WATER TUNNEL IN LIAONING PROVINCE, NORTHEAST CHINA

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ABSTRACT

The Liaoning Dahuofang Reservoir Water Transfer Project is an important development for the Department of Water Resources of Liaoning Province in northeastern China. The 85.3 km water conduit will transport water from the Hun River downstream of the Huanren Reservoir to the outlet on the Suzi River leading to the Dahuofang Reservoir. The additional water is required to sustain the growing cities of Fushun, Shenyang, Liaoyang, Anshan, Panjin and Yingkou. The project is divided into seven contracts. Three TBM contracts comprise almost 75% of the work and the others are drill and shoot. The focus of this paper is about the creditable TBM performances achieved and some of the problems encountered by Chinese contractors; notably two having had no previous TBM experience.

REGIONAL DEVELOPMENT

Liaoning Dahuofang Reservoir Water Transfer Project is a gravity diversion scheme to transfer water from the Hunjiang catchment area in Huanren County, Liaoning Province through a tunnel to the Suzi River in Xinbin County. The additional water then flows in the Suzi River to the Dahuofang Reservoir from where it is regulated to provide water to six cities in the central area of Liaoning Province. The reservoir is in the heart of the grain producing area of Liaoning Province in addition to being close to a heavy industrial region which produces iron and steel, coal, petroleum derivatives, chemicals, electric power, machinery and building materials. The region has a developing economy and a dense population, but it lacks water resources. A 544m^3 per capita of water resource availability and a utilization ratio of 81.9% makes the area one of the most severely lacking in water resources nationwide. In addition, the water quality of Hunhe, Taizi and Daliaohe rivers is seriously polluted, the ecological environment is deteriorating and other problems such as land subsidence are occurring as the result of lowering of the water table due to widespread pumping of underground water. This project came to fruition to strengthen the local economy by providing additional water for industry, agriculture and urban development. The adopted solution was to transfer water from the mountainous area in the upper reaches of the Hunjiang River, which is sparsely populated and enjoys a per capita water resource availability of 4187m^3 and a utilization ratio of only 9.39%. Figure 1 shows the location of the project.

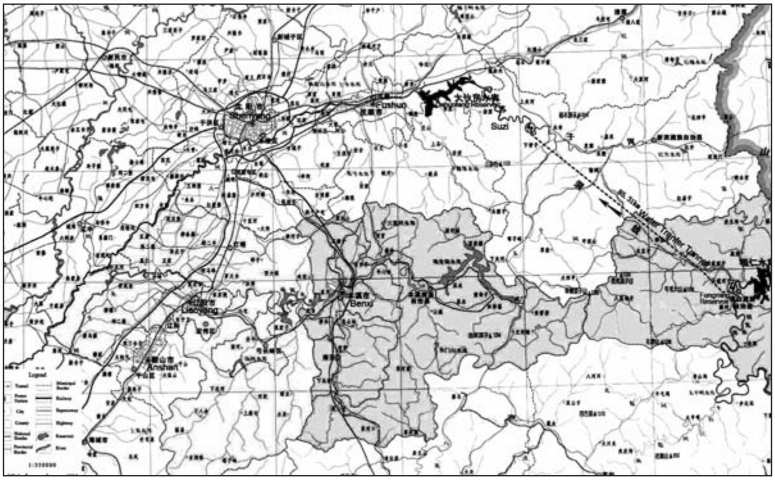

Figure 1. Location of the project. North Korean border, upper right; Shenyang, upper left.

