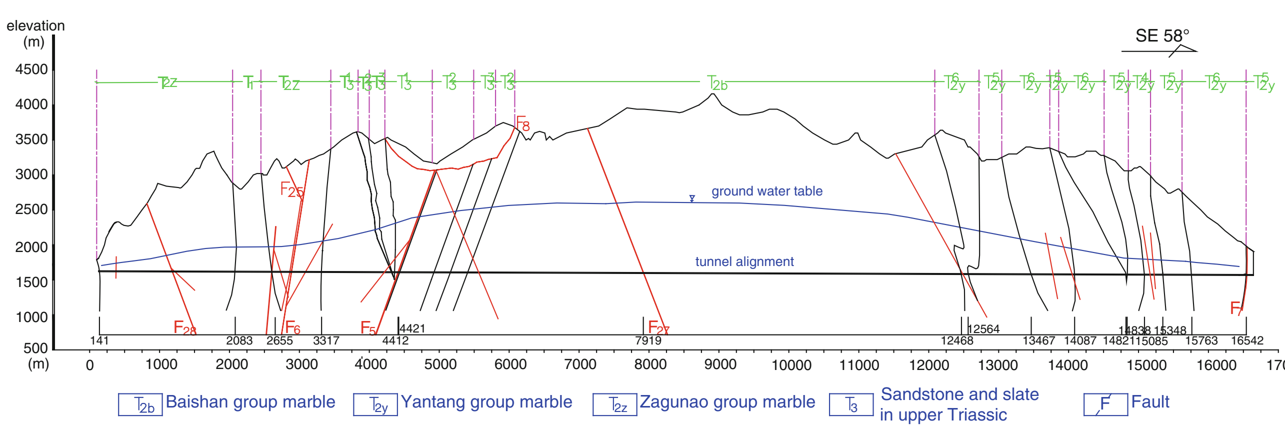

Fig. 2 Geological profile along the tunnel alignment

Table 3 Rock strength and brittleness index of headrace tunnels in Jinping II hydropower station

Rock type	Sample numbers	Weathering degree	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	Brittleness index
Greyish white marble (T_{2y}^{4})	40	Slightly weathering- fresh	90.10 (73.34–113.27)	–	–
	–		100–110	5.0–5.5	20
Black marble (T_{2y}^{5-1})	42	Fresh	92.44 (66.32–113.48)	4.67 (3.24–8.96)	19.79 (20.47–12.67)
Grey marble	29	Fresh	73.64 (60.98–89.92)	4.52 (3.41–7.69)	16.29 (17.88–11.69)
(T_{2y}^{5-2})	3	Fresh	57.99	5.92	9.79
Argillaceous marble	23	Fresh	92.54 (68.53–112.55)	5.49 (3.57–10.14)	16.86 (19.17–11.10)
(T_{2y}^{6})	3	Fresh		8.57	
Argillaceous limestone to marble (T_{2y}^{6})	–	–	70–80	3.5–4.0	20
Crystalline marble (T_{2b})	39	Fresh	136.8 (99.58–183.20)	4.10 (3.40–4.87)	33.37 (29.29–37.62)
	2	Fresh	75.53	7.03	10.74
	3	Fresh	122.71	9.53	12.88
Grey marble (T_{2z})	6	Fresh	89.95 (76.18–106.48)	–	–
Calcite siltstone (T_3)	17	Fresh	110.72 (76.14–137.89)	4.97 (3.95–6.36)	22.28 (19.28–21.68)
Slate (T_3)			80–90	2.4–2.7	33.33
Interbeded sandstone and slate (T_3)	–	–	85–95	2.6–2.9	32.69–32.76

2.69 (2.67–2.71)–average value (minimum average value–maximum average value)

advance rate per month was 278 and 322 m for headrace tunnels 1 and 3, respectively, with a maximum advance of 547 and 628 m/month, respectively.

Between January and April 2010, both TBMs encountered a highly fractured rock mass such that the rock immediately behind the shield fell from the excavation. This resulted in over-break and additional removal of rock, causing delays to the construction. In headrace tunnel 3, instability of the tunnel wall and face led to damage of the TBM cutterhead and cutter bearings at the end of July 2009, which took more than 1 month to repair. At CH.13,791.61 and CH.11,240 m, an underground (karst) groundwater inflow was encountered, reaching 1.4 and 1.8 m^3/s in headrace tunnels 1 and 3 respectively, which caused considerable delay. When the drainage tunnel was constructed, a large rock burst occurred at CH.9280 in the drainage tunnel which buried the TBM such that it had to be abandoned. In the area of the rock burst, a pilot scheme was adopted, resulting in the upper part of headrace tunnels 1 and 3 being constructed using drill and blast. By supporting the crown of the tunnel, some of the high in situ stresses were released.

