Lessons Learned During Excavation of the Incredibly Challenging Yin Han Ji Wei Water Diversion Tunnel

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ABSTRACT: The 2022 breakthrough of an 8 m diameter Main Beam TBM at China's Yin Han Ji Wei project was a triumph of technology and perseverance – crews at the 17.5 km long tunnel encountered over 14,000 rock bursts, some with energy as high as 4,080 kJ. The rock, consisting of mainly quartzite and granite, was estimated to have a rock hardness of between 107 and 309 MPa UCS, with high abrasivity and a maximum quartz content of 92.6%. The incredibly challenging tunnel also experienced at times severe water inflows, with one particular event exceeding 20,000 m3 of water in one day from a single point. In-tunnel ambient temperatures peaked at 40 degrees Celsius and 90% humidity. Throughout the challenges, the crew and support teams found ways to persevere – whether through unique ground support, or increased monitoring and analysis. In this paper, we will examine the successes and lessons learned in the incredibly challenging ground conditions, determining what worked best to confront each condition as it came up. Recommendations will be made towards what could be used successfully on future projects that encounter these geological features.

1 INTRODUCTION

1.1 *Project Information*

The 17.5 km long Yin Han Ji Wei Tunnel is part of an 82 km long through the Qinling Mountains near Xi'an City that will link up the Hanjiang and Weihe Rivers in Shaanxi province. The completed tunnel will secure a water supply for towns and agricultural areas in Central China, while also generating hydroelectricity. The extremely long tunnel is itself part of an even more expansive tunnel network under construction – a total of three tunnels being excavated mainly by drill & blast (see Figure 1).

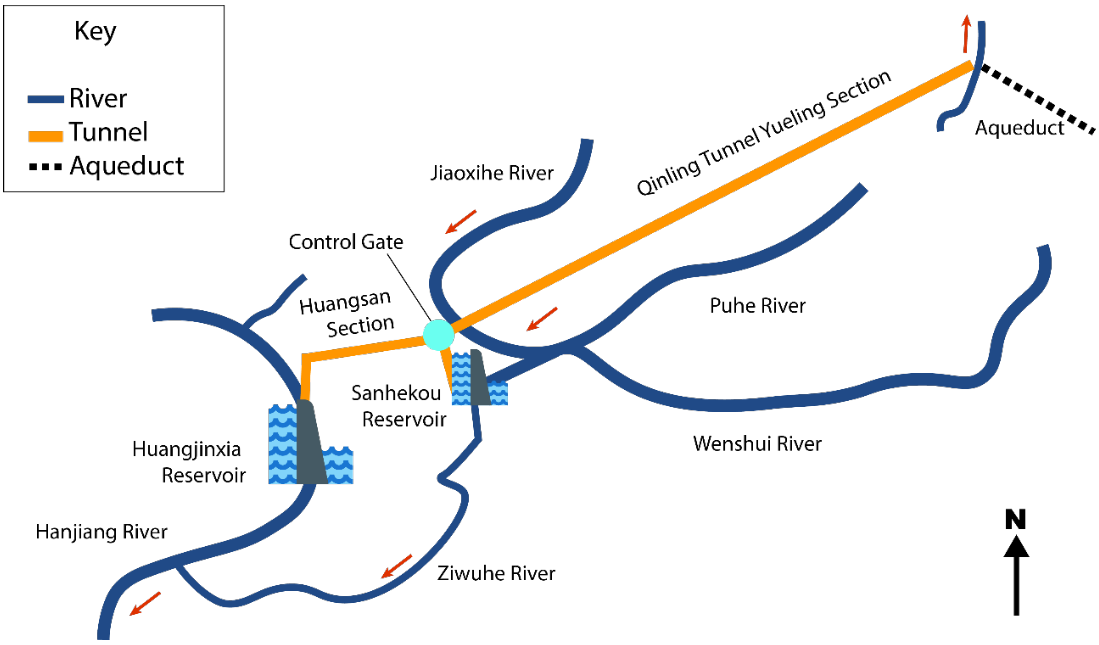

Figure 1. Layout of water diversion project from Hanjiang River to Weihe River.

