7.93 m Open TBM Shotcrete System Improvement and Innovation Jilin Project, China

Desiree Willis ▪ The Robbins Company
Ya Jun Guo ▪ The Robbins Company

ABSTRACT

In May 2018, a 7.93 m diameter open gripper (Main Beam) TBM completed the 24.3 km long Jilin Lot 3 tunnel under a maximum overburden of 272.9 m. The tunneling operation for the water transfer project, located in northeastern China, achieved a national record of 1,423.5 m in one month despite challenging conditions.

This paper will present an improved, innovative shotcrete system for TBM preliminary lining, developed through experience on previous projects. The shotcrete system, along with other structural design elements and a properly developed ground support program, allowed the TBM to bore successfully in variable hard rock and fault zones.

The paper will discuss how the shotcrete system and structural design increased safety and improved performance in a cost-effective manner. It will seek to define the variables that allowed the TBM to advance at rapid rates and will make recommendations for future types of projects that could benefit from the shotcrete system.

INTRODUCTION

The Jilin Yinsong Water Supply Project located in China's Jilin Province is a 736.3 km (457.5 mi) network, making it China's largest scale water diversion project to date. Once operational the water lines will divert the water from Fengman Reservoir at the upper reaches of Di'er Songhua River to central regions of Jilin Province experiencing chronic water shortages. These regions include the cities of Changchun and Siping, eight surrounding counties, and 26 villages and towns under their jurisdiction. The project will optimize water resource distribution, improve regional eco-systems, and ensure better food production and water safety for the people of Jilin Province.

About 134 km of the water supply network is underground. Three open-type TBMs were selected by the owner, Jilin Province Water Investment Group Co., Ltd., to bore about 62 km of tunnel in total (20–21 km boring per TBM contract with adits). The remainder of the underground work was excavated using conventional drill & blast techniques. Robbins supplied one 7.93 m diameter open-type (Main Beam) TBM for Lot 3 of the Jilin tunnel, and the other two TBMs were provided by Chinese suppliers. All three machines were designed to use continuous conveyor systems for muck removal.

The geotechnical baseline report showed that the rock consisted of tuff, granite and andesite with UCS up to 228 MPa and a maximum quartz content of about 43%. More than 80% of rock was predicted as class II & III, with maximum cover of 272.9 m (see Figure 1). Possible squeezing ground was also predicted given the relatively weak rock mass, as well as a total of 24 fault zones. Because of the geology an open-type TBM was selected to give the most flexibility in the expected conditions.

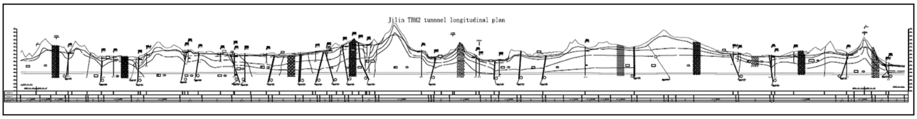

Figure 1. Jilin Lot 3 tunnel profile

Figure 2. Jilin TBM at factory acceptance

Figure 3. Rear view showing McNally pockets

TBM DESIGN

The Main Beam TBM was built in Shanghai, China, and designed for flexibility in terms of ground support. Pockets in the machine's roof shield were provided in order to use the McNally Roof Support System, designed and patented by C&M McNally. By replacing the roof shield fingers on a Main Beam TBM, the McNally system prevents rock movement in the critical area immediately behind the cutterhead support. The system has been tested and proven on projects worldwide—including the world's second deepest civil works tunnel, the 2,000 m deep Olmos Trans-Andean Tunnel in Peru—to increase advance rates while still maintaining worker safety on Main Beam machines in difficult rock conditions (see Figures 2 and 3). The cutterhead was mounted with 20-inch disc cutters, and designed with a maximum cutterhead thrust of 15,880 kN, as well as maximum torque of 9,743 kNm.

ENCOUNTERED GEOLOGY & GROUND SUPPORT

The project started in December 2013, with the first fault zone encountered after just 87 m of boring, requiring cooperation between the owner, contractor Beijing Vibroflotation Engineering Co. Ltd. (BVEC), and Robbins field service. Water inflows and collapsing ground in a section measuring 1,196 m long were resolved with a combination of McNally slats, grouting, and consolidation of the ground ahead of the machine.

Tunnel Reflection Tomography (TRT)—a method of ground prediction using seismic waves—was also used to detect changing conditions ahead of the TBM and was used largely in place of probe drilling. The TRT technique is based on the interface when a seismic wave encounters an acoustic impedance. Partial signals reflect back, while the rest passes through the medium. The change of acoustic impedance is typically observed in the interface between geologic formations or in a fractured rock mass. The reflected seismic signals are received by a highly sensitive seismic signal sensor, and the reflection coefficient is positive when the shock wave propagates from a low impedance material to a high impedance material. The opposite is true when propagating from high to low impedance--the reflection coefficient is negative. When the local seismic wave propagates from soft rock to hard surrounding rock, the deflection polarity and wave source echo are consistent. The signals can detect a number of features, such as a fracture zone inside the rock through a reversal in the echo of polarity. Analysis of the changes helps to characterize ground features including loose rock, broken rock, fault zones, and water, and the location and scale of each feature in front of the tunnel face.