Main factors influencing TBM advance

Along the headrace tunnel alignment, the thickness of the marbles varied from centimeters to meters. With the bedding dipping at 60 to 80° to the tunnel axis, the cutting face was continually encountering different materials.

Table 4 Results of Cerchar test and abrasion evaluation

Rock type	Sampling place	Abrasive diameter (mm)	CAI index	Abrasion evaluation
T_{2b}	ZK (12A-1) & ZK (16-9-2)	0.112	1.12	Low-abrasion
T_{2z}	ZK (6-1-2)	0.075	0.75	No-abrasion
T_{2y}^{5-2}	ZK (A-10-2)	0.077	0.77	No-abrasion
T_{2y}^{4}	FZK (4-6)	0.071	0.71	No-abrasion
T_{2y}^{5-1}	FZK (5-2-2)	0.067	0.67	No-abrasion
T_{2y}^{6}	FZK (6-1-18)	0.10	1	Low-abrasion

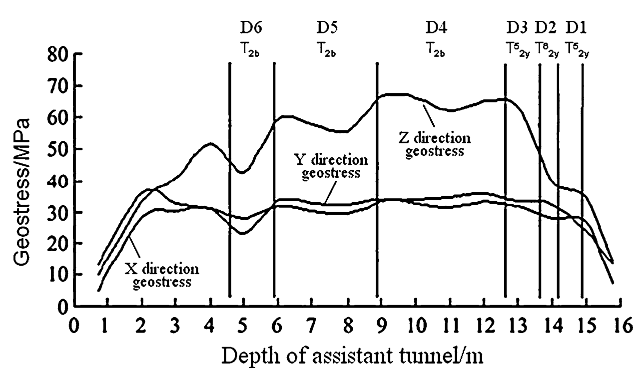

Fig. 3 Initial in situ stress along the tunnel alignment

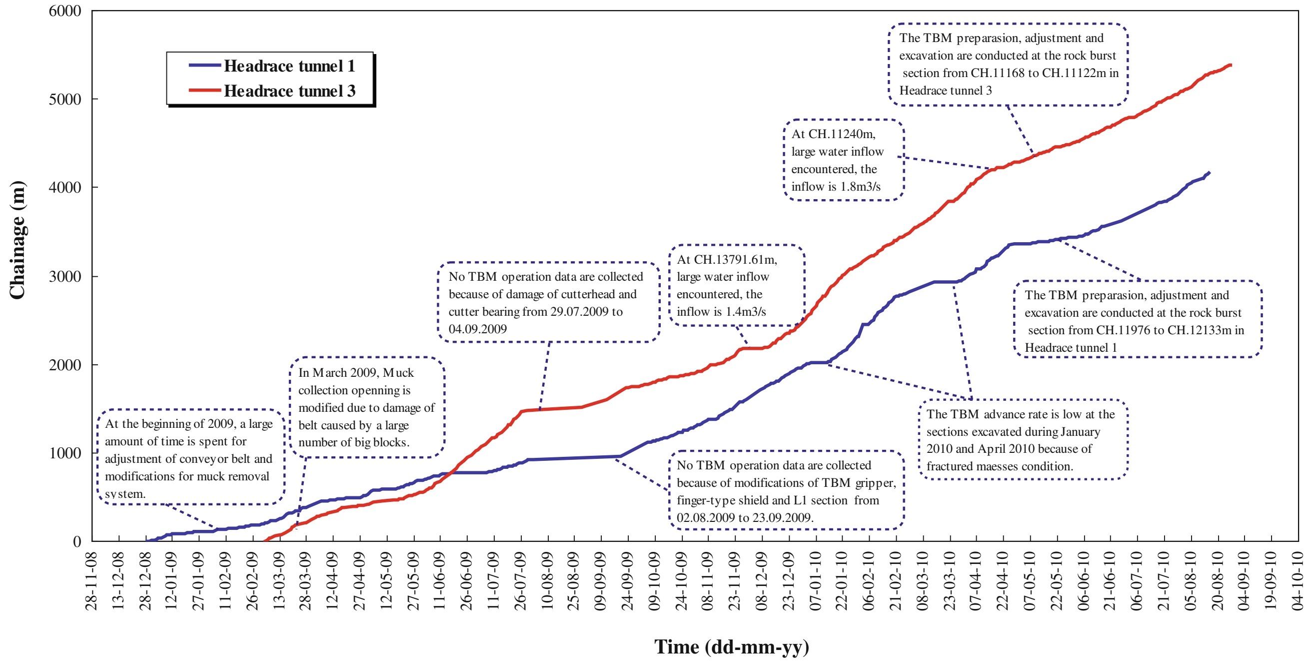

Fig. 4 TBM advance curves for headrace tunnels 1 and 3

In areas of high in situ stress, rock bursts, slabbing and collapse were common. From the site investigation, instability of the tunnel face occurred more often and had a greater influence on the TBM excavation than had been anticipated from the site investigation, while the variation in conditions at the face resulted in significant cutter vibrations and inconsistent loads on the disc cutters. Such conditions directly influenced the penetration rate and also led to excessive cutter wear. It also resulted in large blocks becoming unstable at the cutter face, causing abnormal cutterhead damage.

The instability of the tunnel wall necessitated further support measures and additional drainage work was required to cope with the large, high pressure groundwater inflows.

Fig. 5 Tunnel face at CH.15161.03 m in headrace tunnel 3 (medium layer rock mass)

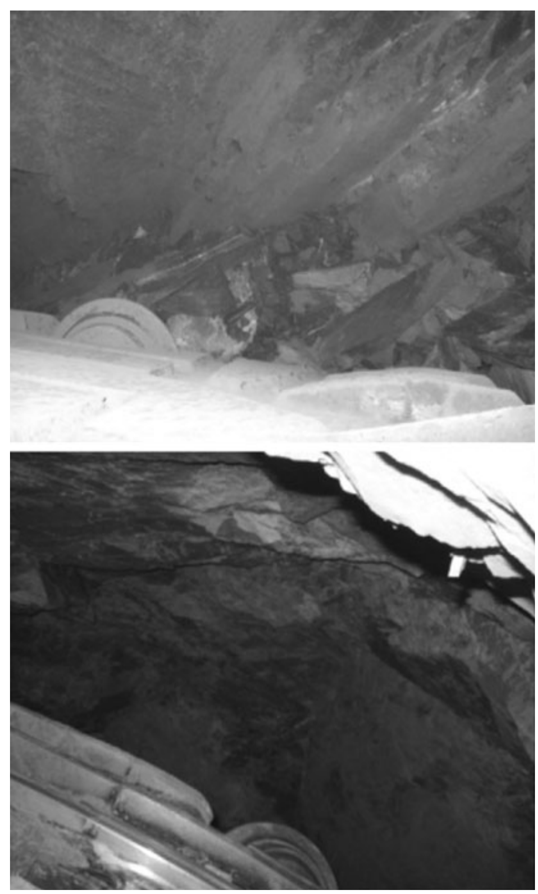