Only the most difficult sections were selected for TBM excavation in efforts to optimize the promoted advantages of TBM excavation—it was determined that higher rates of progress under high overburden where extra headings and intermediate adits were impossible, and TBMs offered the possibility of greater safety by avoiding exposure of workers to the face and into zones of unprotected rock.

These TBM benefits have been borne out at projects like Peru's Olmos Trans-Andean Tunnel, where a Main Beam TBM enabled excavation despite thousands of rock bursts under high cover up to 2,000 m. The project was completed after multiple failed attempts using other methods such as drill & blast (Willis et al., 2012).

It is notable that in meta-studies of tunnels in high cover, mountainous tunnels, the benefits of the TBM can only be realized through proper risk mitigation and meticulous planning. For deep mountain tunnels, with very few exceptions, major disturbance zones associated with faulting have posed the most problems to tunnelling advance, often historically requiring bypass drifts and significant ground treatment before being able to be traversed. The need is to look carefully not just at the basic geotechnics of deep tunnel alignments in terms of Q/RMR/GSI and other key rock mechanics parameters, but also at regional structural geology domains (Carter, 2012). Through working with the equipment manufacturer early on, the proper TBM, tunneling parameters, ground support, and ground prediction methods can be utilized to help mitigate risk.

1.2 *Geology*

Site investigation prior to excavation was limited due to the mountainous terrain, and therefore previous projects within the Qinling Mountains were looked at as reference points. These projects, however, have had mixed outcomes. In the 1990's, two German-made TBMs were imported for use on a rail tunnel through the Qinling Mountains and experienced very challenging conditions. However, in 2010 two 10.2 m diameter Main Beam machines, manufactured by Robbins, were used on the West Qinling Rail Tunnels in phyllite and sandstone and set world records in the 10 to 11 m diameter range. The machines bored up to 235 m in one week and 841.8 m in one month.

With mixed case studies to draw on, limited core drillings on the Yin Han Ji Wei project were also conducted with moderately hard and abrasive quartzite and granite predicted (see Table 1).

Table 1. Limited core drillings were taken – summary of lithology of rock core drillings

rock type	Lithological characteristics	distribution	Length (m)
Quartzite	Quartz, feldspar, fine crystalline, massive structure	K27+93-K28+630	700
Granite	Plagioclase, potassium feldspar, quartz, biotite and hornblende, granular crystal structure, massive	K27+643-K27+930 K28+630-K42+380	14037
Diorite	Plagioclase, quartz, ordinary amphibole, biotite, medium-grained and coarse-grained	K42+380-K46+360	3980
Fractured rocks mylonites	Gray and white gray, the original rock is granite, diorite-based, with massive structure, the rock is more broken, broken material, structural surfaces are developed.	K35+450-K35+480 K45+180-K45+370	220

2 TBM SELECTION AND LAUNCH

When considering the task for the tunnel construction, the project Owner (Hanjiang-to-Weihe River Valley Water Diversion Project Construction Company) and the Contractor (China Railway Tunnel Group (CRTG)) agreed that a Main Beam TBM was necessary. Hard rock, high stresses and high water inflows were anticipated. The Owner and the Contractor together procured an 8.02 m diameter machine, manufactured by Robbins, in 2015.

2.1 *TBM Specifications*

The Main Beam TBM TBM was designed for hard rock, high stresses and high water inflows, with a predicted excavation progress rate of 480m/month (see Table 2 and Figure 3).

Table 2. TBM Specifications

Main Drive Power	3,300 kW
Main Bearing	4,340 mm i.d.; 5,210 mm o.d.
Maximum Torque	14,614 kNm
Maximum Thrust	21,087 kN
Cutterhead Speed	0 to 6.87 rev/min
Cutters	43 x 20-inch single cutters
	8 x 17-inch center cutters

Figure 3. Yin Han Ji Wei TBM

2.2 *Machine Launch*

The machine was assembled in an underground cavern at the end of a 3.9 km drill & blast adit on an 8.18% down gradient to the main tunnel alignment (see Figure 4). Once assembled the TBM was walked to the rock face in March 2015 and began its task. A continuous conveyor system supplied by Robbins as part of the TBM supply contract hauled muck from the advancing TBM to the surface. The machine bored the tunnel in two drives, the first measuring 9.88 km long, and the second measuring 7.63 km long. The remaining 765 m consists of drill & blast adits.