In actuality the ground encountered was more difficult than thought (see Table 1). The ground support scheme was decided as follows:

Type II class ground support parameters: install rock bolt Φ 22, L = 2000.

Type IIIa class ground support parameters: install rock bolt Φ 22, L = 2500. Rock bolt position set local hang Φ 8 @ 200 * 200 wire mesh reinforcement, top injection C20 concrete at ring beam 320° range system, 10 cm thick.

Type IIIb class ground support parameters: install rock bolt Φ 22, L = 2500, 1200 * 1200, bolt spacing hang Φ 8 @ 200 * 200 wire mesh, top injection C20 concrete at ring beam 320° range system, 10 cm thick.

Type IVa class ground support parameters: ring beam adopts 16 I shape steel support, with space width of 1.8 meters, install rock bolt Φ 22, L = 2500, 900 * 1200, bolt spacing set Φ 8 @ 150 * 150 steel fabric hanging, top injection C20 concrete at ring beam 320° range system, thickness of 16 cm.

Type IVb class ground support parameters: ring beam adopts 16 I shape steel support, spacing width of 0.9 meters, install rock bolt Φ 22, L = 2500, 900 * 1200, bolt spacing set Φ 8 @ 150 * 150 wire mesh, top injection C20 concrete at ring beam 320° range system, thickness of 16 cm.

Type IVc class ground support parameters: ring beam adopts 16 I shape steel support, spacing width of 0.45 meters, install rock bolt Φ, 25 L = 3000, 900 * 900, bolt spacing set Φ 8 @ 150 * 150 wire mesh, top injection C20 concrete at ring beam 320° range system, thickness of 16 cm.

Type V class ground support parameters: ring beam adopts 16 I shape steel support, spacing width of 0.45 meters, install rock bolt Φ, 25 L = 3000, 900 * 900, bolt spacing set Φ 8 @ 150 * 150 wire mesh, top injection C20 concrete at ring beam 320° range system, thickness of 16 cm.

SHOTCRETE APPLICATION

In the 1st section of tunnel with length of 9840.187 m, there was a section of 1196 meters of tunnel in poor ground conditions. McNally ground support slats were applied in the middle of this poor section. Also in the 1st section, wire mesh was applied for 5014.87 meters and shotcrete was applied for 9155.187 meters, making shotcrete a primary means of ground support.

Shotcrete was applied at the following two zones on the TBM:

- L1 Zone
- L2 Zone

Initial support was applied at the L1 zone just behind the cutterhead support of the TBM. Te system is a manual spray system including a manual spray nozzle and piping bypass from the L2 zone. Platforms in the L1 zone give 360-degree circumferential

Table 1. Geological report of encountered rock

Chainage		Length	Rock Type	Rock Class	UCS	Quartz	Cover(m)	
26011	26402	391	Tuff	III	153.5		21	104
26402	26892	490	Tuff	IV~V	89.3		21	104
26892	27637	745	Tuff	III	89.3		21	104
27637	27987	350	Tuff, Granite	IV~V	89.3		21	104
27987	28982	995	Tuff, Granite	III	172–188		21	104
28982	29582	600	Tuff, Granite	IV~V	172–188		21	104
29582	30402	820	Tuff, Granite	III	172–188		21	104
30402	30940	538	Tuff, Granite	IV~V	172–188		21	104
30940	31415	475	Tuff, Granite	III	172–188		21	104
31415	31515	100	Tuff, Granite	IV~V	172–188		21	104
31515	32165	650	Tuff, Granite	III	172–188		21	104
32165	32365	200	Tuff, Granite	IV~V	172–188		21	104
32365	32760	395	Tuff, Granite	III	172–188		21	104
32760	32830	70	Tuff, Granite	IV~V	172–188		21	104
32830	33100	270	Tuff, Granite	III	172–188		21	104
33100	33150	50	Tuff, Granite	IV~V	172–188		104	154
33150	33515	365	Tuff, Granite	III	172–188		104	154
33515	33615	100	Tuff, Granite	IV~V	172–188		104	154
33615	34000	385	Tuff, Granite	III	172–188		104	154
34000	34350	350	Tuff, Granite	IV~V	172–188		104	154
34350	34450	100	Granite	III	186–236	37%	88	154
34450	35810	1360	Granite	II	186–236	37%	88	154
35810	35880	70	Granite	III	186–236	37%	88	154
35880	35960	80	Granite	IV~V	186–236	37%	88	154
35960	36163	203	Granite	III	186–236	37%	88	154
36523	37240	717	Granite	II	186–236	37%	69	88
37240	37540	300	Granite	III	186–236	37%	69	88
37540	37740	200	Tuff, Granite	IV~V	43–64	37%	69	88
37740	38255	515	Tuff	III	43–64		69	91
38255	38355	100	Tuff	IV~V	43–64		69	91
38355	38950	595	Tuff	III	43–64		69	91
38950	39030	80	Tuff, Andesite	IV~V	108–157	43%	69	91
39030	39530	500	Andesite	III	108–157	43%	69	91
39530	40030	500	Andesite	II	108–157	43%	69	91
40030	40490	460	Andesite	III	108–157	43%	69	91
40490	40820	330	Andesite	II	108–157	43%	69	91
40820	41400	580	Andesite	III	108–157	43%	69	91
41400	41550	150	Andesite	IV~V	108–157	43%	69	91
41550	42290	740	Andesite	III	108–157	43%	69	91
42290	42410	120	Andesite	IV~V	108–157	43%	69	91
42410	42610	200	Andesite	III	108–157	43%	69	91
42610	43110	500	Andesite	II	108–157	43%	69	91
43110	44270	1160	Andesite	III	108–157	43%	69	91
44270	44345	75	Andesite, Granite	IV~V	108–157	43%	69	91
44345	45200	855	Granite	III	108–157	43%	69	91
45200	45300	100	Granite, Tuff	IV~V	108–157	43%	69	91
45300	46700	1400	Tuff	III	90–277		69	91
46700	47010	310	Quartz Diorite	III	79–83		37	91
47010	47360	350	Quartz Diorite	IV~V	79–83		37	91
47360	47510	150	Quartz Diorite	III	79–83		37	91
47510	47519	9	Quartz Diorite	II	79–83		37	91