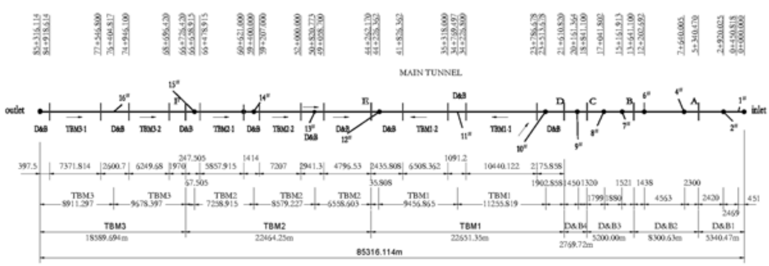

Figure 2. Schematic layout of Dahuofang water diversion project

PROJECT OVERVIEW

The project comprises an intake structure, the main diversion tunnel, an outfall and a dissipating structure. The total tunnel length is 85.31km, with an excavated diameter of 8m. The designed open channel flow within the tunnel is 70m^3/s, with allowance for a peak of 77m^3/s. The gradient is 1:2380. The tunnel construction was divided into seven contracts, three utilizing TBM excavation and the remaining four being drill + shoot methodology. In addition to the inlet and outlet portals, there are 14 intermediate adits used for construction access. A schematic arrangement of the tunnel and adits is shown in Figure 2. A summary of the contract limits and the contractors is shown in Table 1.

The access adits are of varying lengths and gradients. In the TBM sections, the adits are used to move the operation forward as the excavation progresses, to reduce the distance for muck removal and the travel time for people and materials to and from the face. The steeper adits are serviced by a rail haulage way with motive power provided by a surface winch. Table 2 summarizes the adit dimensions. The adits with larger cross sections have been designed to accommodate the installation and removal of the TBMs.

Table 1. Summary of contract limits and contractors

Contract	Contract Limits (stations)		Total Length	% of Total	Contractor
	Start	Finish			
D&B1	0 + 000.0	5 + 340.5	5,340.5	6.3	China Railway 13th Bureau Co. Ltd
D&B2	5 + 340.5	13 + 641.1	8,300.6	9.7	China Railway 13th Bureau Co. Ltd
D&B3	13 + 641.1	18 + 841.1	5,200.0	6.1	Sino Hydro Engineering Bureau 6th
D&B4	18 + 841.1	21 + 610.8	2,769.7	3.2	Liaoning Water Conservancy Bureau (LWCB)
TBM1	21 + 610.8	44 + 262.2	22,651.4	26.6	Beijing Vibroflotation Engineering Co. (BVEC)
TBM2	44 + 262.2	66 + 726.4	22,464.2	26.3	China Railway Tunnel Group (CRTG)
TBM3	66 + 726.4	85 + 316.1	18,589.7	21.8	Liaoning Water Conservancy Bureau (LWCB)
Total (m)			85,316.1		

Table 2. Adit dimensions

Adit No.	Length (m)	Decline %	Dimensions (m)
1	277.9	4.5	5 × 5
2	796.2	14.0	5 × 5
4	843.0	46.6	5 × 5
6	377.1	24.9	5 × 5
7	519.1	20.8	5 × 5
8	925.6	12.0	5 × 5
9	1,408.7	8.0	5 × 5
10	1,573.7	10.0	6.6 × 6
11	1,004.7	21.5	5 × 5
12	2,606.7	12.0	6.6 × 6
13	1,371.3	16.9	5 × 5
14	1,283.2	11.6	5 × 5
15	1,776.2	9.0	6.6 × 6
16	642.4	10.7	6 × 6.6

The agency responsible for the project is the Department of Water Resources of Liaoning Province. The construction management is undertaken by the Liaoning Runzhong Water Supply Company Limited. The Water Supply Company is an "arm's length" subsidiary of the Department of Water Resources. The Department, a Government Agency, is prevented by law from managing construction work. The design is performed by the Design and Research Institute of Water Resources and Hydropower Group of the Water Conservancy Ministry of China for Liaoning Province. The Department of Water Resources is based in Shenyang. The main construction office for the Water Supply Company is in Huanren which is close to the intake, with a subsidiary office at Yongling towards the outlet.

This is an ambitious project, even by world standards. TBMs are not new in China, but the related management skills and construction workforce proficiencies are still developing. Construction started in September 2002 and project completion was originally scheduled for December 2008. Overall progress has been less than scheduled