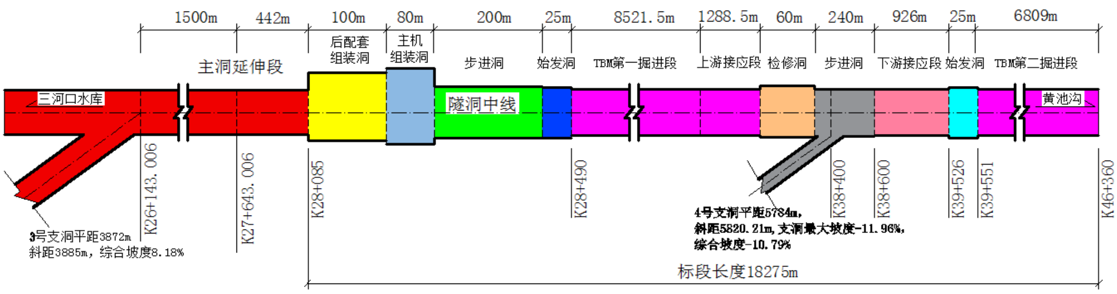

Figure 4. TBM was assembled in an underground cavern (yellow) at the end of a 3.9 km drill+blast adit. The TBM drives are between long, steep intermediate drill & blast adits. Figure Key:
1. TBM assembly chamber: 100m (yellow) + 80m + 200m (TBM walking area)
2. TBM first boring section: 25m (deep blue) + 8521.5m tunnel length
3. TBM maintenance and repair chamber: 60m (brown) +240m (TBM walking area)
4. TBM second boring section: 25m （light blue) + 6809m tunnel length

3 EXCAVATION: CHALLENGES & LESSONS LEARNED

From the start of the first drive, it was evident that the original excavation prediction for a progress rate of 480m/month would be too optimistic. The TBM operated well, but high cutter wear, high water inflows, incredibly hard and abrasive rock, and stoppages for installing support impacted boring progress.

3.1 *Ground Conditions*

As the drive progressed it became evident that the geological conditions had been underestimated by 50% or more. Unconfined compressive strengths on the drive ranged from 107MPa to 309MPa and averaged UCS 193.8Mpa. Abrasivity of granite rock ranged from 4.65 to 5.81 with an average abrasive index of 5.36 with quartz content ranging from 43.6% to 92.6%, and averaging 71.6% with an average integrality coefficient of 0.8.

In July 2018, Robbins invited an independent geological consultant to the jobsite. The consultant confirmed that from the mineral composite, rock of such rich quartz content should be better described as quartz granitoid. Granite normally has a quartz content of 25% to 30%. This quartz content at 60% to 90%, “is beyond that to be expected in granite, producing a very abrasive rock of high strength from the dominance of the bond between the abundant quartz crystals”, according to the report (see Figure 5).

Figure 5. Quartz granitoid core samples analyzed.

At Qinling, the TBM operating schedule was continuous, 7 days/week, 24 hours/day with a routine 4 hour/day TBM maintenance period. No one, however, could have predicted the conditions to be encountered. Due to the incredibly difficult rock, the crew spent much of their working time on ground support, changing cutters and repairing damage due to strong rock bursting and the hard abrasiveness of the rock. This resulted in a low TBM utilization rate of 20%.

To expedite the program, an up-gradient drill & blast heading started from the TBM destination adit, completing 1.2 km and reducing the TBM drive to 8.5 km and permitting a hard-won breakthrough into the in-line cavern in December 2018. After a much-needed overhaul, the TBM began it second down-gradient drive in March 2019 to progress under the highest overburden and through conditions that were anticipated to be more difficult than on the first (Wallis, 2021).

3.2 *Mitigating Wear*

In the strong, massive, high quartz content rock, thrust was high, TBM vibration was high, and cutter wear was exceptionally high. Changes were usually carried out during the 4-hour maintenance period per day but boring had to stop to repair damaged cutters. CRTG confirmed that cutter consumption was an extraordinary 0.7 cutters/m with cutter changes amounting to 15% of the total construction time.

