ONSITE ASSEMBLY AND HARD ROCK TUNNELING AT THE JINPING-II HYDROPOWER STATION POWER TUNNEL PROJECT

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ABSTRACT

Unique onsite assembly of a 12.43 m Main Beam TBM and back-up system was completed on September 18, 2008 in the remote mountains of the Sichuan province of China. The equipment was assembled onsite, without previously having been assembled and tested in a factory, utilizing a method called Onsite First Time Assembly (OFTA). The Jinping-II hydroelectric project features four parallel headrace tunnels approximately 18 km long, two of which will be excavated by TBMs and two by drill and blast. A nearby fifth tunnel is being excavated by a 7.2 m TBM to draw down ground water in advance of excavating the headrace tunnels.

This paper addresses the following topics:

- Project description including geology and terrain;
- The decision process leading to onsite first time assembly, the assembly process and logistics, and lessons learned;
- Design features of the TBM and back-up system; and
- Operational history from startup to the writing of the paper.

PROJECT DESCRIPTION

Jinping-II will be the largest power station (see Figure 1) in an ambitious 21-station mega project for owner Ertan Hydropower Development Co. Ltd. (EHDC). The total 21-station project will harness power from the Yalong River for China's West to East Electricity Transmission Project. EHDC began the scheme in 1991, constructing the Ertan Hydroelectric Project in the west of Sichuan Province. The project was officially completed in 2000 with an installed capacity of 3,300 MW. Additional projects in the lower reaches of the Yalong are planned for completion before 2015, including Jinping-I (3,600 MW), Jinping-II (4,800 MW), Guandi (2,400 MW) and Tongzilin (600 MW). All remaining projects are to be finished by 2025. Currently, three power stations are being built or are already online (Ertan, Jinping-I, and Jinping-II), while the others are in various preparatory stages.

Power from these stations and other resources in the west will be transmitted to Guangdong, Jiangsu, and Zhejiang Provinces, as well as the cities of Shanghai, Beijing, Tianjin, and other eastern locations, where electricity is now in short supply. The entire scheme is envisaged to go online in 2030 and will have a generation capacity of close to 30 GW.

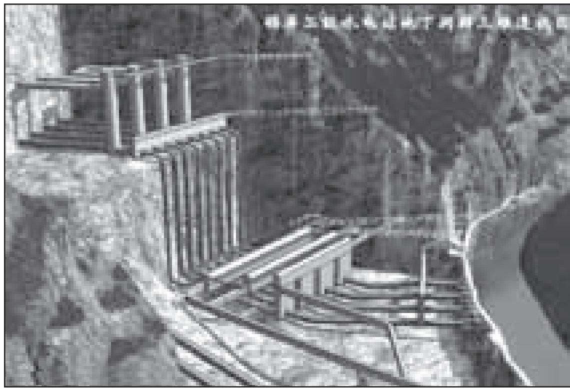

Figure 1. Jinping-II underground power station

Preliminary geological surveys, feasibility studies, and necessary approvals for the large scale development of Jinping-II and other stations have been ongoing for the past 40 years. In 2003, work began on the 62 km long main road leading up to the Jinping-II jobsite.

The Jinping-II site is unique in that it will utilize a 180 degree natural hairpin bend in the Yalong River, a tributary of the Yangtze, to generate a multi-year average annual generation of 24.23 TWh. From the intake structure, the river flows northward before turning abruptly southward as it flows around Jin Ping Mountain. The distance along the river from intake to outlet is approximately 150 km during which the river drops 310 m. From intake structures near Jingfeng Bridge water will flow through the four Jinping headrace tunnels downgrade at 3.65% to the underground Dashuigou powerhouse. The powerhouse will utilize eight 600 MW turbine generators for a total generating capacity of 4,800 MW. The four (4) parallel headrace tunnels, with an average length of 16.6km, are separated by 60m from centerline to centerline. Two access tunnels and a drainage tunnel run parallel to the headrace tunnels on the southern side.