Table 3. Rock classifications in tunnel

Rock Class	Rock Characteristics	Rock Mass Index T	Stress Ratio S	Type of Support
II	Basically stable. Rock is integrally stable, without plastic deformation. Blocks may fall locally	85≥T>65	>4	Random rock anchors or thin layer of shotcrete. For large span, pattern rock anchors with mesh reinforced shotcrete
IIIa	Rock is integrally stable, generally without plastic deformation. Local stability is poor with blocks falling and walls caving	65≥T>55	>2	Pattern rock anchors. Mesh reinforced shotcrete, minimal thickness
IIIb	Poor local stability with the likelihood of plastic deformation. Rock falls may occur without support although softer rock without discontinuities may have a limited stand up time	55≥T>45	>2	Pattern rock anchors. Mesh reinforced shotcrete, increased thickness. For 20–25m spans, place concrete lining
IV	Unstable. Very short stand up time. Large scale deformations and failures will occur without support	45≥T>25	>2	Initial support: Pattern rock anchors and mesh reinforced shotcrete. Permanent support: Concrete lining
V	Extremely unstable. Rock will not stand unsupported and deformations will occur	T≤25		

and although mitigating measures have been adopted, the currently projected completion date is April 2009. The final cost of the project is expected to be approximately RMB 5 billion ($654 million).

A follow on project (Stage 2) is in the planning stage. This work will consist of a network of pipelines and distribution structures to convey water from the Dahuofang Reservoir to the aforementioned cities and surrounding districts. There will be a total of 260km of spirally prestressed concrete pipes ranging in diameter from 3.2m to 1.4m.

DESIGN OVERVIEW

The tunnel route is located in an area of low mountains, passing under about 50 peaks, the maximum height being 885m, although most are within the 500–650m range. The depth of cover varies between 52m and 600m; 8% is less than 100m; 55% is between 100m and 300m; and the remaining 37% is in excess of 300m. The tunnel route passes through Archean, Proterozoic and Mesozoic strata, the rock being mostly medium hard to slightly weathered. A total of 29 faults have been identified along the tunnel alignment, of which 5 are considered to have an influence on the design.

The classification of rock is based on the method used in the *Code for Geological Survey in Water Resources and Hydropower Project Ref: GB50287-99.* The Rock Mass Index "T" is derived from (1) the uniaxial saturated compressive strength, (2) the seismic velocity coefficient, (3) the condition and spacing of the joints, (4) the water inflow and (5) the strike of the main joint. Table 3 identifies the rock classifications that apply to the tunnel.

Table 4. Distribution of rock types and classifications

Station	Length of tunnel (m)	Length of various classes of rock sections (m)					Stratum Code	Rock Description
		II	IIIa	IIIb	IV	V		
0+000–1+060	1,060		520	250	260	30	K_1l	Volcanic breccia, tuff
1+060–2+050	990			830	140	20	Mr_2^1 / Pt_1gx	Compound granite, marble
2+050–12+420	10,370	5,270	2,930	1,770	360	40	Qny	Quartz sandstone
12+420–20+320	7,900	1,210	700	2,100	3,490	400	Pt_1d/ Pt_1gx	Marble, granulite
20+320–30+045	9,725	3,345	1,090	4,880	380	30	$\xi\pi_5^{3(1)}$	Syenite
30+045–32+855	2,810		2,800			10	Mr_1	Compound granite
32+855–42+560	9,705	6,020	2,145	1,320	200	20	M_1	Migmatite
42+560–49+040	6,480		3,565	2,715	185	15	K_1xl/ J_3x	Brecciated lava, andesite, tuff
49+040–66+760	17,720	8,700	3,260	4,330	1,320	110	M_1	Migmatite
66+760–69+330	2,570			2,040	520	10	K_1xl	Tuff
69+330–75+450	6,120	1,800	990	2,970	340	20	M_1	Migmatite
75+450–85+315	9,866		1,950	6,653	1,243	20	K_1xl	Brecciated lava, andesite, tuff

The distribution of rock types and classifications along the tunnel alignment is summarized in Table 4.

Figure 3 illustrates the initial and final ground support specified for the various rock classifications. It may be noted that the minimum support required is random rockbolts and 80mm shotcrete lining. Also, as a minimum, a concrete invert is maintained throughout the entire length of the tunnel. The requirement for a full circle shotcrete lining in the most competent rock is a departure from the practice in other countries, at least in North America. Furthermore, the shotcrete is placed immediately behind the TBMs during the course of excavation. In North America there are many miles of water tunnels under pressure, and more specifically open flow, in unlined competent rock that have provided years of satisfactory service. A second observation is that all the rockbolts are identical—22mm dia. $\times$ 2m long, for all ground classifications. They are more accurately described as untensioned rock dowels. The rock dowels are installed with cement grout capsules which require one day to set up and acquire a working strength. The outer ends are pre-bent to a "J" configuration. There is no anchor plate or nut. A final point of note is the size of the I-16 steel ring beams. This is a slender section of $160 \times 88 \times 20.5$kg/m with a section modulus of 141cm^3. In North America, an appropriate steel section for this diameter of tunnel would be a W6 $\times$ 25 wide flange ($150 \times 150 \times 37.2$kg/m) which has a modulus of 274cm^3.

