Use of a Tunnel Boring Machine on Nepal's First and Second TBM-Driven Tunnels in Mountainous Terrain: Sunkoshi Marin and Bheri Babai Hydropower Projects

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Intro

Nepal's mountainous terrain, in particular the Himalaya, have historically been a challenge to tunnel through. That very terrain also holds great promise for hydropower – a resource that the country is now beginning to tap into.

Launched in October 2022, a 6.4 m Double Shield TBM is making Nepal's hydropower plans into a reality as it bores the 13.1 km headrace tunnel for the Sunkoshi Marin Diversion Multipurpose Project (SMDMP) in southern Nepal. The tunnel is connected to a new 28.6 MW surface powerhouse on the Marin River to alleviate the shortage of power supply in the area. It will also be used for farmland irrigation in the districts of Dhanusha, Mahottari, Sarlahi, Rauthat and Bara in the Terai Plain, diverting water from the Sunkoshi River to the Marin River.

The headrace tunnel is being bored through mostly igneous rock with maximum overburden of 1,320 m. Geological conditions are predicted to include squeezing ground, fault zones, and water inflows. In particular, a major fault zone is located approximately 4 km in, and is scheduled to be reached by June 2023.

The SMDMP is the machine's second tunnel: on its 12.2km first tunnel (the Bheri Babai Diversion Multipurpose Project/BBDMP), the TBM finished nearly one year early and achieved 1,202 m advance in one month. It was the first instance of TBM use in the country.

As a predominantly mountainous country, Nepal has tremendous possibilities for tunnel construction. Most of the tunnels constructed in Nepal, however, have historically used Drill & Blast (D&B) as the primary method of excavation. This, combined with the fact that most tunnels for hydropower have been shorter in length with a smaller diameter and horseshoe-shaped cross section, means that mechanized tunneling methods have gone unexplored by project owners until recently.

These considerations, coupled with limited capital and the overall negative perception of Tunnel Boring Machine usage in Himalayan geology, have prevented mechanized tunneling from gaining traction in Nepal. However, that looks to be changing: After successful tunneling at the BBDMP using a Tunnel Boring Machine and with a second project in the works, the perception is more positive.

In this paper, we will examine the successes and lessons learned in Nepal's mountainous conditions during excavation of both the SMDMP and BBDMP. Recommendations will be made towards what could be used on future hydropower projects in similar conditions.

1. Bheri Babai Diversion Multipurpose Project (BBDMP)

The Bheri Babai Diversion Multipurpose Project (BBDMP) is one of Nepal's 11 National Pride Projects—a prioritized plan sanctioned by the Government of Nepal to further develop the mainly rural country. This project irrigates 60,000 hectares of land in the southern region of Nepal, benefitting an estimated 30,000 households. It diverts 40 cubic meters of water per second from the Bheri River to the Babai River under a head of 150 m using a 15 m tall dam, providing year-round irrigation in the surrounding Banke and Bardia districts. The water is also used for hydroelectricity, with a generating capacity of 48 MW benefiting the country with NPR 2 billion (20 million USD) annually.

Contractor China Overseas Engineering Group Co. Ltd. Nepal Branch (COVEC Nepal Branch), represented by China Railway No.2 Engineering Co., Ltd Chengtong Branch, were responsible for the headrace tunnel and prepared for the challenges associated with tunneling in the tough geology of the Siwalik Range, part of the Southern Himalayan Mountains, with procurement of a custom-designed Double Shield TBM. The Siwalik range consists of mainly sandstone, mudstone and conglomerate, requiring a TBM that could withstand squeezing ground, rock instability, possibly high ingress of water and fault zones. Maximum cover above the tunnel is 820 m.