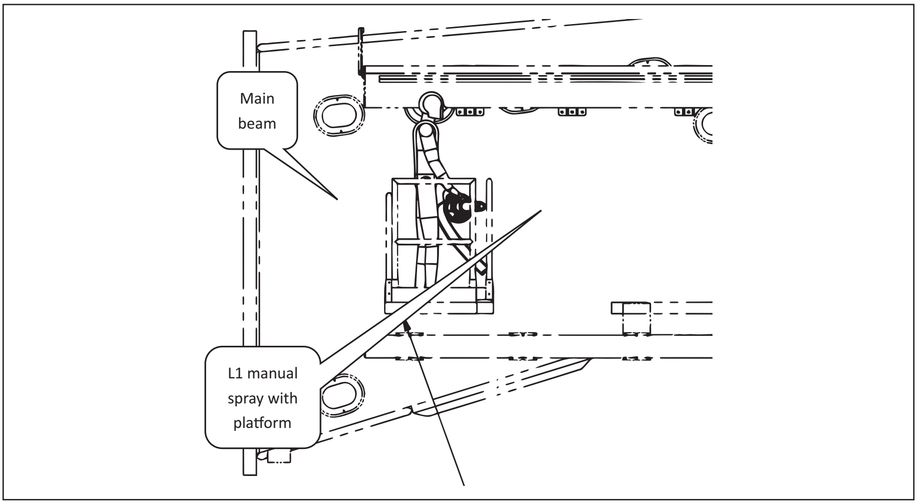

Figure 4. L1 manual spray diagram

Figure 5. L1 typical ground support on open-type TBMs

and 2 meters axial spray range. Figure 4 shows the L1 Manual Spray Diagram, used primarily to secure any loose rock and limit the convergence of the rock mass. Initial support typically consisted of rock bolts and mesh, McNally slats and ring beams. Figure 5 shows the L1 Typical Ground Support of Open-type TBMs.

Shotcrete was installed systematically at the L2 zone and formed the upper 285° of the permanent lining of the tunnel. Figure 6 shows the Jilin TBM layout.

L2 Shotcrete Zone

The L2 zone was located 50 meters behind the cutterhead. The system consisted of two boom type spray robots mounted on two independent movable rings. The boom can retract/extend 1.5 meters and the mechanical ring can move an additional 4.5 meters along the direction of the tunnel. The maximum coverage of the L2 shotcrete system was 285° of the tunnel circumference. The boom was covered by a protection roof to keep the rebound material out of the boom. Figure 7 shows the L2 shotcrete