Fig. 6 Examples of tunnel face collapse

Fig. 7 Chips and big rock blocks

Fig. 8 Large block (2 × 2 × 4 m) ahead of cutterhead

Instability of tunnel face

Tunnel face collapse occurred where the marble was in thin bands dipping at high angles. In view of the high in situ stresses, tensile fractures were created. The consequential tunnel face collapse increased the torque of the TBM and, rather than advancing the tunnel, much of the machine effort was taken in removing the blocks (rather than chips) which fell in front of the cutterhead. To avoid jamming the TBM, the thrust and RPM had to be decreased in an attempt to reduce the impact of the rock blocks on the cutters and cutterhead.

Slabbing and collapse occurred at the tunnel face in areas where the rock layers were thin to medium (Fig. 5). The high in situ stress induces slabbing which facilitates rock breakage by the TBM cutters, but can result in instability when the cutter is too close to the slabbing surface (Fig. 6). In this case, the muck includes both normal rock chips and rock slabs (Fig. 7).

The third failure type is the most unfavorable for TBM operations. In this case, the rock masses are composed of medium to thick or very thick layers of marble and there are large discontinuity surfaces, such as faults and large joints. Intense or very intense rock bursts accompanied by slabbing result in large rock blocks reaching the TBM cutters and cutter-head, and the creation of an arch-shaped tunnel face. The largest rock block found in the tunnel face mapping was 2 m wide × 2 m high × 4 m long (Fig. 8). Such large blocks frequently jammed the cutter-head causing abnormal damage. In addition, the penetration rate had to be decreased in order to clear away the rock blocks falling from the tunnel face.