1.1 Project site & Considerations

The Bheri Babai project site is 56 km from Nepalgunj, which is the nearest town as well as one of the largest business hubs in western Nepal and location of the nearest airport (see Figure 1). About an hour's drive away from Nepalgunj, the tunnel portal is located in a river basin valley between 700 and 1000 m above sea level. The project site is a crossroads to highways that lead to much higher Himalayan towns and villages popular among trekkers and mountain climbers. The roads and bridges in the area, capable of handling heavy loads, were a very important factor when considering a TBM for the project. The area is prone to flooding during the rainy season, but overall the weather is sub-tropical and quite warm in the winter, as it is close to the Indian border.

One of the most intriguing aspects of the location is that it is in the middle of Nepal's largest wildlife reserve. Bardia Wildlife Reserve shelters Royal Bengal Tigers, two types of Asian Rhinos, Elephants, Asian Black Bears and many other types of vulnerable flora and fauna. Monkeys and foxes are an everyday occurrence around the jobsite, as well as colorful birds. Laborers even spotted a tiger. The reserve is guarded by the Nepalese Army and there are many check-posts along the highway. Anyone traveling through the reserve or to the project site that is not a local must show valid paperwork to pass through.

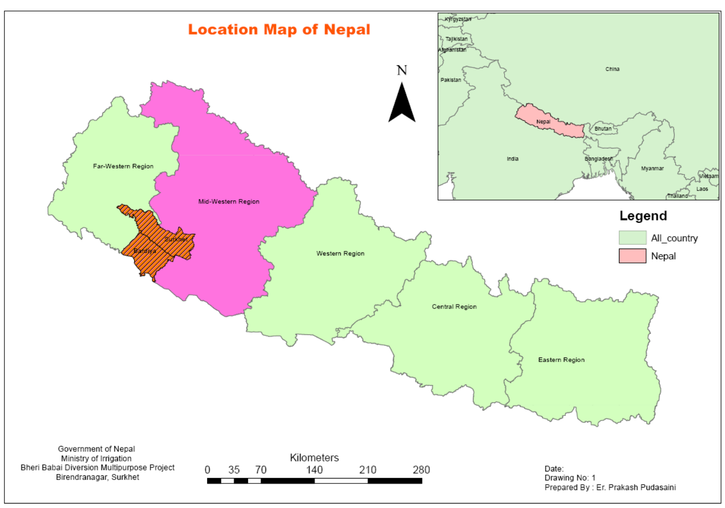

Fig. 1. Map of Nepal and BBDMP location

1.2 Choosing the Construction Method

Because of the notoriously difficult high mountain geology, TBMs had not been previously used in Nepal prior to this project. With years of planning and internal lobbying for the use of a TBM, the project was finally agreed upon.

The project owner, the Government of Nepal's Ministry of Irrigation (MOI), chose a TBM over the traditional method of Drill and Blast due to the faster mobilization and rate of advance offered by mechanized mining. Feasibility studies predicted an excavation time of 12 years for the tunnel, which simply wasn't an option. The TBM was also seen as an opportunity to prove the viability of the method in Himalayan geology.

To put this decision into perspective, the starting portal for this tunnel was 150 m long and excavated using the Drill and Blast method. It took five months to complete and this was without any unforeseen geological difficulties. Once the TBM was up and running, under normal boring conditions in similar strata, this same length of tunneling was achieved in less than a week.

1.3 Geology

In order to connect the two river valleys, the TBM had to bore 12,210 m under a mountain range with a maximum rock cover of 800 m and gain an altitude of 152 m. The alignment was known to contain at least one large fault zone. The flow rate of water expected to be encountered was 40 m^3/sec (see Figure 2).