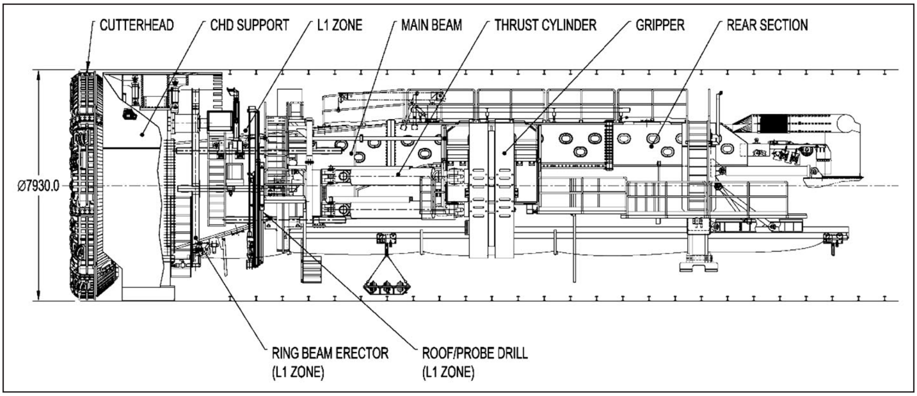

Figure 6. Jilin TBM layout

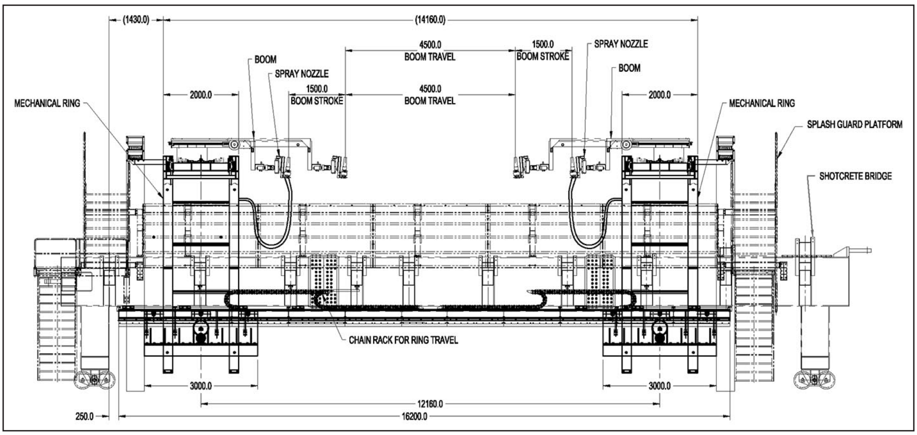

Figure 7. L2 shotcrete system arrangement

system arrangement, while Figure 8 shows the L2 shotcrete mechanical ring during shop assembly.

Figure 8. L2 shotcrete mechanical ring during shop assembly

Stages of Shotcrete Application at the L2 Zone

The following chart in Figure 9 shows the different stages of shotcrete transport and application.

The concrete was first mixed at the TBM batching plant located in an underground assembly chamber. Because of the minus 40.2 °C extreme cold winter at the jobsite, the TBM batching plant was located inside the tunnel to ensure good conditions for concrete mixing. This required an over-cut chamber and was more convenient for concrete transport to the TBM. It was then loaded into shotcrete bin. The locomotive was then driven from the assembly chamber to the TBM while the shotcrete was agitated in the shotcrete transit car. Upon arrival at

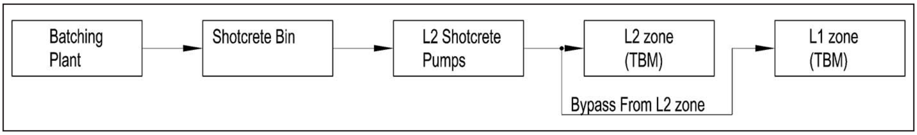

Figure 9. Stages of shotcrete transport and application

the TBM the shotcrete transit car was lifted from the locomotive and positioned above one of the shotcrete pumps on the TBM. When ready the contents of the shotcrete transit car were discharged and the shotcrete was pumped to the L2 zone where it was then applied as the final lining. In emergency cases, the L1 shotcrete could be used with the concrete material bypass from the L2 zone.

LESSONS LEARNED FROM PREVIOUS L2 SHOTCRETE & NEW SUPPLIER SELECTION

In the last 20 years, Chinese tunnel contractors have purchased more than 30 open-type TBMs. The end users are more and more familiar with the TBM and shotcrete system. They have learned based on experience and have made the following major changes:

- Higher safety requirements
- Higher reliability and performance
- More spray nozzle travel length and coverage. Normally 6 m or 8 m per robot
- More automation with less manpower
- Easy to clean and maintenance

In general, there are two primary kinds of L2 shotcrete system type used on previous projects, called bridge type and boom type (Figure 10 & Figure 11).

The following are major weakness was found for the typical telescopic boom type and bridge type on past projects:

Telescopic Boom Type With Fixed Ring Weakness

- The telescopic boom has insufficient rigidity. The deflection is more than 300 mm and even more deflection once the guiding plates are worn. This

