Breaking Through Tough Ground in the Himalayas: Nepal's First TBM

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ABSTRACT

Years of hard work and planning have paid off at the Bheri Babai Diversion Multipurpose Project. This 12 km tunnel is not only breaking through a historically difficult mountain range, but it has also managed to break down the notion, to the people of Nepal, that drill and blast is this only way to excavate the extreme conditions in the Himalayas. This paper will highlight the first TBM in Nepal and how it is managing to bore at an exceptional advance rate of over 700 m per month, with a high of 1202 m in one month. It will examine which design features of the Double Shield TBM are contributing to the great excavation rates, and how the crew's operational methods have maximized these results.

BHERI BABAI DIVERSION MULTIPURPOSE PROJECT

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 will irrigate 60,000 hectares (almost 15,000 acres) of land in the southern region of Nepal, benefitting an estimated 30,000 households. It will divert 40 cubic meters of water (1,400 cubic feet) per second from the Bheri River to the Babai River under a head of 150 m (492 ft) using a 15 m (49 ft) tall dam, providing year-round irrigation in the surrounding Banke and Bardia districts. The water will also be 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, is 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 can withstand squeezing ground, rock instability, possibly high ingress of water and fault zones. Maximum cover above the tunnel is 820 m (0.5 mi).

JOBSITE

The Bheri Babai jobsite 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 jobsite 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.

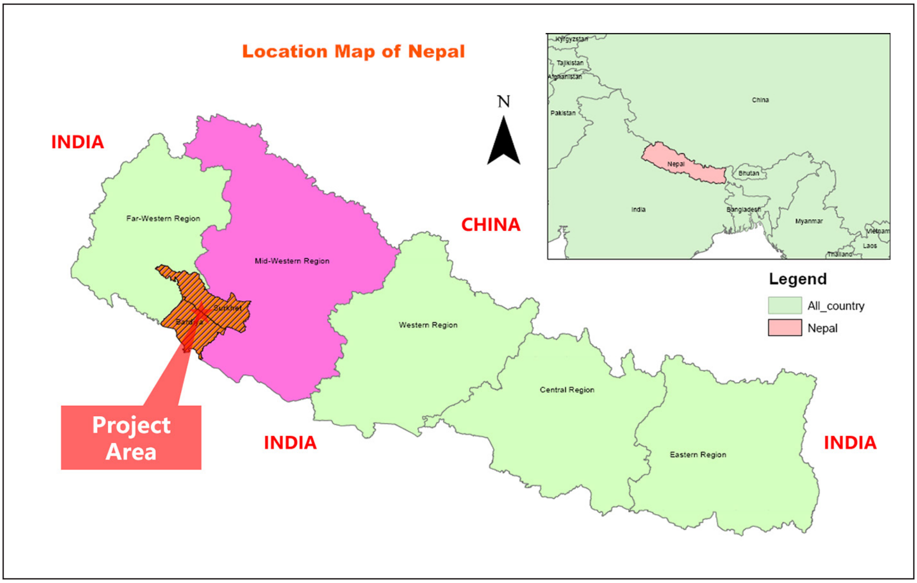


Figure 1. Map of Nepal and jobsite location

One of the most intriguing aspects of the jobsite 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 have 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 jobsite that is not a local must show valid paperwork to pass through.

TBM VS DRILL AND BLAST

Because of the notoriously difficult terrain and hard rock of the mountainous region, 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, this 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 notoriously difficult 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.

THE BEST MACHINE FOR THE JOB

In order to connect the two river valleys, the TBM will have to bore 12,210 m under a mountain range with a maximum rock cover of 800 m and gain an altitude of 152 m.

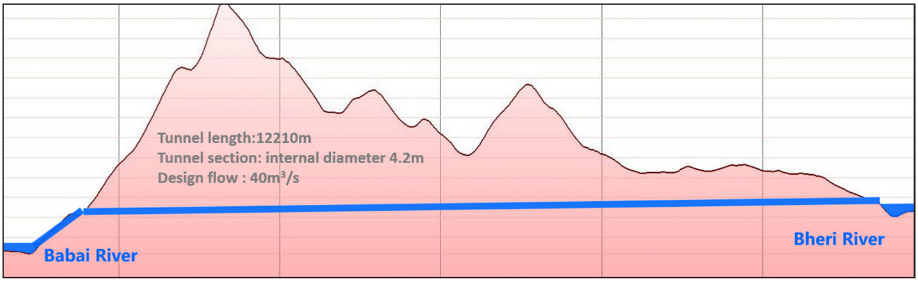


Figure 2. BBDMP tunnel alignment

The alignment is known to contain at least one large fault zone. The flow rate of water expected to be encountered is 40 m^3/sec (see Figure 2).