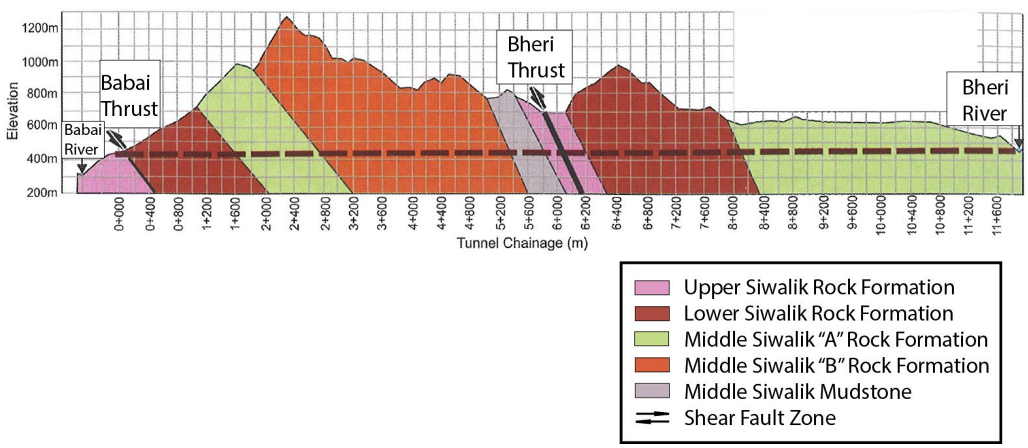

Fig. 2. BBDMP Tunnel Alignment

Geological studies found the following types of rock, all part of the Himalayan Siwalik range that comprises sandstone, mudstone, and conglomerate (see Figure 3):

- Upper Siwalik
- Siwalik Mudstone
- Middle Siwalik 'B'
- Middle Siwalik 'A'
- Lower Siwalik

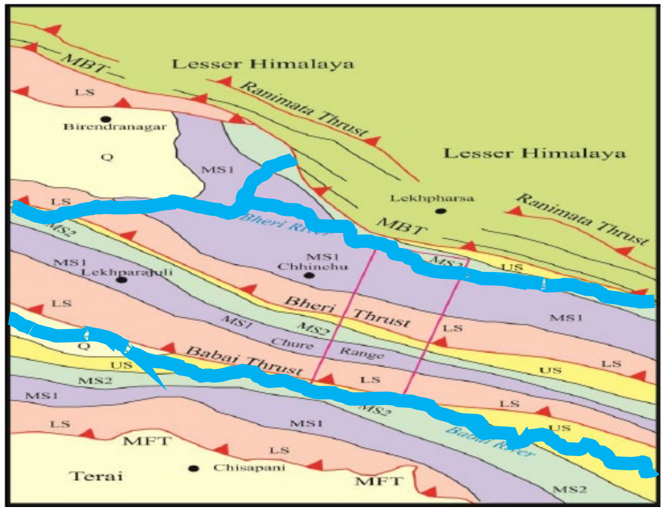

Fig. 3. The geological formations along the tunnel alignment

The Siwalik rock formation borders the Himalayan range for more than 2,000 km from East India to West Pakistan. The Siwalik rocks are relatively young, varying in age from 14 million years to two million years old. Generally, the Siwalik rock formation is sandwiched between the Main Boundary Thrust (MBT) at the north and Main Frontal Thrust (MFT) to the south. It is the MBT, a major thrust system along the entire Himalayas, which separates the young sedimentary rock formation of the Siwalik from lesser Himalayan rock formations where meta-sedimentary and crystalline sequences of relatively good quality are found (Panthi, 2019).

The Siwalik rock formations can be divided into the lower, middle and upper Siwalik formations. In general terms, the Siwalik rock formations are buried beneath the cover of the Southward tilted (over-thrusted) lesser Himalayan meta-sedimentary rocks along the MBT. Being sandwiched between two active tectonic thrusts, the rock mass of the Siwalik formation is weak, highly deformed, folded, and often fragile, easily erodible and porous. Tunneling through the Siwalik rock mass is in general challenging except for where areas of bedded and massive sandstones meet.