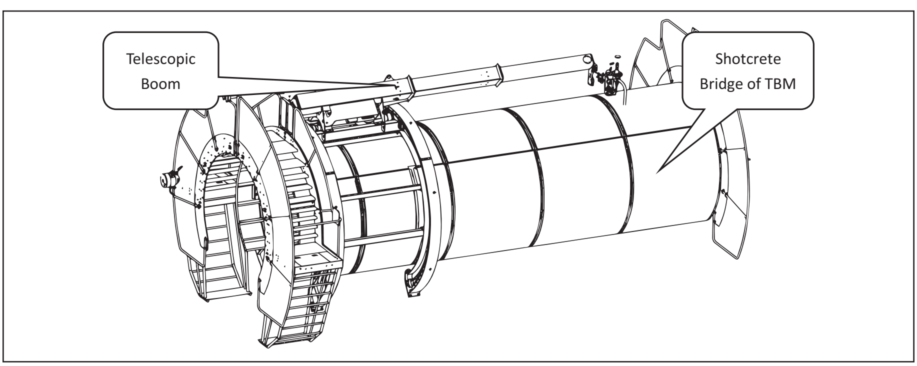

Figure 10. Telescopic boom type with fixed ring

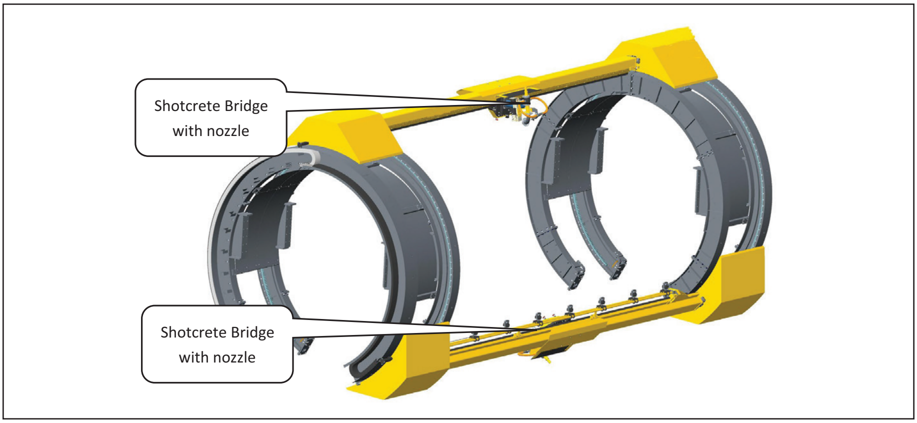

Figure 11. Bridge type with fixed ring

can be seen on the 6 m boom very often (Figure 12). Once spraying, the nozzle has a tendency to shake, which causes more rebound concrete and the decreased performance.

- There is a telescopic cylinder inside the boom. Because of the boom deflection and lower safety factor, the cylinder often leaks and can break (Figure 13).
- The motor power on the drive carriage force is insufficient when the carriage is at its max. force position (9 o'clock & 3 o'clock). Once the boom is fully extended, the carriage can become stuck, and move intermittently or be completely blocked (Figure 12). The drive motor also has a tendency to leak (Figure 14).

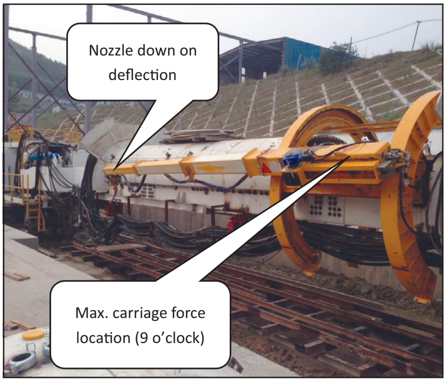

Figure 12. Telescopic boom deflection—Site assembly & testing

Bridge Type With Fixed Ring Weakness

- Normally two sets of robots are required by the customer. One robot is used as a spare and as a reserve capacity in case emergency conditions. If two bridge type robots are on one ring, then the customer must use both robots for spraying to achieve circumferential 270°–290° range. That means the customer has to clean both systems, and the cleaning and maintenance tasks double (Figure 15).
- The spray nozzle is often located beside the bridge. With this arrangement the rebound material always piles up on bridge, causing an additional force on the drive system and increasing clean time. The spray range is also smaller than with boom type due to the bridge structure.
- There are two carriages to support one bridge. The synchronous movements are always an issue once the encoder has failed, and the ring gear is prone to becoming damaged.

Figure 13. Telescopic cylinder broken

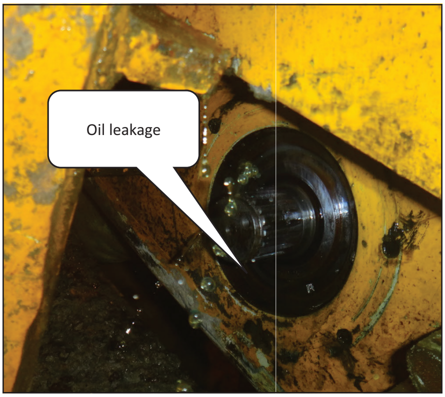

Figure 14. Drive motor leakage

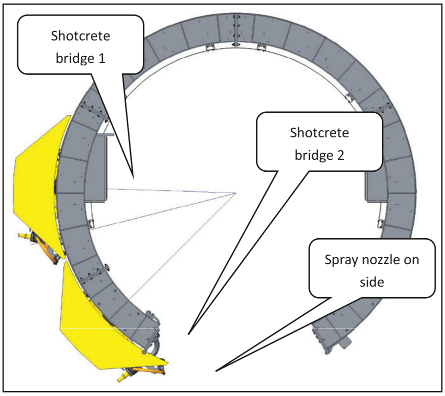

Figure 15. Two bridges on same ring

- Another option is to use one robot per ring only, but with each additional robot a 20 meter long shotcrete deck needs to be added. This increases the back-up length, the tunnel conveyor, and all the cables and hoses for the TBM to operate, making it a very costly expense.