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 Siwaliks
- Siwalik Mudstone
- Middle Siwaliks 'B'
- Middle Siwalkis 'A'
- Lower Siwaliks

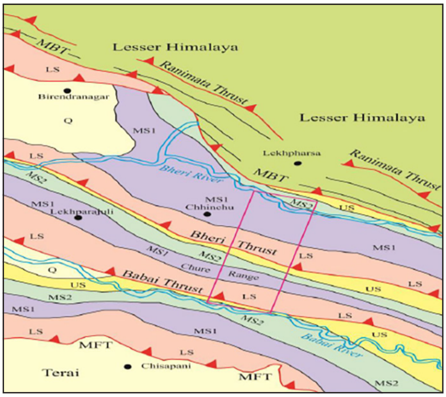


Figure 3. The geological formations along the tunnel alignment

With the amount of water and expected ground conditions, a shielded machine was necessary. Also, with the desire to complete the tunnel as quickly as possible, a 5.06 m diameter Robbins Double Shield machine was selected.

Figure 4. BBDMP TBM in factory in Shanghai, China

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

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, opens up the annular gap at the tail of the machine.

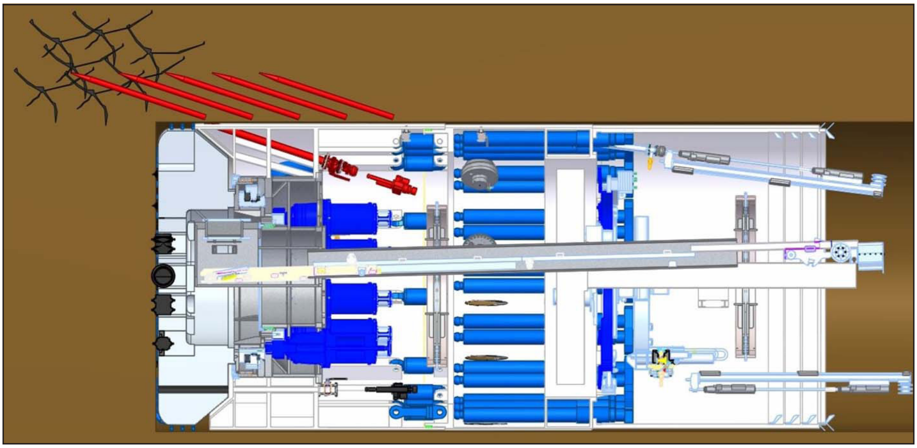


Figure 5. Forepole drilling

This helps to allow for more space around the machine for the ground to contract and lessens the chance of the shield becoming stuck.

- Probe Drilling: By probing drilling in front of the machine, the upcoming ground conditions and water content can be checked. If poor ground is found, grouting can take place to consolidate the zone ahead of the machine. This creates 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 are in line with a rear probe on a ring. There are also eight ports in the forward shield at seven degrees that can he drilled by hand. In case of large amounts of water, this array of drilling and grouting gives 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 can be inserted into the ground above the machine in an overlapping pattern to stabilize the ground (see Figure 5).

MACHINE PERFORMANCE

The start of boring commenced on October 15, 2017. With the exception of a few occurrences, which will be highlighted below, the current progress of this tunnel has consistently exceeded the expected excavation rates. See Table 1 for the highest excavation rates so far.

Table 1. Best TBM performance

Record Excavation Time Frame	Meters Bored	Date/Time Period
Daily Best	61.8	August 2, 2018
Weekly Best	337.8	Week #38
Monthly Best	1202	August 2018

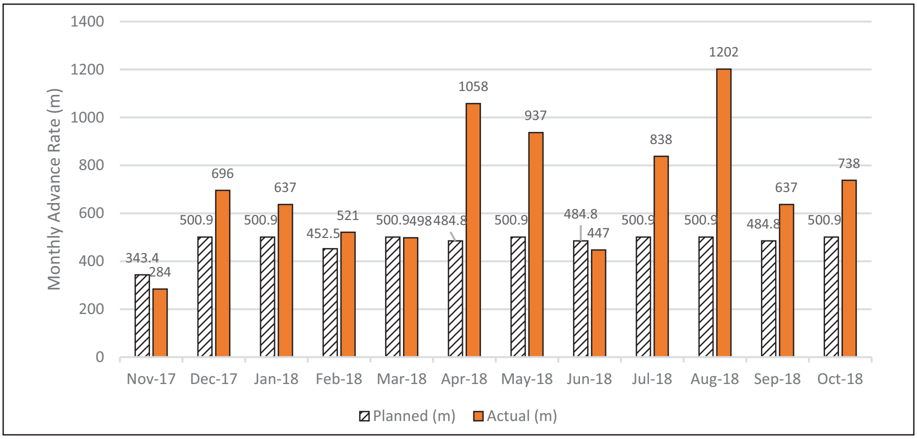


Figure 6. Average monthly excavation rates vs. planned rates

As can be seen in Figure 6, after the initial startup period, most months the excavation rates exceeded and sometimes doubled the planned rates. As of October, the tunnel had bored 8493 m compared to the planned 5756 m. This is 2736 m ahead of schedule, all despite encountering two points of high water ingress and two incidents where the machine was not able to move.