The rock mass along the BBDMP headrace tunnel alignment belongs to the lower Siwalik (LS) rock formation consisting of fine to medium grained grey sandstones and silty, sandy and calcareous mudstone; and the middle Siwalik (MS) rock formation consisting of medium to coarse grained grey mica rich sandstones with an intercalation of siltstone and mudstone. The middle Siwalik (MS) formation is gradually overlapped by the conglomeratic to sandy conglomeratic facies of the upper Siwalik (US) rock formation. The BBDMP headrace tunnel passes through the tilted anticline and syncline Siwalik rock formation sequences as indicated in Figure 2. The headrace tunnel crosses the Bheri Thrust (BT), which is among the two tectonic contacts found within the MBT and MFT at the project area (Figure 2). Therefore, it was envisaged during planning that extreme care should be taken during TBM excavation through this thrust.

Given the expected ground conditions, a shielded machine was deemed necessary. Also, with the desire to complete the tunnel as quickly as possible, a 5.06 m diameter Robbins Double Shield machine was selected.

1.4 Machine Design

The 5.06 m diameter Robbins Double Shield machine was designed to be able to bore through broken rock conditions. Because of a double thrusting system, the machine could bore forward with the auxiliary thrust cylinders while simultaneously using the rear thrust cylinders to build a segment. This process drastically reduced the time needed to bore the tunnel. The shielded machine was also beneficial to protect the workers from water and broken ground (see Figure 4).

Fig. 4. BBDMP TBM in factory in Shanghai, China

In order to ensure that the machine was successful, additional features were built into the design, to prevent the machine from becoming stuck while navigating the possible squeezing ground and water ingress:

- Stepped shield: Making the shield sections step down to smaller diameters, from the head to the tail, opened up the annular gap at the tail of the machine. This allowed for more space around the machine for the ground to contract and lessened the chance of the shield becoming stuck.
- Probe Drilling: By probing drilling in front of the machine, the upcoming ground conditions and water content could be checked. If poor ground was found, grouting could take place to consolidate the zone ahead of the machine. This created a solid plug to bore through. Because high water was planned for, this machine was equipped with several probe drilling locations. 14 ports in the gripper shield at seven degrees were in line with a rear probe on a ring. There were also eight ports in the forward shield at seven degrees that could be drilled by hand. In case of large amounts of water, this array of drilling and grouting gave a full 360 degrees of coverage.
- Shield Lubrication: Although this system was not used, ports were designed radially into the gripper shield that could be used to pump bentonite or other additives to the shield skin to help lubricate the surface and keep the machine moving in squeezing ground.
- Forepoling: Ports were also designed into the forward shield for the option of adding a forepoling drill in the upper forward shield area. This feature would be able to drill holes at 22 degrees, where poles could be inserted into the ground above the machine in an overlapping pattern to stabilize the ground (see figure 5).

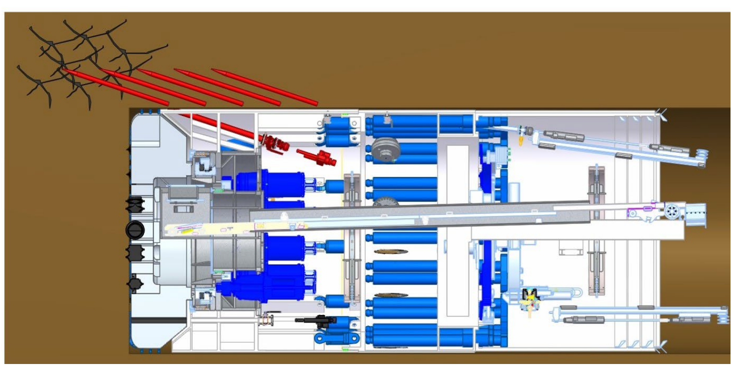

Fig. 5. Forepole Drilling

1.5 Machine Performance

The start of boring commenced on October 16, 2017. As can be seen in Figure 6, after the initial startup period, most months the excavation rates exceeded and sometimes doubled the planned rates. The TBM averaged over 700 m per month (see Figure 7), excavating up to 1,202 m in one month and completing the project about one full year earlier than planned.