There were 51 cutters on the 8.02 m diameter cutterhead and on the first TBM drive of 8.5 km from March 2015 to December 2018, total cutter consumption was 6,122. Of these 5,961 were single cutters and 161 were center cutters.

Cutters from Robbins, as well as from other suppliers and from a domestic manufacturer, were all tested on the TBM. Concerned also about overall progress in these extreme conditions, Robbins produced 20-inch extra heavy duty (XHD) discs as part of the efforts to test different cutters and establish the most effective design. According to a comparison test by the contractor, Robbins cutter life was longer and wear speed was significantly lower than other suppliers (see Table 3). As well as durability of the disc rings, other quality considerations were the disc seals, bearings, housing and locks for mounting on the cutterhead. The trade-off was that cutter quality had a direct impact on the thrust that could be applied for cutter penetration and on overall excavation advance (see Table 4).

Table 3. Comparison of the life of different cutters on the TBM

Cutter brand	Cutter position								Rock strength MPa
	#41	#42	#43	#44	#45	#46	#47	#48	
Domestic cutters	0.92	0.92	0.92	0.92	0.92	0.81	0.62	0.55	120 - 150
Imported cutter	0.67	0.80	0.83	0.73	0.73	0.67	0.50	0.50	130 - 140
Robbins cutters	0.54	0.62	0.75	0.56	0.54	0.5	0.5	0.45	180 - 200

Table 4. Optimized thrust, rotation and torque parameters

UCS MPa	Thrust in bar	Rotation rev/min	Torque kNm	Penetration mm/rotation
≥160	300 - 320	5 - 6	2,000 - 2,200	3 - 5
100 - 160	150 - 200	3 - 4	1,800 - 2,000	7 - 9
60 - 100	80 - 150	2 - 3	2,000 – 2,200	9 - 12

3.3 *High Ground Stresses & Rock Bursting*

According to the geological summary in the bid documents, high stresses and the potential for rock bursts were to be anticipated for 95.5% of the original two drives to a total 18.3km. Slight rock bursts were predicted in 545m of the alignment, moderate bursting for the majority 13,030m and strong bursting in a total of 3,880m. To prepare for these conditions, the TBM was equipped with the McNally support system. Applying the McNally system on time improves productivity and greatly increases safety of the workers and prevents rock fall damage to the machine. It is however unable to withstand heavy stress deformation and high energy rock bursting when extra support methods are needed.

Across the first 9.6km of the two drives, with the highest overburden of 2,000m, there 397 sections of rock burst activity across a total 4,808m or some 53.8% of the total excavated length. In the second drive, there were more than 18,045 rock bursts. Of the events, 5,444 were classified as strong with 1,736 recorded at an energy of more than 100 kilojoules. There were 88 bursts of more than 800 kilojoules with the highest energy rock burst reaching 4,080 kilojoules. A series of 739 rock bursts across a total of 1,864.6m long required stoppage of the machine boring to install additional support to stabilize the rock and lower the risk of injury to the workers and damage to the TBM.

Shotcrete with new fiber and nano materials was also introduced for application by the support shotcreting system located on the L1 backup gantry area on the TBM. Heavy jacks were also introduced to prop deformed ring beams and support steel arches. Rock bolts were installed quickly for 90° across the crown. In efforts to relieve high rock stresses, water was also sprayed to the bored surface and stress relief holes were drilled around a 120° arch in the crown.

In zones of medium to heavy rock bursting, progress slowed to about 90m/month due to the need for repairs and for installing extra support. Bursting at the face caused frequent damage to the cutters and the cutterhead while bursting in the crown and in the sidewalls damaged the gripper and thrust cylinders and other TBM mounted equipment.

On the second drive, rock bursting was active for 96.5% of the first 1,933m with heavy rock bursts occurring 23 times in the crown well after excavation passed through, and 11 times in the invert. The project was aware of the high risk of rock bursting and there was much advice for managing safety of the workers and installing support.

In efforts to predict rock bursting, a micro-seismic monitoring system was introduced. This system utilized a borehole 20m in front of the face to record rock stresses-- the potential for rock bursting could be predicted following comparative analysis with rock burst data from similar projects and with data from nearby sections in the Qinling South TBM drives. The accuracy rate of the rock burst prediction was said to be more than 70%; however, while the relative risk of a section could be predicted, the timing and severity could not be predicted (see Table 5).