Ertan Hydropower, the owner, split the tunneling contracts in two. One contract was let for headrace tunnel Nos. 1 & 2, and a separate contract was let for tunnel nos. 3 & 4. The tender documents specified that two 12.4 m diameter TBMs would excavate 16.7 km long sections of headrace tunnel Nos. 1 and 3. As a result, each of the construction contracts includes one TBM bored tunnel and one drill and blast excavated tunnel. China Railway 18th Bureau (Group) Co Ltd. won the construction contract for headrace tunnel Nos. 1 and 2, while China Railway 13th Bureau (Group) Co Ltd. won the contract to construct headrace tunnel Nos. 3 and 4.

Parallel to the headrace tunnels is the 15.3 km long dewatering tunnel which is being excavated under separate contract by Beijing Vibroflotation Engineering Company (BVEC) with a 7.2 m diameter TBM. This tunnel is being excavated ahead of the four headrace tunnels in order to reduce the water inflow in the headrace tunnels well below the 5 m^3/s otherwise expected (see Figure 2).

GEOLOGY AND TUNNEL ALIGNMENT

All four tunnels are located on the slopes of Jinping Mountain in reportedly stable geology consisting of massive to blocky marble with limestone, sandstone, slate and chlorite schist with unconfined compressive strength (UCS) of between 50 and 85 MPa. A high overburden, with over 70% of the cover greater than 1,500 m and a maximum

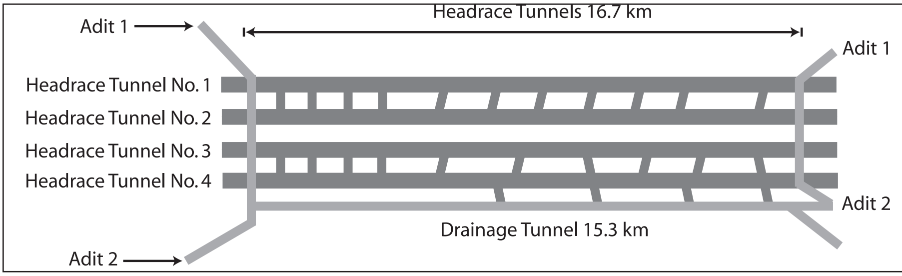

Figure 2. Jinping-II project layout

Figure 3. High cover at Jinping-II jobsite

of 2,525 m, creates a risk of squeezing ground and rock bursts (see Figure 3). Pre-excavation core tests typified rock in the tunnel as:

- Class II (RMR 61 to 80): 29.1% of tunnel
- Class III (RMR 41 to 60): 53.6% of tunnel
- Classes IV and V (RMR < 41): 17.3% of tunnel

Though the rock should provide relatively good conditions for excavation, there are several challenges to overcome. One is the potential for sudden inundation of the tunnel during the excavation work. Underground water in the vicinity is reportedly conveyed by fissures and a network of channels with a continuous water source, resulting in the possibility of high pressure and large flow rates. Core tests revealed a potential for steady flows in the range of 2 to $3m^3/s$ with maximum water flows of up to $5m^3/s$ (Wu & Huang, 2008).

Another challenge is rock bursts, which may occur as a result of the high in-situ stress caused by high cover. Again, according to Wu & Huang, measured maximum major principal stress is approximately 42 MPa vertical, indicating that gravity stress dominates. They reported that the major and minor principal stresses could reach 63 MPa and 26 MPa respectively in the headrace tunnel at the point of maximum overburden. Severe rock bursts occurred during excavation of the access tunnels and an adit; therefore, some rock bursting is expected during construction of the headrace tunnels.

In response to the core test results and high cover, an aggressive ground support program has been developed with various support designs specified based on the rock mass classification. In relatively stable rock, support is minimal including sparse rock bolts. In rock mass Class III, systematic rock bolts up to 6 m long are installed, as well as steel-fiber reinforced shotcrete. Class IV and V sections are also stabilized with rock bolts and reinforced shotcrete, and final lining will include concrete up to 70 cm thick.