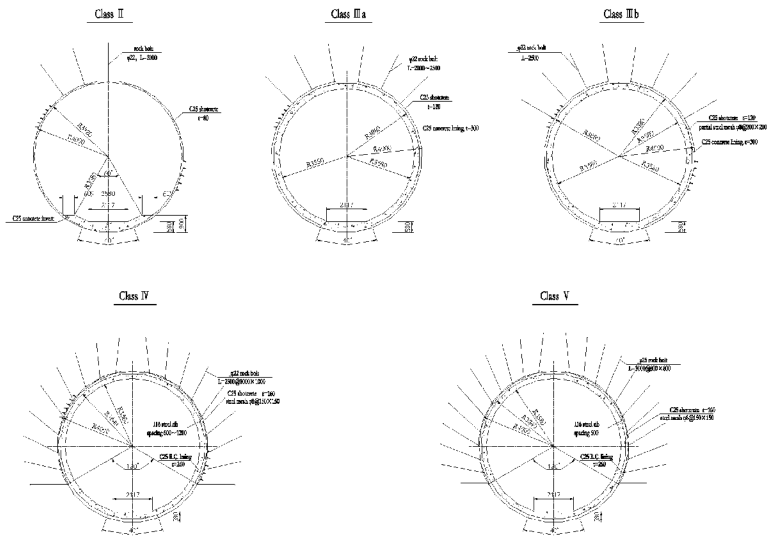

Figure 3. Structure of initial support and lining in TBM

TBM PROCUREMENT AND SPECIFICATIONS

Three TBMs were furnished for three separate contracts on this project. Two machines were designed and furnished by The Robbins Company of Solon, Ohio, USA and the third was supplied by The Wirth Company of Erkelenz in Germany. The Robbins machines and back up were manufactured in Dalian, Liaoning Province. The Wirth machine was remanufactured in Erkelenz. The back up was designed by Rowa of Wengen in Germany and fabricated and assembled in China with components supplied from Europe. This machine was originally built in 1992 for the 12 km T4 section of the Vereina tunnel in Switzerland.

The Robbins machines are identical. They were manufactured by Dalian Huarui Heavy Industry International Co. Ltd., (DHI). DHI did not have previous experience with TBMs, but they were a logical choice as a manufacturer of heavy equipment such as steel mill machinery, coal mining equipment, and heavy bridge and gantry cranes. Other factors included the encouragement by the Water District to use a Liaoning based facility for manufacture and the availability of good transportation to the project site. Robbins provided significant supervision at DHI. The senior shop manager and two shop technicians from Robbins USA were seconded to Dalian for the entire duration of manufacture. Their function was to provide quality assurance and to monitor the schedule. Four engineers and eight mechanics from Robbins China worked at DHI for the entire duration. During final assembly and commissioning, a hydraulics technician, an electrician and two field service supervisors provided expertise. In addition, Robbins USA engineers and the project manager provided support as required.

A comparison of the basic TBM specifications is summarized in Table 5.

Table 5. TBM specifications

Description	Unit	Robbins	Wirth
Machine Diameter (nominal)	m	8	8
Number of Cutters	no.	51	59
Diameter of Cutters	in.	19	17
Maximum individual cutter load	kN	311	240
Cutterhead Operating Thrust	kN	17,105	16,500
Maximum Operating Thrust	kN	22,934	21,000
Maximum Hydraulic Pressure	bar	345	325
Number of Drive Motors	no.	10	12
Power/Drive Motor	kW	300	280
Total Cutterhead Power	kW	3,000	3,360
Cutterhead Speed (constant torque)	RPM	0–4.63	0–7.4
Cutterhead Speed (constant power)	RPM	4.63–6.93	
Number of Thrust Cylinders	no.	4	8
Stroke	m	1.83	1.8
Primary Voltage	V	10,000	10,000
Secondary Voltage	V	690/380	690/380
Conveyor Capacity	m^3/hr	1,110	780