Instability of tunnel walls and roof

The effect of tunnel wall instability on the TBM excavations is well known (Myrvang et al. 1998; Kaiser et al. 2000; Zhao et al. 2007; Kaiser 2009). In the case of headrace tunnel 1, the advance rate was reduced to effectively zero for some 10–20 days between January and June 2011 when the combination of the stress on the tunnel wall induced by the gripping action of the TBM and the high in situ stresses resulted in spalling and rock bursts (Fig. 9). The gripping of the TBM arms against the tunnel wall is a pre-requisite for the machine to progress.

It was found that the large amount of rock blocks falling from the tunnel roof was the main factor influencing the scheduled excavation time. These failures necessitated

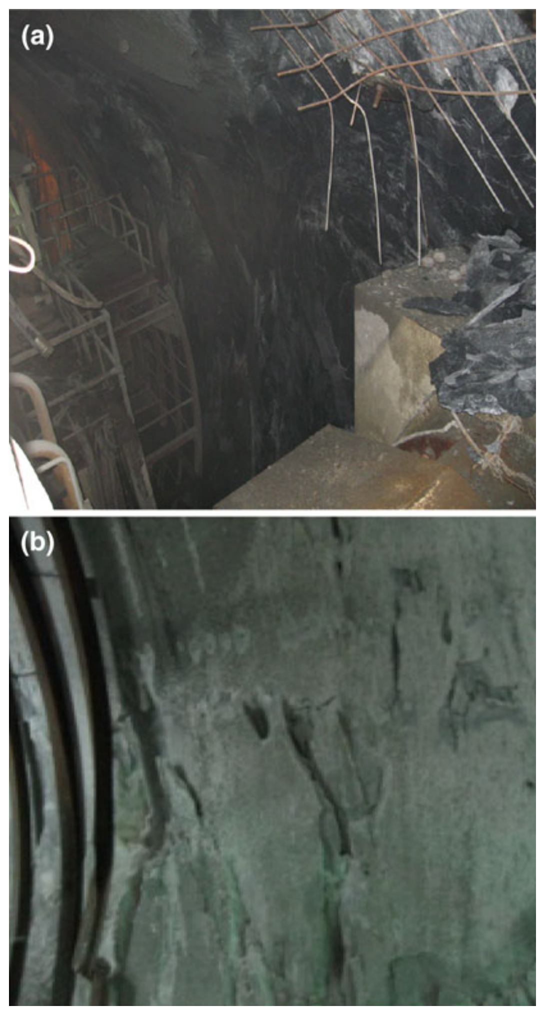

Fig. 9 **a** Gripper instability induced by tunnel wall failure; **b** Failure of steel arch

Fig. 10 **a** Support at unstable section **b** steel arch and structural support at rockburst section

additional support using steel arches, anchors and shotcrete (Fig. 10); while these were being installed TBM operations had to be suspended, significantly affecting the overall advance rate.

Cutterhead damage and abnormal cutter wear

As seen in Fig. 11, the cutters/cutterheads experienced considerably more wear than was anticipated. In headrace tunnel 1, the cutters had to be replaced 145 times between 6 October 2009 and 15 August 2010 with only 15 cutters normally weared 42 due to ring chipping and 48 to ring cracking (Fig. 12a). In headrace tunnel 3, the total number of cutter replacements was 510 between December 2008 and August 2010, with 29 being replaced due to ring chipping and 322 as a result of ring cracking. As seen in Fig. 12b, the majority of the replacements (67 %) related to face cutters and gauge cutters.

According to the function proposed by Bruland (1998), the predicted cutter life for massive rock masses is 2,486 m^3/cutter. The data recorded for the headrace tunnels indicated an average of 2,431 m^3/cutter in headrace tunnel 1 and 1,208 m^3/cutter in headrace tunnel 3.

Based on the Cerchar abrasivity results (Table 4), the excavated marble is of low abrasivity and hence it would be anticipated that the cutter wear would be low. There are two main reasons for the abnormal wear experienced:

(a) The blocks from the rock bursts and slabbing directly impact the cutters
(b) The uneven tunnel face results in an inconsistent impact load on the cutters, especially at high RPMs and increased cutterhead vibrations.

Many cracks inside the cutterhead were found, as an example shown in Fig. 13. It took almost 50 days to replace the cutters and reinforce the cutterhead structure.