Measures to Handle Ground Water

During excavation of the headrace tunnels, the contractor will attempt to reduce and control volume water inflows using several approaches:

Pre-excavation Draining. This plan specifies dewatering the mountain by draining water into the 7.2 m dewatering tunnel, which is being excavated by TBM in advance of excavating the headrace tunnels.

Pre-excavation Probing. Rock drills are employed to drill ahead of the TBM, probing for changing geological and hydrological conditions. Information so gleaned will be used to specify pre-excavation rock consolidation and water cutoff grouting programs, as well as to anticipate near-future rock support measures for safe tunneling. It is imperative that any incoming water flow be limited to allow continued excavation by the TBM.

Post-excavation Draining. The construction design, including the TBM design, allows for large volumes of water to be drained through the bored headrace tunnel as they are excavated, minimizing impact on excavation logistics and TBM operations.

Controlling. The concept for this step is to give the constructor the ability to control the rate at which the groundwater is drained into the tunnel, from every point in the excavated tunnel. In this way, it is hoped that water can be allowed to flow into the bored tunnel to the maximum allowable volume rate which will allow continued TBM operations. Ideally, if successful, the system would permit the constructor to drain where and when necessary to maintain operations. This will require, of course, high quality water cutoff grouting, drain pipes and valves.

Rock Bursts

The high in-situ stress along the headrace tunnel can cause rock bursts during excavation. Measured stresses may reach 63 MPa at the site of maximum overburden. Several measures have been specified by the project owner to reduce the potential for rock bursts during headrace tunnel excavation:

TBM Usage. Headrace tunnel Nos. 1 and 3 will be excavated by TBM to a total length of about 16.7 km. The rock mass surrounding a TBM-bored tunnel is disturbed less than it is with drill and blast excavation. It is hoped that the use of TBMs on two of the four headrace tunnels may reduce the rock stresses enough to reduce the probability of rock bursts somewhat in all four tunnels.

Reinforcement of the Surrounding Rock Masses. Maintaining as much of the rock in place as possible after excavation (i.e. minimizing over break or rock fall) results in better total rock support through the formation of a natural arch and reduces post excavation stress. Rock support has been design to keep as much rock in place as possible:

a. shotcrete or steel fiber reinforced shotcrete applied immediately after the excavation
b. patterned rockbolts to prevent the loss of rock blocks and slabs
c. wire mesh or steel ribs

Figure 4. Partial shop assembly

ONSITE FIRST TIME ASSEMBLY (OFTA)

Onsite First Time Assembly (OFTA) was selected for the 12.4 m TBM due to fast track project scheduling and a limited seasonal window for delivery to site by river. The OFTA process, developed by The Robbins Company, allows machines to be assembled at the jobsite without need of pre-assembly in a manufacturing facility. The process was first utilized in 2006 on the 14.4 m diameter TBM at the Niagara Tunnel Project—the world's largest hard rock TBM. OFTA has since been used on several projects around the world, resulting in reduced TBM startup schedules and cost savings due to decreased shipping costs and man hours.

OFTA was identified as essential for the Jinping project because it would enable early shipment of large components of the TBM. Rapid shipment of the large components was needed in order for them to be moved via barge on the Yangzi River before the onset of the low water season between November and April. The area sees vastly different seasonal rainfall, with the May to October rainy season accounting for as much as 95% of annual rainfall.

All of the heavy structural parts of the TBM were manufactured in a facility located in the city of Dalian in Northeast China. Under the original site assembly plan, pre-assembly of some TBM components was to have begun on site in late November 2007. That assembly schedule required that all of the parts arrive at the Le Shan dock near the city of Chengdu on the Yangtze River in early November 2007 before the low water season started. However, by the end of the summer of 2007 the original assembly schedule was delayed because the site was not ready to receive the equipment. Additionally, the Yangtze River experienced unusually heavy flows that year. For these reasons the decision was taken to partially assemble some of the critical parts in the Dalian factory before shipping. The main bearing, gear, and pinions were installed in the cutterhead support so the ring gear—pinion mesh could be verified. Later, the muck chute, side supports, roof support, and front support were attached. The remaining components were assembled for the first time on site (See Figure 4).