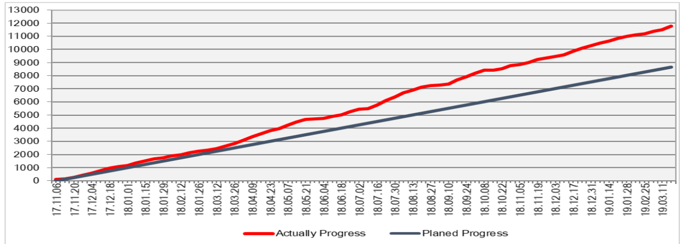

Fig. 6. Accumulative Excavation Rates vs. Planned Rates

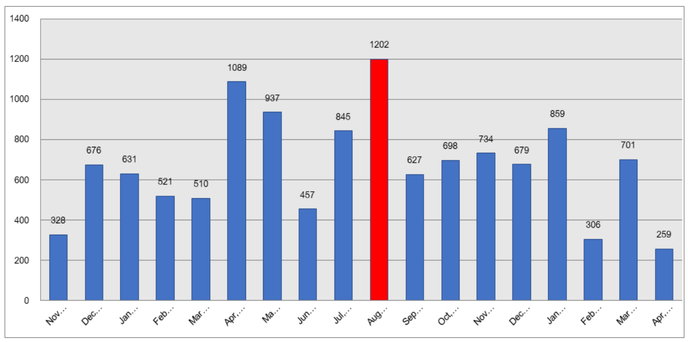

Fig. 7. Average Monthly Excavation Record

During the excavation, similar types of rock were encountered as compared to those described in the Geotechnical Baseline Report (GBR); i.e., alternating beds of mudstone, siltstone, sandstone and conglomerate.

During tunneling, 73% of Type 1 segments (having less reinforcement) and 26% of Type 2 segments (having more reinforcement) were planned to be erected. However in actuality, 92% of Type 1 and 8% of Type 2 segments were used instead, as ground conditions were better than predicted.

The TBM also navigated a major fault zone shown in the GBR, known as the Bheri Thrust Zone. Clay and water ingress were expected throughout the fault, which is about 400 to 600 m wide. However, through a series of effective measures taken by the contractor, the fault zone was navigated safely and without delay. Construction organization was carried out from the aspects of equipment maintenance, resource mobilization, technical preparation, emergency drills, etc., and the Horizontal Sonic Profile Method (HSP) was introduced to predict the stratum 100 meters ahead of the tunnel face. The HSP prediction results were verified with probe drilling, so that the TBM passed through the fault zone safely and smoothly within only one week without any construction danger.

2. TBM Refurbishment

After successful completion of the Bheri Babai tunnel in 19 months, the TBM was dismantled, packed and stored at the project site. The contract for the Sunkoshi Marin Diversion Multipurpose Project (SMDMP) was signed on 10 March 2021 and the use of the BBDMP TBM after re-engineering by Robbins was formally approved. The entire re-design and re-engineering works were carried out by Robbins including the main body, cutterhead etc. and additional features like auxiliary cylinder, transformer, MEC cabin, secondary ventilator, etc.

The back-up system refurbishment was carried out by the contractor, China Overseas Engineering Group Co. Ltd (COVEC) and China Railway No. 2 Engineering Group Co Ltd (Bureau-2), under the close supervision and guidance by Robbins' officials based at the site including the segment erector, segment feeder, main girder etc. thereby ensuring full compliance to the technical requirements of the re-designed TBM.

COVEC / Bureau-2 had commenced works on land acquisition and site mobilization from mid-2021 and were completed by early 2022 including TBM Platform and Segment Plant. The Bheri Babai TBM and all the components were transported to the Sunkoshi site starting from 22 February 2022.

Manufacture of re-designed and re-engineered TBM components was completed in August 2022 and all components had arrived at the Sunkoshi Project Site by mid-September 2022. The final phase of re-building and re-assembling of the TBM commenced from 17 September 2022 at the project site using Onsite First Time Assembly (OFTA) – a method of TBM assembly that can save months on delivery time and reduce costs as compared with a shop-assembled TBM. The 6.4 m diameter machine was launched just one month later in October 2022.