TBM CONTRACTS

Summary of the Work

The schematic layout in Figure 2 provides an indication of the limits of the three TBM contracts. Each TBM contractor is responsible for a defined length of the main tunnel, which in addition to the TBM excavation, includes construction of the access adits, underground work areas and surface maintenance facilities including shops, warehouse, office and camp. Each contract spans at least 2 adits and in the case of TBM2, the contract extends to 3 adits. The adit spacing is typically 10km or less. This distance is considered the optimal maximum for an efficient tunnel operation. As each TBM holes through to the next adit, the entire operation is jumped forward, leaving the completed reach available to complete the permanent lining. A noteworthy feature common to all the TBM contracts is the muck removal by continuous conveyor. The reaches as shown on the schematic have not necessarily been excavated by TBM. In fact for reasons discussed later, excavation of a significant length of tunnel has been substituted by drill + shoot methods. Another noteworthy feature is the sophistication of the chambers at the foot of Adits 10 and 15 that are equipped with overhead bridge cranes for underground assembly of the TBMs. These cranes continue to be used for materials handling during the tunnel operations. See Figure 4.

TBM1 Contract encompasses 22,651m of tunnel. BVEC is the contractor. The contract calls for two reaches to be excavated by TBM—11,256m and 9,456m. The work started at Adit 10 with the mining progressing downhill. Adit 11 is the intermediate adit and the machine is due to be removed through Adit 12.

TBM2 Contract encompasses 22,464m of tunnel. There are three reaches—5,982m, 8,579m and 6,559m. Contractor CRTG started at Adit 15, mining uphill. The

Figure 4. Adit 10 TBM assembly and materials handling chamber

intermediate adits are Adit 14 and Adit 13 with a planned TBM recovery at Adit 12 at the end of Reach 3.

TBM3 Contract starts at the outlet portal, without the need for an access adit. LWCB is the contractor. The contract calls for two reaches of 8,911m and 9,678m for a total of 18,589m. The intermediate adit is Adit 16 and the mining continues uphill towards Adit 15 where the machine will be recovered.

Equipment

This section discusses the differences in approach relating to the equipment used by the TBM contractors.

TBM1 Contractor BVEC uses a Robbins TBM with Robbins backup. The tunnel and adit conveyors are Robbins supplied. The tunnel conveyor has an advancing tail-piece mounted on the backup with the storage magazine located at the foot of the adit. The Chinese made conveyor belt is steel cored. The uphill (loaded) conveyor requires a 600kW (2 × 300kW) main drive at the head drum and 3 intermediate 600kW booster drives in the tunnel. The conveyor capacity is 800t/hr, equivalent to 5.85m of TBM advance. All the contractors have become proficient at splicing the belt using their own forces. A typical belt splicing time including curing is about 15 hours. The adit conveyor is 1,629m long with one 600kW drive unit. The adit gradient is 10%. Outside the adit there is a muck discharge station that loads directly into trucks, without any surge pile except for an emergency. For most of the time, the trucks are able to keep up with the TBM progress. Relatively small battery electric locomotives (8–10t) are used to service the tunnel. The battery charging station is located underground in the back drive at Adit 10. Shotcrete is batched underground and transported to the backup in open top cars with spiral agitator paddles. The shotcrete pump and robot system on the backup is of Meyco supply. The Robbins backup straddles the mainline track and runs on jump rails. The shotcrete cars have to be hoisted from the mainline for discharge into the shotcrete pump on one side of the backup. BVEC has a cutter maintenance contract with Robbins. This work is done at a shop off site at Muqi which also services TBM3.

TBM2 Contractor CRTG utilizes a Wirth TBM with a Rowa backup. The tunnel and adit conveyors are supplied by REI of France. The conveyor capacity is 750t/hr with 900mm belt width. The tunnel conveyor has a single 800kW drive (4 × 200kW). The

Figure 5. TBM3 at downstream portal

storage magazine has 600m capacity. The muck discharge station at Adit 15 is similar in concept to TBM1. The tunnel locomotives are Schöma diesels, approximately 18t. Shotcrete is batched at a surface plant into frame mounted diesel powered Moran-type drum carriers which are trucked down the adit and transferred to rail cars. The Rowa backup has a raised deck onto which the shotcrete cars can be driven for direct discharge into a Sika pump and robot system. CRTG has a cutter repair shop on site and uses its own workforce to maintain cutters.