In previous projects, Robbins has sourced systems from European suppliers. However due to critical time constraints and customer requirements this was not possible for Jilin. Instead, Robbins China took the lead to develop an innovative system and source parts from three vendors to meet requirements and lower costs:

Imported parts from European Supplier

- Shotcrete pumps with cabinet controls
- Dosing unit
- Telescopic Boom with robot
- Partial cables & hoses

Structure and System from Local Supplier

- Movable mechanical ring with remote controls
- Carriage & drive system
- Hydraulic power unit

- Telescopic Boom with robot
- Partial cables & hoses

Accessories from Robbins China

- Piping
- Hoses
- Couplings & Elbows
- Cables

L2 SHOTCRETE SYSTEM IMPROVEMENT AND INNOVATION

Shotcrete Bin Movement to Position

The innovative shotcrete system included several key changes. The shotcrete bin is transported from the underground station via the locomotive and flat car. The empty bin on the machine needs to be moved to the storage area before the train arrival. The storage area is normally located on the opposite side of the shotcrete pump. On previous projects a winch system or electrical crane was used for lifting., but the new system makes use of a hydraulic crane (Figure 16). The new design of the hydraulic shotcrete bin lifting crane has more advantages than the original design as below:

- Fast speed with easy operation. Normally under 3 minutes time to put the bin in position.
- The crane can handle Max. 30 ton bins and the performance is more stable than a winch with wire ropes.
- The shotcrete bin car structure is simpler, and the hydraulic crane requires less headroom than using the winch to handle the shotcrete bin.

Mechanical Ring & Travel System

The project required a min. 6 meters travel length for each spray nozzle. Considering the traditional boom type and bridge type weaknesses, a new type of ring was developed as in Figure 17 and Figure 18. One set of travel track with hydraulic drive carriage is added on the bridge structure of the TBM. The circular ring is then connected