At the end of 2007, all of the heavy structures were loaded on a barge, shipped up the river, and placed in a storage yard near Chengdu until the job site was ready to receive them.

Though all of the structural components of the TBM and backup were manufactured in China, sub-systems such as hydraulic, lubrication, water, electrical, and ventilation were manufactured and tested in facilities in the USA or Europe before being shipped to the site.

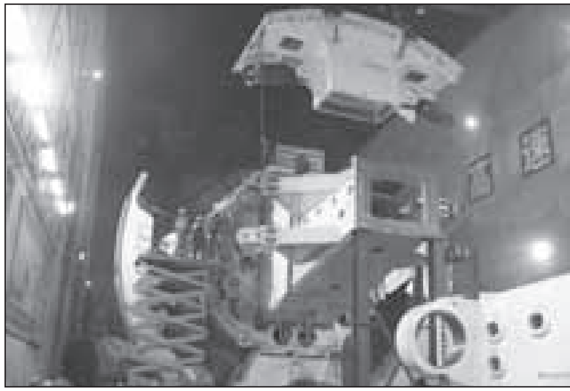

Figure 5. TBM assembly in the chamber

Key components of a successful OFTA program include:

- Quality control of component manufacture to ensure proper fit up at site
- Absolute control of the total system bill-of-materials, to ensure that everything required for the system is sent to the job site
- Logistical planning and control, to ensure that everything arrives at the job site in the order that it is required for efficient assembly and use of storage space
- Resources planning, to ensure that all tools and personnel of every type and quantity required for assembly are on site when required
- Advance alternative recovery planning, in order to be ready to react quickly to possible failures in any of the above steps

Much of the challenge of the assembly was a result of the remote location. Once at the site, the 12.4 m machine was erected in an underground assembly chamber measuring 20 m wide × 26 m high. Limited space required that many of the smaller TBM components, the parts imported from outside China, and all of the back-up structures be staged about 80 km away in the town of Manshuiwan, where warehouse space and a large outdoor yard were provided by Ertan.

Every morning a coordination meeting was convened to plan which parts should be sent to the site for the next day's scheduled work. The designated parts were loaded on trucks that day and sent to the assembly chamber, arriving later that evening to be available for the next morning's assembly (See Figure 5).

Because of the remote location and because the TBM had not been previously assembled, it was necessary to equip several shipping containers as workshops. A hydraulic workshop was set up with the hose ends and adapter fittings needed, as well as a high production hose crimping machine (See Figure 6). Similarly, an electrical container, a tool container, a workshop container, and an office container were mobilized in the assembly chamber.

Assembly of the TBM and back-up system began in July 2008 and finished on September 17, a schedule comparable to that for site assembly of a large diameter TBM which has been pre-assembled in the factory. Crews then walked the TBM and the first three back-up gantries 200 m forward from the assembly chamber to a launch chamber. The vacated assembly chamber was then used to erect the conveyor system and six more back-up gantries.

In general, the assembly sequence proceeded according to the plan, with one major exception. Early in the assembly program, it was discovered that the gripper