TBM3 Contractor LWCB has a Robbins TBM and backup that is identical to TBM1. There is no adit at the outlet portal. Robbins supplied the 693m long transfer conveyor linked to the discharge conveyor supplied by the contractor that runs along the embankment of the Suzi River. The conveyor discharges to a stockpile. The tunnel conveyor has a single 900kW (3×300kW) head drive and a 600m storage magazine. The service locomotives are battery electric and although small, have proven to be adequate for the task over the full distance of Reach 1. Battery charging is done within a building at the portal site. Shotcrete is made at a plant at the portal site and transported to the back up in open top rail cars of the same design as used in TBM1. LWCB has a cutter maintenance contract with Robbins. Figure 5 shows TBM3 assembled at the portal.

Commentary

It should be noted that two of the contractors, BVEC and LWCB, had little or no previous experience with TBM operation, although CTRG has worked on a number of TBM contracts before. Certain key people with TBM experience were hired by BVEC and LWCB for this project. The principal author of this paper was initially engaged to offer construction advice about the tunnel operations. On subsequent visits the improvements to the work practice became increasingly evident. In some instances, personnel changes were made to strengthen the expertise within management. Contractors in China are experienced and proficient in conventional drill + shoot tunneling and produce very high quality work. The transition to TBM tunneling is an evolving procedure, as in any country. To the outside observer, however certain work practices seem arduous, although in China they are commonplace. For example, there is nothing unusual about a 24-hour 7-day work schedule in tunneling. What is unusual is that the workforce, living in camp, has no regular schedule for time off. Employees who need time to travel and visit their family will make individual arrangements with their foreman and their absence is covered by other people on the crew. If there is any downtime on the machine, scheduled or unscheduled, the employees who are not required for the repair work will take time off until production resumes. Typically there are two production shifts and an overlapping maintenance shift. Another practice which seems arduous to the outside observer is that in order to provide more rest time for the employees there are three crews to cover the two production shifts. The crews rotate so that after coming off shift they are not due back to work until two shifts later, resulting in a constant dayshift/nightshift regime.

One of the problems that hampered early production was crews' lack of understanding about the need for containment of bad ground, particularly in the case of TBM3. Main beam machines do not perform well in broken ground and special precautions need to be taken. The philosophy early on was to allow the ground to collapse and take remedial action later, causing endless problems. The importance of standing the ring steel square to the tunnel axis, expanding the rings, providing longitudinal restraint and blocking the rock was emphasized. In fairness to the tunnel crews, certain factors contributing to these problems should be noted. The slender ring beams with narrow flanges make ground support very difficult. The J-type rock dowels without nuts or anchor plates and a cement grout that takes 24 hours to gain strength could not be used to provide immediate anchor for steel strapping or steel wire mesh. The ring beam erectors needed modification and access platforms had to be added to the machines. A mishap occurred on TBM3 when the sidewall broke away allowing the grippers to over-extend causing the bolts to shear at the spherical connection to the gripper shoe. This type of failure is not uncommon on main beam machines, and serves to illustrate importance of understanding the limitations TBMs and anticipating problems which only develops with experience. As time progressed, the crews gained experience and confidence in overcoming day-to-day problems.