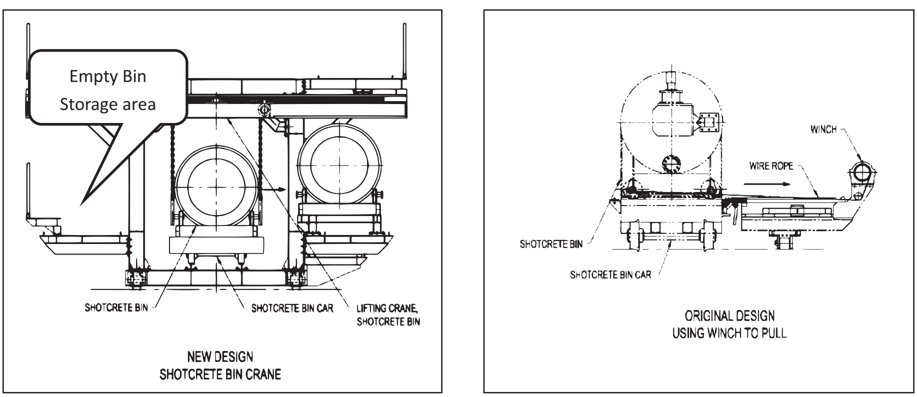

Figure 16. Shotcrete bin movement layout

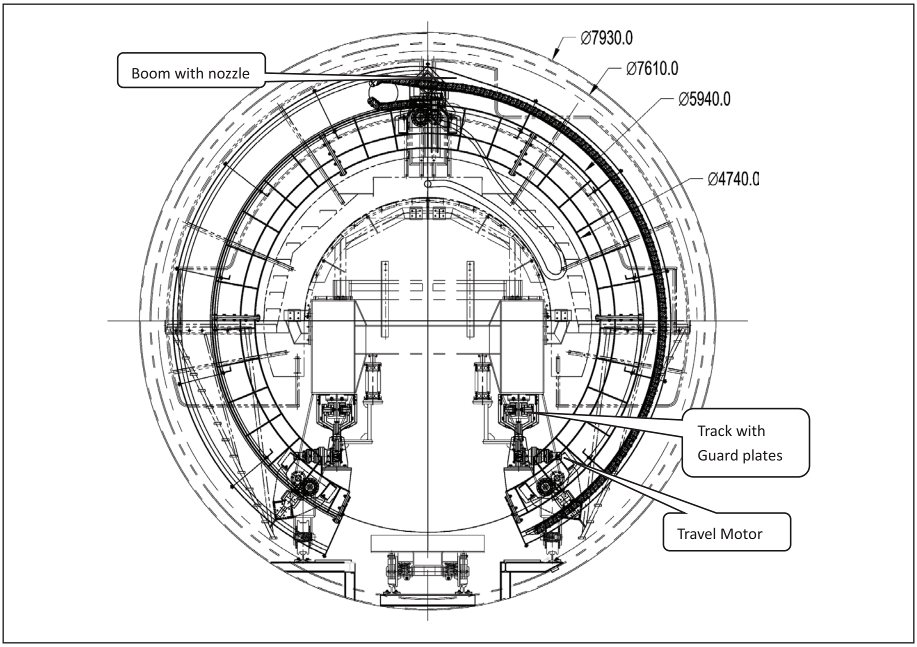

Figure 17. Mechanical ring & travel system

Figure 18. Mechanical ring & travel system

with the travel carriage and the travel length is set up to 4.5 meters plus a 1.5 m short boom for more flexible operation.

The track wheel assembly is installed under the bridge with side guard plates to keep dirt out of the track area. The mechanical ring travel is powered by hydraulic motors.

Considering the weakness of the circumferential drive carriage capacity, the drive motor was increased to allow for 25% more displacement and the max. continuous

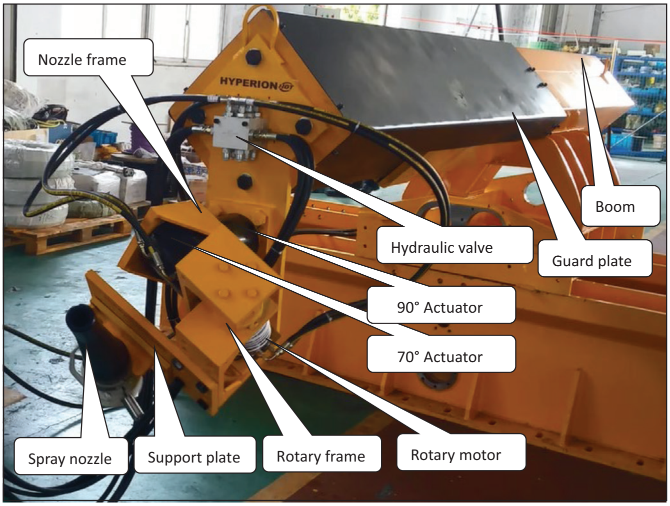

Figure 19. 1.5 m boom with spray nozzle

torque increased from 490Nm to 610 Nm. The weight of the boom was also reduced by 30%, all while achieving a high safety factor.

Shotcrete Robot

The boom and robot were redesigned as below:

- Change the longer telescopic boom to 1.5 meters (Figure 19).
- Change the drive motor and bearing to higher capacity. Increase plate thickness and spray distance adjust range. Added additional supports, etc.
- Hydraulic valve update for new drive capacity
- The spray nozzle was tested and used on the Jilin project for a short time until arrival of the imported components. The newly designed spray nozzle was used on the next section of tunnel for more than six months with very good performance (Figure 20).

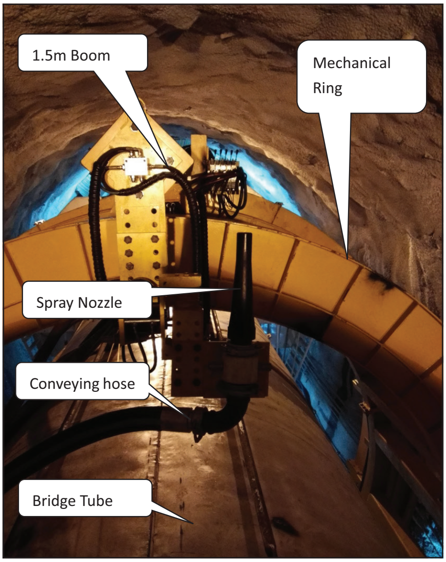

Figure 20. Spray nozzle installed on site

Shotcrete Pumps

The shotcrete pumps were located on gantry 1 and gantry 2, just behind the shotcrete bridge. The distance from the pump to spray nozzle is about 20 meters. The short conveying distance makes for easier cleaning and reduces the possibility of hose blockages. Figure 21 shows the shotcrete pump locations.