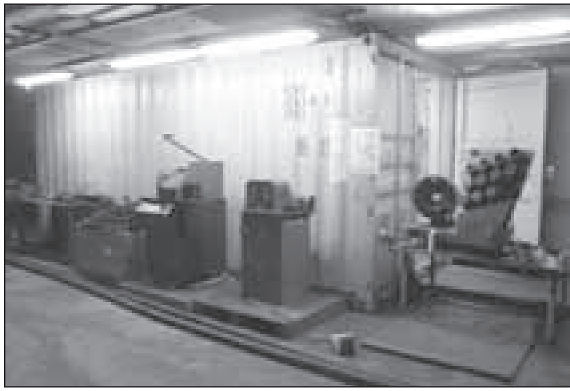

Figure 6. Hydraulic workshop

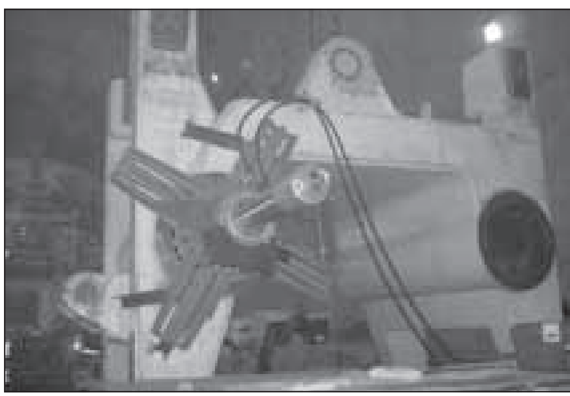

Figure 7. Portable boring machine

carrier bushings had not been finish machined in the manufacturing facility in Dalian. Shipping the carrier to the nearest machine shop in Chengdu for repair would have been the preferred way to solve the problem. However, this was impossible because of damage to machine tools and factories resulting from the severe earthquake that hit Sichuan province in May 2008. Instead, a contractor in Shanghai was brought to site with a portable boring machine and the gripper carrier bushings were line bored in 3 days. (See Figure 7).

Another major difficulty was the lack of skilled local workers. For this reason, intense supervision and training of these workers was necessary to ensure the quality of the final product. Robbins had as many as 16 supervisory personnel from the USA and Europe and 26 engineers, mechanics, and electricians from Robbins (China) Underground Equipment Co., Ltd. at the peak of the assembly effort.

The equipment was successfully assembled and launched in only three months, despite record snowstorms that caused major delays, as well as 2008's magnitude 8 earthquake centered near Chengdu, which caused heavy road damage and further delays to the schedule (see Figure 8).

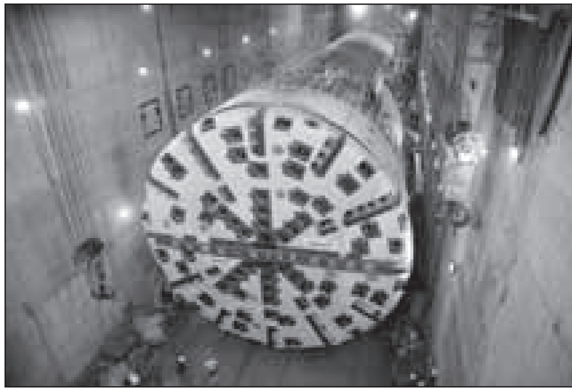

Figure 8. Fully assembled 12.43 m diameter TBM

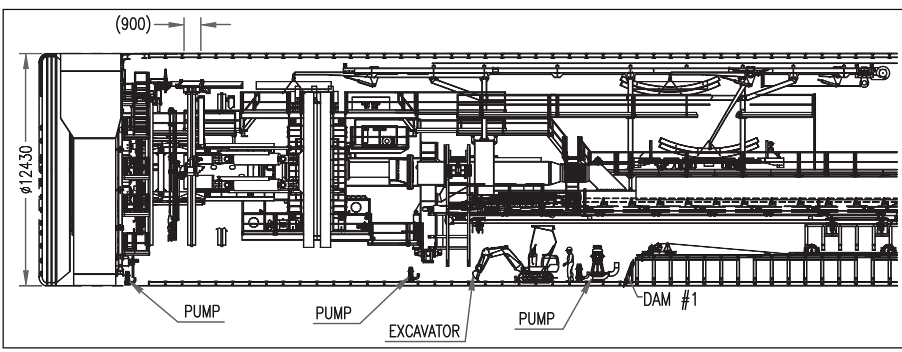

Figure 9. TBM general assembly

TBM FEATURES AND DESIGN CRITERIA

Robbins specially designed the 12.43 m TBM for high water inflows and difficult ground conditions (see Figure 9). Several measures are being taken to address the possibility of deep, flowing water in the invert under the TBM. With the exception of the cutterhead and cutterhead support, the lowest parts of the TBM, back-up, and continuous conveyor systems are 1.5 m above the tunnel invert. In addition, the tunnel train track is assembled on a continuously installed steel framework, also 1.5 m above the tunnel invert. Keeping all of the equipment 1.5 m above the tunnel invert allows a water inflow of approximately 4,000 liters per second to pass under the boring equipment and trains with minimum impact on tunnel excavation.