Progress

Considering the remoteness of the region, inexperienced work crews and that two of the three contractors had virtually no previous TBM experience, the project schedule is ambitious. The projected rate of progress for TBM1 was 697m per month. Assuming an effective working year of 350 days, this represents an average of 23.9m per day. There are a number of factors contributing to the deteriorating schedule. The Robbins machines were late in being delivered. There were reasons for this which included quality control problems at DHI and some contractual issues between the companies that had to be resolved during the course of manufacture. It is perhaps worth mentioning that Liaoning Province now has a facility that is trained for the production of future TBMs, of which there will be many in China. The Wirth machine, although delivered on schedule, has not been trouble free. Early on in the first reach it was discovered that there were main bearing problems. As a result, the rate progress was limited by reduced thrust, until the machine reached Adit 14 where the bearing was changed. The down time for refurbishment at Adit 14 was more than 3 months, considerably longer than scheduled. Adding to these delays, the contractors have been unable to achieve the projected rates of progress. Figure 6 illustrates the monthly progress records of all the TBMs. There have been some impressive performances. Both TBM1 and TBM3 have progress records in excess of 1km in one month. The best month's performance for TBM2 has been 732m. The total excavation distances, measured at the end of December 2006, were TBM1—10,438m; TBM2—10,133; TBM3—7,624m. It

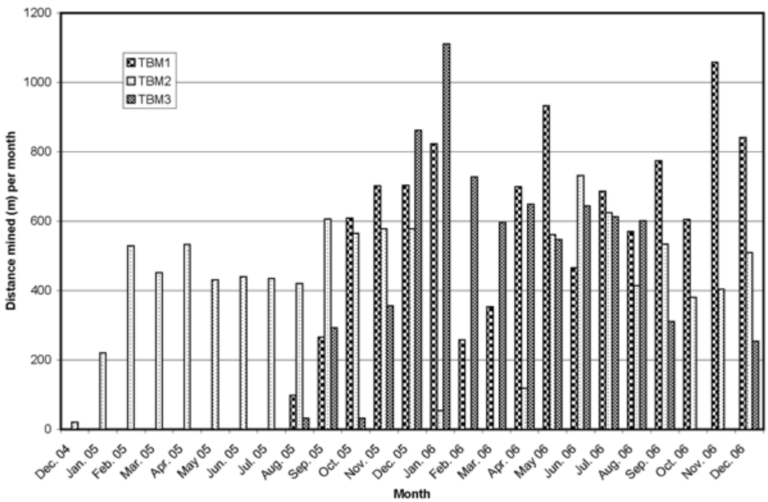

Figure 6. Comparison of TBM progress

is worth noting that in November 2006, when TBM1 achieved 1,058m, the daily utilization was in the order of 16 hours.

The measures adopted to recover the project schedule have been to substitute sections of tunnel originally planned to be excavated with TBMs for drill + shoot methods. This procedure although slower, allows concurrent working to make up time. For example, when Adit 16 was developed to receive TBM3, some 2,600m of main tunnel had been excavated before the TBM holed through. Additionally, the entire 6.5km long Reach 3 for TBM2 will now be excavated by drill + shoot methods. There may be an added benefit to this approach because Reach 3 has some of the worst ground in the TBM2 Contract. The TBM contractors are responsible for 74% of the tunnel length. The projected amount to be excavated by TBM was 72%. With the remedial recovery measures in place, this amount will be reduced to less than 60%.

CONVENTIONAL TUNNELING

As originally designed, excavation by drill + shoot methods was confined to the upstream section (approximately 25%) of the tunnel. The reason for this decision was because the more difficult geological conditions in this area are less suitable for TBM excavation. For reasons already discussed, the total length has increased for this type of construction. Local contractors are proficient at this work using simple equipment. The quality of the product, particularly the concrete lining is excellent. This section of the work is divided into four contracts and is accessed from seven adits. Some of the work is challenging, having encountered significant water inflows that required grouting.

The face is drilled from a gantry platform with decks using jack legs; see Figure 7. In Class II ground the round length is about 3.5m. In Class IV and V ground the round length is reduced to 1.5m. The muck is loaded with side dump loaders into trucks where there is rubber tired access. The steeper adits have a winch haulage system and rail equipment. At Adit 6 there is a storage bin for the muck at the bottom of the decline. For headings with truck access the cycle time is approximately 18 hours and about 25 hours where there is winch access.

Figure 7. Drill + shoot platform jumbo

Concrete is typically placed in forms 12m long. The lining contains bar reinforcement and the construction joints have water stop. Concrete is pumped through the form. The finished walls are typically very high quality and the need for concrete repairs or patching is rare.

CONCLUSION

This is an important development for northeast China. The contractors and management have stepped forward from an established conventional tunnel industry to newer methods, using a mainly local workforce and adjusting to the challenges without the need for foreign joint venture partners.

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