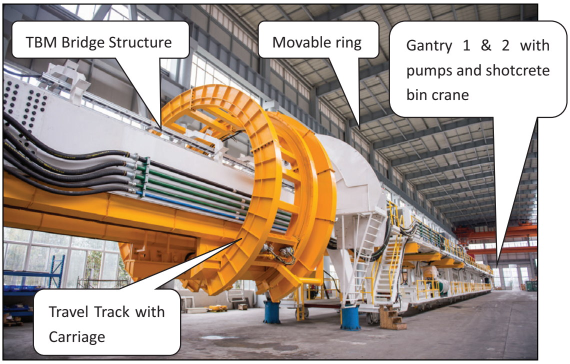

Figure 21. Shotcrete pump locations

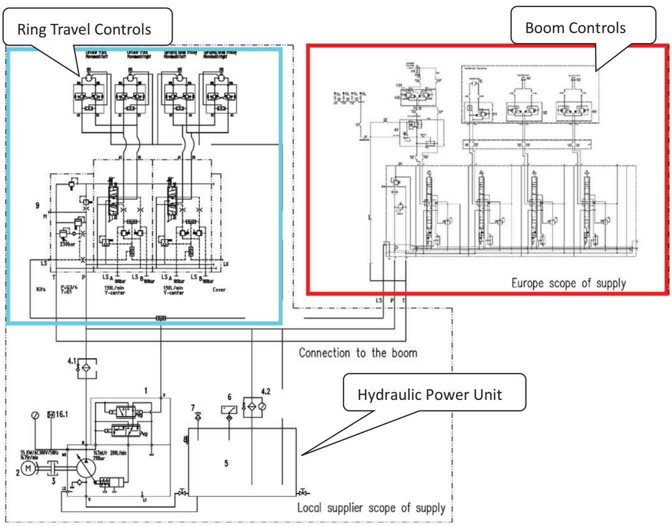

Figure 22. Shotcrete hydraulic schematic

HPU and Hydraulic System

The hydraulic system was updated as well--the power of the HPU changed from 22kw to 55kw, and new valves were added for mechanical ring travel. The schematic is as below (Figure 22).

Control System

The electrical control system governs shotcrete pump control, boom and spray nozzle control, and movable mechanical ring control. The controls come from different suppliers and Robbins merged these together with a public communication protocol. Figure 23 shows the shotcrete electrical control schematic.

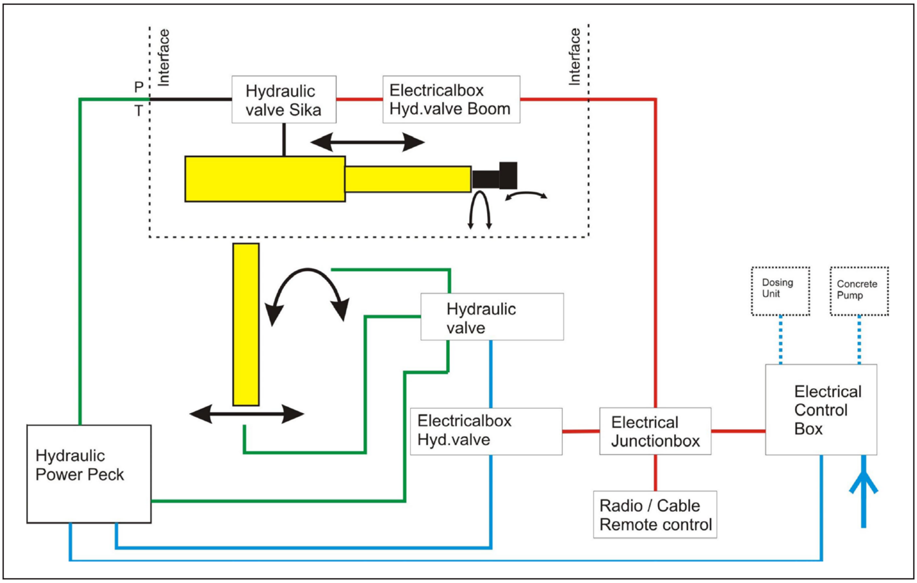

Figure 23. Shotcrete electrical control schematic

CONCLUSIONS AND RECOMMENDATIONS

In mid-May 2018 the national-record-setting 7.9 m (26 ft) Robbins Main Beam TBM at the Jilin Lot 3 Tunnel broke through. A formal ceremony followed to commemorate the stellar performance of the tunneling operation and its early completion. The project broke through nearly five months (147 days) earlier than scheduled. The project achieved the fastest monthly advance rate record—1423.5 m/4,670 ft—ever recorded for 7 to 8 m diameter TBMs in China. And the machine reached over 1000 m per month for three consecutive months. The shotcrete system played an integral part in the swift tunneling process.

The new designed L2 shotcrete system worked well on the Jilin project. Based on experiences the following recommendations should be considered for future projects:

- A hydraulic crane is a smarter system with fast speed and lower headroom suitable for shotcrete bin movement
- Considering the tunnel operation environment and shotcrete operating conditions, a drive system with a safety factor of at least 2 is recommended.
- A movable mechanical ring is a good choice for tunnel bore over 5 meters in diameter. With a 1.5–2 meter short boom. the bending moment on the robot is much smaller and the hoses can be fixed and protected easily.
- The shotcrete pump should be as near as possible to the robot as it will experience fewer stoppages and blockages in the hoses.
- Professional, experienced local supplier are needed for good communication, reduced delivery time and fast response. An experienced TBM supplier can improve the system performance and find ways to lower the cost.