Primary rock support activities are performed from platforms on top of the TBM. Ring beams are delivered in the top of the tunnel, through the back-up and over the top of the TBM main beam to the ring beam erector. A panel erector can install specially designed steel panels over fissures in the rock where water is entering at high pressure, in order to deflect and redirect the water spray.

Moveable steel dams can be placed in the invert just behind the TBM and dewatering pumps are available to relay water from the cutterhead support area to the end of the back-up to keep the water level as low as possible under the TBM, in the primary tunnel working area.

Figure 10. Back-up system with steel canopies

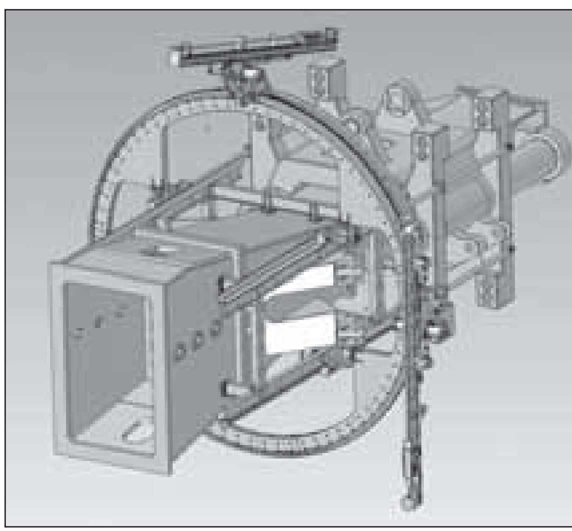

Figure 11. Rock drills on TBM (L1 zone) are used for both rock bolting and probing

The working decks on top of the backup are covered by steel canopies to protect personnel from high pressure or high flow water (see Figure 10).

Rock bolting is done in two locations on the TBM. The L1 zone, located just behind the cutterhead support, has two drills and the L2 zone, on the backup just behind the bridge conveyor, has two more drills. Shotcrete can be applied both in the L1 and L2 areas. In L1 a single robot is used for emergency application of shotcrete. Production shotcreting is done in the L2 area with two robots, one on each side of the backup. The L2 robots have an axial stroke of 12 m and a pumping capacity of 25 m^3/h each. The backup gantries where the L2 drills and shotcrete robots are located are configured as 6m diameter steel tubes. All shotcreting and drilling takes place on the outside of the tubes to protect the facilities on the inside of the tubes and to allow free passage of workers and materials during ground support activities (see Figures 11, 12 and 13).

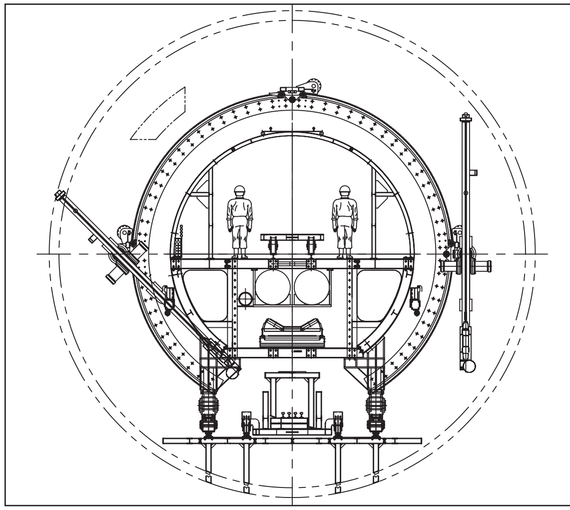

Figure 12. Additional rock drills are on the backup for secondary bolting, outside of 6 m tube