3. Sunkoshi Marin Diversion Multipurpose Project (SMDMP)

COVEC and Bureau-2 are operating the Double Shield TBM on the 13.1 km headrace tunnel for the SMDMP located in southern Nepal. The project is funded by the Government of Nepal and is a designated Priority 1 project under the scheme of National Pride Projects, which assures cash flow commitments from the Government of Nepal. The tunnel is connected to a new 28.6 MW surface powerhouse on the Marin River to alleviate the shortage of power supply in the area. It will also be used for farmland irrigation in the districts of Dhanusha, Mahottari, Sarlahi, Rauthat and Bara in the Terai Plain, diverting water from the Sunkoshi River to the Marin River. The hydropower plant contract includes construction of a 12 m high diversion dam and intake structure on the Sunkoshi River, a surface powerhouse, a surge shaft and tailrace and installation of four generator turbines (see Figure 8).

Fig. 8. Layout of the hydro plant and tunnel outlet.

Located about 150 km from the capital city Kathmandu, the 13.3 km long TBM contract includes the construction of about 2 km of access road, about 1 km of highway diversion roadway, the TBM launch and working site, the TBM exit platform, about 2 km of river retaining works, construction of a camp for the contractor, consultant and employer, and some geotechnical and geophysical investigation works before, during and after the construction. About 900,000 m^3 of earthworks were required for site establishment (Wallis, 2020).

3.1 Geology

While in the Siwaliks like Bheri Babai, the tunnel passes through all three formations of Siwaliks that consist mostly of interbedding sandstone, siltstone, mudstone and conglomerate. The overburden in in the Siwalik region varies from tens of meters to about 550 m. Except for about 1km in a slate formation that belongs to the Lesser Himalaya Region, the majority of the remaining tunnel alignment, or about 8.3 km, passes through the relatively old Higher Himalaya Region mountain range formed during the Paleozoic Era. This region is mostly composed of medium to highly metamorphosed schists, quartzite, granite and gneiss with occasional calcareous beds of limestone and dolomite. Because of the long stress history of the mountain range, this region consists of several minor and major folds, faults and shear zones with the alignment passing through the major syncline of the Nepal Himalayas known as the Mahabharat Synclinorium. The tunnel route passes through the core of the Synclinorium where the overburden is at its highest of about 1,320m, and through the anticipated granite rock type (see Figure 9).

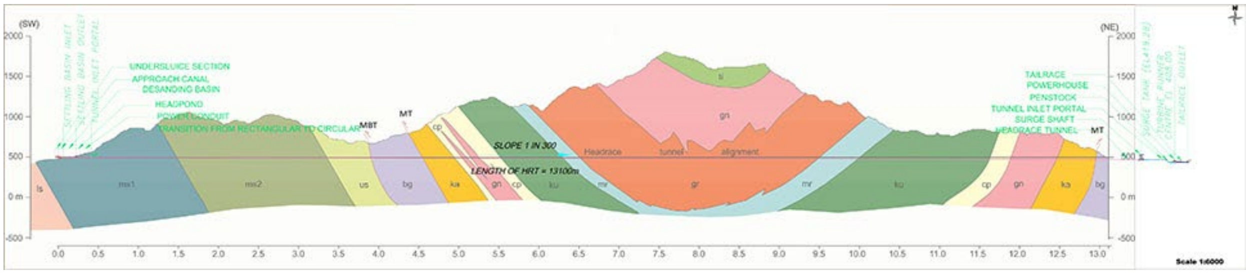

Fig. 9. SMDMP tunnel alignment

The two contrasting geological units of the alignment are separated by a low angle reverse fault known as the Main Boundary Thrust. On the surface, this fault is marked by the Dhanamana Khola where the overburden to the tunnel horizon is about 200m. In addition to that, another boundary, the Mahabhrat Thrust, is present immediately after the slate formation and between the Lesser Himalaya and Higher Himalaya. The thrust area is marked by a breakage in topography in the tunnel alignment. Another Mahabharat Thrust will be found at about chainage 13+020m. Another perennial river, the Tyan-Tyan Khola, crosses the tunnel at about chainage 10+550m and at an overburden of about 500 m. As the rocks are dipping north or south at different angles, the TBM must bore through mixed face conditions of competent and incompetent strata.