Groundwater ingress

During the TBM excavation, two large water inflows were encountered in headrace tunnel 3: 1.4 m^3/s at CH. 13791.61 and 1.8 m^3/s at CH.11240 (Fig. 14). It took almost a month and 2 weeks, respectively, to solve the problems of damage to the TBM equipment. Plugging and drainage was very difficult and time-taking, significantly reducing the rate of advance.

Measures taken to optimize TBM operations

Measures to solve the problems involved both the machines themselves and the excavation process.

Modifications to TBMs

(i) In order to overcome the problem of large blocks damaging the machine, a steel plate was welded to the muck scoop and additional teeth cutters installed.
(ii) The size of the gripper plates was increased by 28.6 %, such that the impact of the grippers was reduced and the gripper stability increased.
(iii) To improve the support installation, a finger-type shield was placed behind the cutterhead. This was reinforced by two layers with a steel mesh between, and enhanced both the strength of the finger shield and the safety of workers (Fig. 15). These modifications and an increase in the work space improved the progress.
(iv) Attempts made to improve the conveyor belt system (Fig. 16) were largely unsuccessful due to the small width of the accessorial belt and the small dipper teeth.

(a) Normal cutter wear **(b)** Cutter ring chipping **(c)** Cutter ring cracking **(d)** Cutting ring cracking and flat cutter wear **(e)** Cutter ring lost **(f)** Cutter ring overturned

Fig. 11 Types of cutter wear and damage

Optimization of TBM operation

(i) The key factor for TBM excavating is highly effective rock fragmentation under the rolling cutters (Kou et al. 1995; Rostami 1997; Gong 2005). The physical and mechanical properties of the rock, joint spacing and direction, etc., were analyzed and as far as possible taken into account in the operational parameters chosen for the TBM.

(ii) The TBM thrust and RPM were carefully assessed to avoid excessive disturbance of the surrounding rock mass. For example, where closely fractured marble was encountered (from CH.12550 to CH.12700 in headrace tunnel 3), the TBM operated with a smaller thrust force, high torque and low RPM.

(iii) Based on the analysis of cutter wear, total thrust and RPM were decreased.

(iv) Where significant groundwater inflows occurred, the timely implementation of plugging and drainage measures could allow the continued progress of the TBM.

Conclusions

At the Jingping hydropower project there were three types of tunnel face failures induced by high in situ stresses during the TBM excavation: tunnel face collapse, slabbing and collapse; and intense rock bursts at the tunnel face, each of which contributed to cutterhead damage/abnormal cutter wear, an increase in the TBM torque and a decrease in the rate of advance.

The instability of the tunnel wall has a significant effect on TBM excavation. It reduces the ability of the TBM to

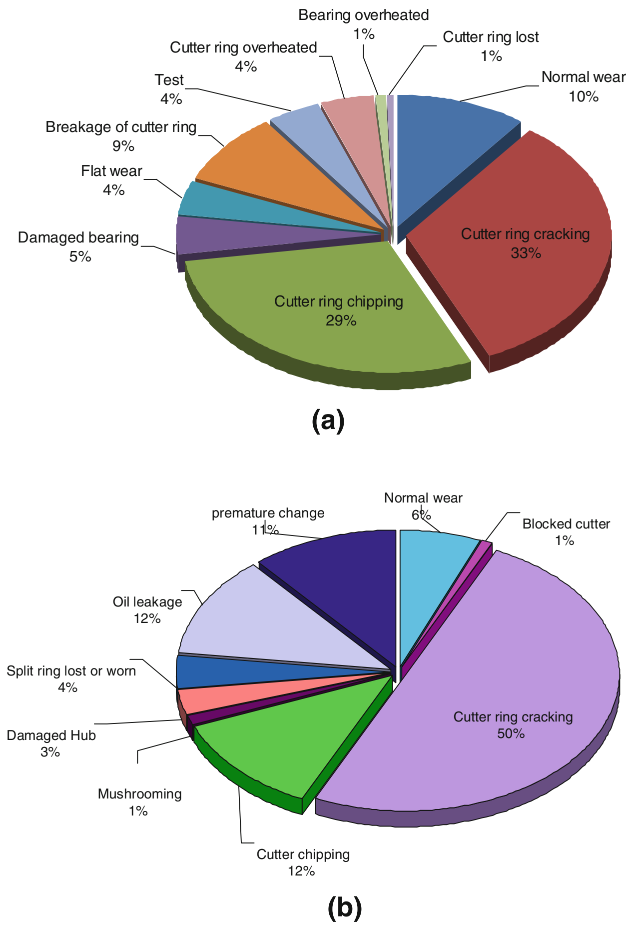

Fig. 12 Reasons for cutter replacement **a** from 12.2008 to 08.2010 in headrace tunnel 1 and **b** from 03.2009 to 08.2010 in headrace tunnel 3