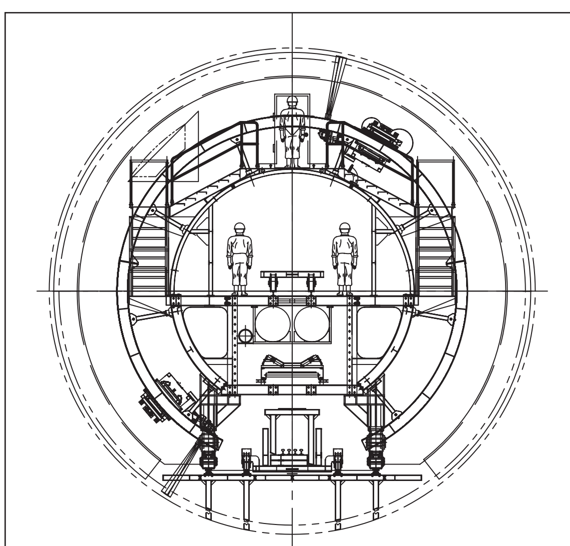

Figure 13. Shotcrete robots work outside of the totally enclosed central working area

Following the L2 zone rock support equipment decks are several three-level backup decks on which various equipment is mounted and various workstations are located (see Figure 14).

The TBM is a Robbins HP-TBM (High Performance TBM) which combines very heavy structural steel components, a very high capacity 3-axis/3-roller main bearing, high thrust and high power. Cutterhead has 4,410 kW of power and is fitted with 19-inch

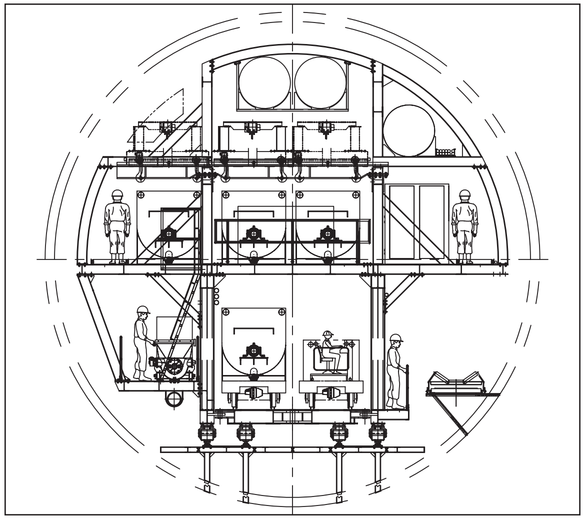

Figure 14. Typical back-up cross section

back loading cutters with two extra housings installed in the gage area for overboring in the event squeezing ground is encountered (see Table 1).

MUCKING SYSTEMS

In anticipation of high water inflows, the conveyors on the TBM and backup are designed to be completely horizontal to minimize the high spillage rates associated with inclined conveyors carrying muck and large amounts of water. The bridge conveyor located just behind the TBM conveyor is straight for two thirds of its length and then curves to the side to discharge directly into the advancing tailpiece on the right hand side of the tunnel. Curving the conveyor was necessary to eliminate the usual transfer conveyor between the bridge conveyor and tunnel conveyor. With the elimination of the transfer conveyor it was possible to keep the bridge conveyor completely flat.

Muck is transported from the TBM by a continuous conveyor system which will eventually be 16.7 km (See Figure 15) in length. The steel cable core conveyor belt system utilizes a 1,200 kW main drive with a 1,200 kW booster drive, which will be installed at the midpoint of the tunnel. The TBM tunnel No. 1 conveyor capacity is large, at 1,800 tons/hour, in order to be able to handle crushed rock from the adjacent drill and blast tunnel No.2 in addition to the TBM generated muck from Tunnel No.1. The tunnel conveyor discharges to a series of conveyors intended to handle muck from all four headrace tunnels and the dewatering tunnel. Final disposal is in a deep valley 7 km from the portal. The dewatering tunnel utilizes a similar steel cable belt system 15.4 km in length.