3.2 Machine Design & Performance

The machine is designed for challenging geology including a high overburden, two major fault zones and variable rock types. Its design retained features including a tapered shield to reduce the risk of becoming stuck in squeezing ground, as well as an enclosed cutterhead design to reduce the collapse of surrounding rock. The TBM has overcut capabilities, and a high thrust. It has also been equipped with an extra high torque cutterhead drive, as well as strong auxiliary thrust to be used in squeezing ground or weak fault zones to keep the machine from becoming stuck (see Figure 10).

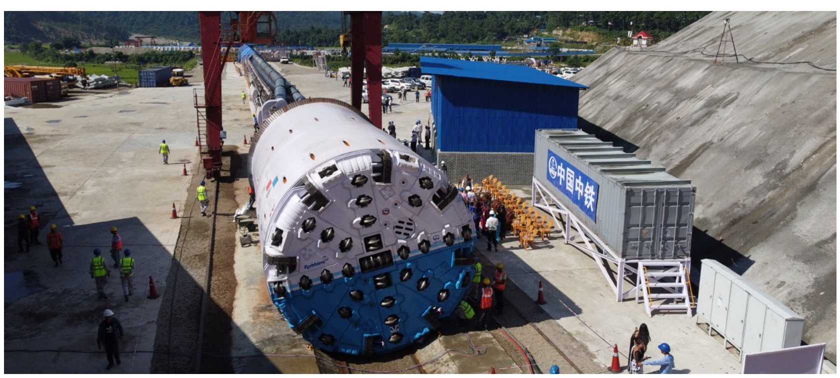

Fig.10. Sunkoshi Marin TBM at launch

At the end of June 2023, the machine turned in an impressive advance rate of 1,224.13 m in one month – a record for Himalayan geology and believed to be a TBM record within the Indian Subcontinent. As of August 2023, the TBM was more than 7.9 km into the tunnel and boring in high strength granite, having passed through the two major fault zones predicted on the tunnel alignment.

4. Thoughts on TBM Performance

On reflection, there have been multiple reasons for the extremely good performance at both tunnel sites. There are several points that ensured both the BBDMP and the SMDMP's fast progress:

- *Full study of the geological conditions and targeted design for the TBM.* Prior to the production of the TBM for the BBDMP, the contractor organized professional geological engineers to conduct a detailed survey of the geology of the whole area and analyzed the regional geological conditions by using remote sensing technology. According to the geological characteristics, the TBM was designed to match the actual situation of Siwalik strata to the greatest extent. Design features included 360-degree advance grouting holes, forepoling capabilities, a stepped shield, a good grouting system, a large diameter Main Bearing with a ratio to tunnel diameter of 0.65; separate Main Bearing and Ring Gear; specialized Variable Frequency Drives; etc. When the machine was refurbished for the SMDMP, it was again refurbished based on the geology after a detailed geological survey.

- *Advanced management and planning*. As this was the first TBM in Nepal and there was a lack of skilled construction personnel and operation teams in Nepal, the contractor appointed COVEC managers and utilized a three-level management plan where COVEC managed local workers. More than 40 professional TBM construction professionals were introduced from China, and more than 600 local workers with high loyalty, diligence, and work and professional skills were selected to ensure long-term stable production. The same contractor managed both the BBDMP and SMDMP.