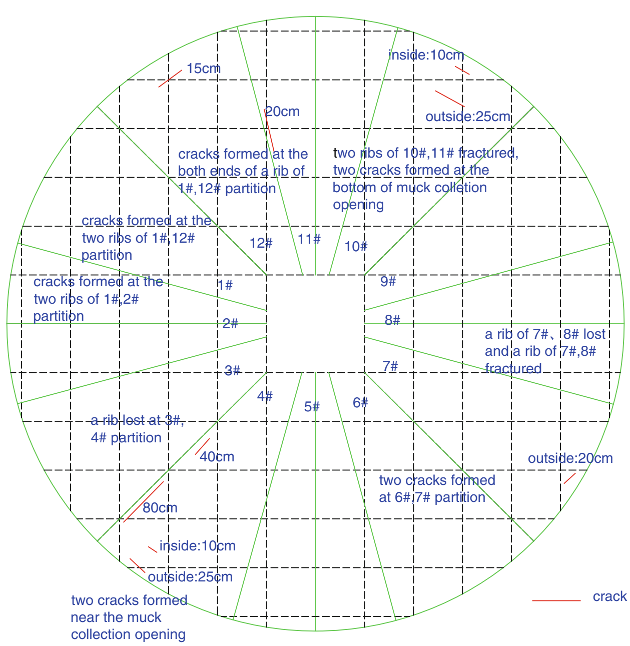

Fig. 13 Distribution of cracks on the cutterhead

Fig. 14 Groundwater inflow at CH.11240 m in headrace tunnel 3

obtain a firm grip on the tunnel wall, as well as increasing the difficulty of installing support and muck removal.

The large groundwater inflows encountered damaged the TBM equipment and created difficulties in clearing and track laying, all of which adversely affected the advance rate.

The measures taken to resolve the problems included modifications to the TBM grippers, support system, finger-type shield and muck removal system and careful control

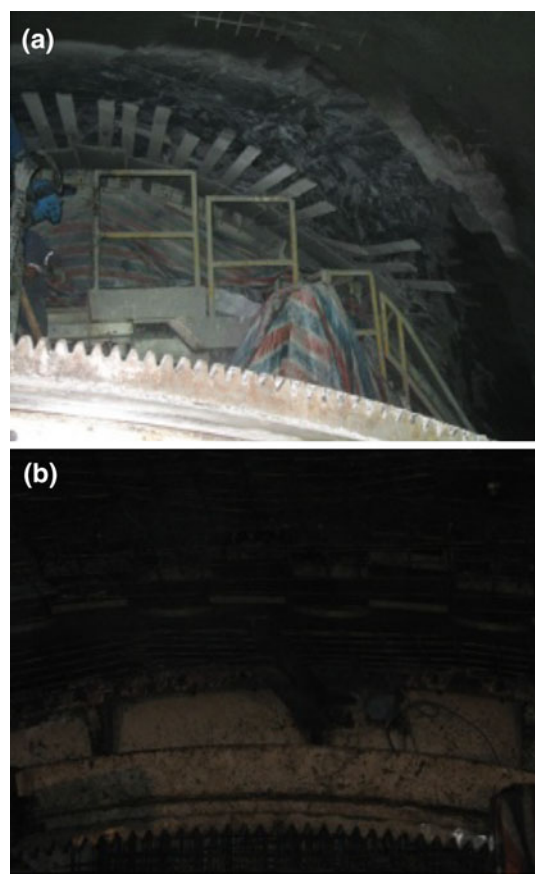

Fig. 15 Original (**a**) and modified (**b**) finger-type shield in headrace tunnel 1

Fig. 16 Accessorial belt conveyor machine installed in TBM of headrace tunnel 1

of the operational parameters to reflect the very different geological conditions encountered.

The paper has demonstrated that through a combination of research on the geological conditions, machine technology and practical experience, TBM technology can continue to be advanced to meet the challenges of constructing long tunnels at great depths where high in situ stresses and large groundwater inflows are encountered.

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