OPERATIONAL HISTORY

The assembly of both 12.4 m machines was completed in the autumn of 2008, while the 7.2 m machine was launched earlier, in May 2008. As of late October, the Robbins machine at headrace tunnel No. 1 was undergoing testing and had advanced more than 300 m of its 2,000 m long commissioning bore. Increased ground support was required at the interface between the starting chamber and the bored tunnel and

Table 1. TBM general specifications

Year of Manufacture	2008
Machine Diameter (new cutters)	12.42 meters (40.7 ft)
Cutters	
Face/Gage	Series 19 (482.6 mm)
Center	Series 17 (431.8mm)
Number of Disc Cutters (overcut not included)	78
Number of Disc Cutters Overcut	2
Maximum Recommended Individual Cutter Load	267 kN (60,000 lbs.)
Cutterhead	
Recommended Normal Operating Thrust	20,826 kN (4,681,871 lbs.)
Cutterhead Drive	Electric motors/safe sets,
	gear reducers
Cutterhead Power	4,410 kW (14 x 422.4 HP) (5,914 HP)
Cutterhead Speed	0-5.61 rpm
Approximate Torque (low speed) 0-2.55rpm	16,519 kNm
Approximate Torque (high speed) 5.61 rpm	7,509 kNm
Thrust Cylinder Boring Stroke	1,884 mm (74.2 inches)
Hydraulic System	225 kW (300 HP)
System Operating Pressure at Maximum Recommended Cutterhead Thrust	300 bar (4,351 psi)
Maximum System Pressure	345 bar (5,000 psi)
Electrical System	
Motor Circuit	690 VAC 3-phase, 50 Hz
Lighting System/Control System	230VAC/24 VDC
Transformer Size	2 x 3000 kVA, 1 x 2000 kVA
Primary Voltage	20,000 V 50 Hz
Secondary Voltage	690 VAC drive motors, 400 VAC hydraulic pump motors
Machine Conveyor	
Width	1,370 mm (54 inches)
TBM Weight (approximately)	1,256 metric tons, excluding drilling equipment

Figure 15. Tunnel conveyor

took some time to be agreed. The resulting design included ring beam installation every 900 mm and a 17-bolt pattern of rock bolts every 1.5 m. Progress has been slow to date due to very poor rock conditions. The face is fractured and collapses. Similar rock conditions were present during the first 1.5 km of the dewatering tunnel then improved. It is hoped that conditions will also improve in the head race tunnels in the near future.

Excavation at the dewatering tunnel has advanced a total of 2,890 m as of January 2009, at rates of up to 50 m per day. Boring is done in two 10-hour shifts with a 4-hour maintenance shift. Operations at the drill and blast tunnels were also underway and had advanced approximately 2 km in headrace tunnel Nos. 2 and 4.

The TBM for the dewatering tunnel is expected to finish in late 2009/early 2010, while the machine at headrace tunnel No. 1 is slated for a mid-2012 breakthrough.

CONCLUSIONS

Excavation of the Jinping II headrace tunnels presents many formidable challenges. A condensed construction schedule required a new approach to TBM design and manufacture which resulted in the use of OFTA for rapid launch of the machine, shaving months off the schedule. The extremely high water inflow potential required new methods. Some of the bold new methods planned to battle the water are untested. Tunneling under more than 2 km of cover and the attendant rock stresses and potential for spalling and rock burst would be very challenging, even in the absence of water. At Jinping the extremely remote site location, high water pressure and inflow potential, and 2 km of cover combine to make it one of the most challenging tunneling projects of the day. Regardless of the tunneling production rates finally achieved on the project, one outcome is inevitable; lessons will be learned on this project which will make possible future projects in mountainous regions of China, and even larger ranges such as the Himalayas and the Andes.

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