- *Strict control of the construction organization.* The TBM's rapid overall tunneling was based on good equipment maintenance and tunneling management. Pursuing and focusing on only high daily advance rates would eventually fail to maintain stable production for the complete tunnel. There is also the risk to increase the manpower cost; equipment maintenance cost and could even lead to serious equipment damage and safety matters causing accidents. From the initial stage of TBM tunneling, the contractor adhered to the idea of "no quick success, but steady tunneling, close attention to working procedures and continuous cycle operation". Through strengthening equipment maintenance, paying attention to working procedures and other aspects, this construction organization laid a solid foundation for the TBM's continuous and rapid tunnelling on both projects.

- *Use of diversified materials.* The remoteness of both projects meant there were limited resources, so the project teams considered diversified material supply channels in order to ensure the timely supply of materials and equipment. To a larger extent, materials and equipment were purchased from China, the United States, France, India, Japan and other countries. The project teams established a three-dimensional transportation plan integrating air, sea and land, established close ties with relevant suppliers, logistics providers, customs, highways and airlines, and maintained long-term cooperation with these suppliers. They selected the best transportation mode and route in combination with road conditions, climate, political environment and other factors to ensure that materials and accessories could enter each jobsite on schedule and reduce downtime.

- *Good safety and risk awareness*. During the construction of both tunnels, the contractor provided safety education to all employees through on-site education, safety training, on-site inspection and other methods. For key jobs in special positions, the contractor also formulated detailed safety management manuals and carried out regular emergency drills to strengthen the safety awareness of construction personnel.

4.1 Thoughts on Fast Advance

There were multiple reasons for the extremely good performance at both tunnel sites.

- The site staff made it a high priority to maintain the machine daily on both projects, and were vigilant with their cutter changing standards. The operators took the approach to boring of maintaining a continuous and stable excavation thorough the difficult areas as opposed to stopping to drill and grout.

- The use of hexagonal segments may be another contributing factor (see Figure 11). The hex segment design is well suited to Double Shield TBM tunneling. Only four segments are needed per ring, and these are built concurrent with boring. The hex shape of the 300 mm segments prevents cruciform intersections at radial joints, while cast-in pads on each invert segment allow it to be built directly on the invert, via the hooded tail shield. Lastly, the staggered arrangement of the hex shape allows segments to be built in two half cycles when using a long thrust jack stroke.

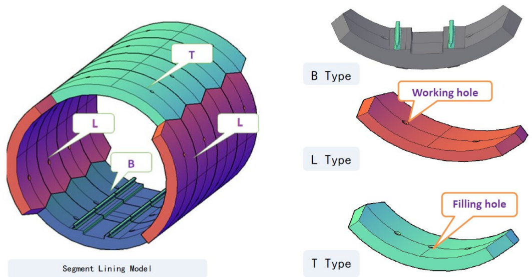

Fig.11. Hexagonal segment lining model

- As is the case in most long tunnels, logistics are key to keeping advance rates high. Coordination of trains and continual supply of components was needed to keep up with the fast pace of ring builds in both tunnels. In addition a geologist on each site conducted daily face mapping so that operational parameters and other measures could be adjusted accordingly. This type of mapping is critical in mountainous tunnels where the expected geology may differ from the geological report.

5. In Conclusion

The successes of both the BBDMP and the SMDMP are critically important for the country as well as the TBM industry. The projects help aide the food crisis in the mid-western region of Nepal by increasing agricultural yields and invigorating socio-economic development in the region. The success of the first TBM in the country has proven the tunneling method to those involved and the government is planning more TBM projects. This will open up future areas of infrastructure such as water diversion and irrigation, hydropower generation, transportation and more. By proving that TBM tunneling can be done in these conditions, economically and with high advance rates, many more hydro projects within Nepal will become feasible. More than 100 km of tunnelling – many of which are hydropower projects – are planned for Nepal in the next five years. More than 50% of those projects are considered feasible for TBM excavation. Many projects that would previously have recommended Drill & Blast only are now considering TBMs as an option.

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P. Shrestha is the Country Manager for Robbins Nepal, and has played an instrumental role in the TBM supply for both the BBDMP and SMDMP Projects.