Table 5. Prediction standard of rock bursts by micro-seismic monitoring

Seismic parameter rock burst level	**Fre-quency**	**Moment magni-tude**	**Energy 10,000 Joules**	**Standard event distribution range**	**Number over standard event time**
Slight	<10	<1.0	<3	>30m	0 - 3
Medium	10 - 30	1.0 - 2.5	3～10	20m - 30m	>3
Strong	30 - 60	2.5 - 3.5	10～80	10m - 20m	>8
Super	>60	>3.5	>80	<10m	>15

An in-situ concrete final lining was required in necessary sections of the TBM tunnel drives to meet a required 100+ year design life. In the 8.5km long TBM first drive, some 4.7 km is lined. In the second 3.8km long TBM drive, all 3.8km is concrete lined.

3.4 *Sudden and Extreme Water Ingress*

Sudden water ingress occurred on the project a total of 69 times, six of them extreme. The greatest water inflow occurred at the face on February 28, 2016 and exceeded 20,000m^3/day from one point. Total water flow into the down gradient heading exceeded 46,000m^3/day, flooding the lower TBM motors and the electrical cabinets on the lower deck of the backup gantries. In total the TBM was down for 75 days during the extreme flood event and many extra personnel were required (see Figures 6 and 7).


Figure 6 (left). Water ingress in the crown. Figure 7 (right). Crews working to drain the tunnel during the extreme flooding event in February 2016.

After the dramatic flooding event in 2016, the in-tunnel pumping capacity was increased to 41,000m^3/day. This was a 20% additional capacity and a new capacity 3.4 times greater than the maximum water ingress prediction in the original design documents.

Systematic probing was a constant in the TBM heading for predicting the potential of rock bursting ahead of the face as well as water ingress. When ingress exceeded 70% of the in-tunnel pumping capacity, TBM boring had to stop to carry out grout injections. The use of special grouting materials reduced water ingress along the entire length of tunnel to about 50,229 m^3/day.

3.5 *High Ground Temperature*

Through all the difficulties faced, work efforts by the TBM and tunnel excavation crews were under extreme environmental conditions. The temperature inside the tunnel reached as high as 36°C with more than 90% humidity. Temperature inside the cutterhead exceeded 50°C. To counter worker fatigue and low efficiency, the ventilation system was upgraded and a chilling system was added to the TBM ventilation system.

3.6 *Meeting of Experts, May 2016*

In May 2016, after the major flooding event of February 2016, the Contractor invited a panel of eminent experts to inspect the jobsite and attend a discussion meeting in Xi'an. These experts included major design institute engineers and university professors in China, as well as members of the Robbins field service team. Given the conditions observed during the visit and after studying onsite surveys and boring statistics, and without considering the major geological deviations from predicted to encountered, the panel of experts agreed that a reasonable monthly production advance rate expectation should be about 240m or less. This was half of the contract program rate of 480m/month. For the TBM boring distance to 8004.5m from March 2015 to September 2018, average progress was 186.2m/month.

After the experts meeting in May 2016, TBM boring reached the predicted 240m/month and even exceeded 300m/month repeatedly. June 2017 recorded the best boring month of 483.7m with the TBM breaking through at the end of the first TBM drive in December 2018. The TBM completed its second heading in early 2022.

4 CONCLUSIONS

Yin Han Ji Wei is an example of a long tunnel under high mountains, with little opportunity for economical and practical access to obtain accurate samples of the main rock formations to be encountered at the tunnel alignment. The difference in Class I and Class II granite, granitoid and quartzite are very subtle but have enormous influence on advance per day. Most geologists do not appreciate the net effect of these subtle differences when it comes to TBM daily advance. Even the most experienced geologist, with experience on how geology affects TBM performance, would have had difficulties in properly identifying what was inside this mountain. Underestimating the geological conditions to be encountered remains the greatest risk for long distance, deep level TBM headings; however, TBM technology is advancing at a rapid pace to meet even the most difficult of challenges.

5 REFERENCES

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