During the excavation, more or less 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.

In the nearly 9 km of TBM excavated tunnel so far, 66.58% of Type 1 segments (having less reinforcement) and 33.42% of Type 2 segments (having more reinforcement) were planned to be erected. However, 92.52% of Type 1 and 7.48% of Type 2 segments have been used instead, which indicates better ground conditions 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, the TBM passed smoothly through this section without any problem. The rock mass in this section was found to be completely dry and belongs to rock class IV (RMR).

EXCAVATION ISSUES AND RESOLUTIONS

- On December 27, 2017 at ch 1+174.782, large amounts of water were pouring from the 8 o'clock position. As the machine advanced, the ingress of water shifted to the 11 o'clock position. An estimated rate of greater than 2000 L/min was seen. Excavation continued at a slower rate, without any interventions.
- A second occurrence of high water happened on January 6, 2018 at ch 1+337.457. Water entered at the 12 o'clock position at an approximate rate of greater than 2000 L/min. Again, the resolution was to slowly bore through the water without any drilling or grouting to stop the water (see Figure 7).
- On October 10, 2018 at ch8+588.860 the machine became stuck and could not progress. Up until this point, the axis of the tunnel was perpendicular

Figure 7. Water ingress on January 6, 2018

to the grain of the rock. This is the most favorable condition for tunneling. Around ch8+400 the ground conditions changed, and the grain became nearly parallel to the tunnel axis. The machine alignment also started to shift and reached deviation from center of around 131 mm. At this point the machine became lodged in place. A high thrust of 18,500 kN was exerted and was not able to move the machine. In order to move the machine, a bypass passage was excavated from the right side of the telescopic section up to the cutterhead. It was cleared out from around the 5 o'clock position to the 12 o'clock position. A thrust of 10,000 kN was the applied and the machine was able to start boring again. The bypass was completed and the machine was moving again in just five days.

- At ch 8+606.262 the cutterhead became jammed. Loosely cemented sandstone and high-pressure water ingress around the 11 o'clock position triggered an over-break at the left crown area and jammed up the cutterhead. To control the water ingress, 1287 kg of polyurethane was injected through a 16 m deep probe hole. This almost completely stopped the water. A torque of 440 kNm was then applied to the cutterhead and it was able to become dislodged.

REFLECTIONS ON THE PROJECT: FAST ADVANCE

On reflection, there have been multiple reasons for the extremely good performance at this tunnel site. The site staff has made it a high priority to maintain the machine daily, and they have been vigilant with their cutter changing standards. The operators have also taken the approach to boring of maintaining a continuous and stable excavation thorough the difficult areas as opposed to stopping to drill and grout. Besides the two exceptions previously discussed, this method has proven to be successful.

The use of hexagonal segments may be another contributing factor (see Figures 8–9). 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.

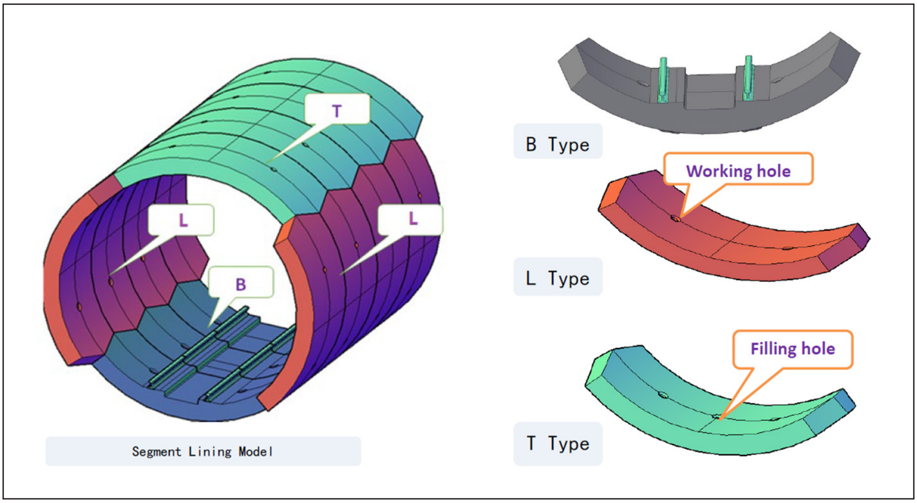


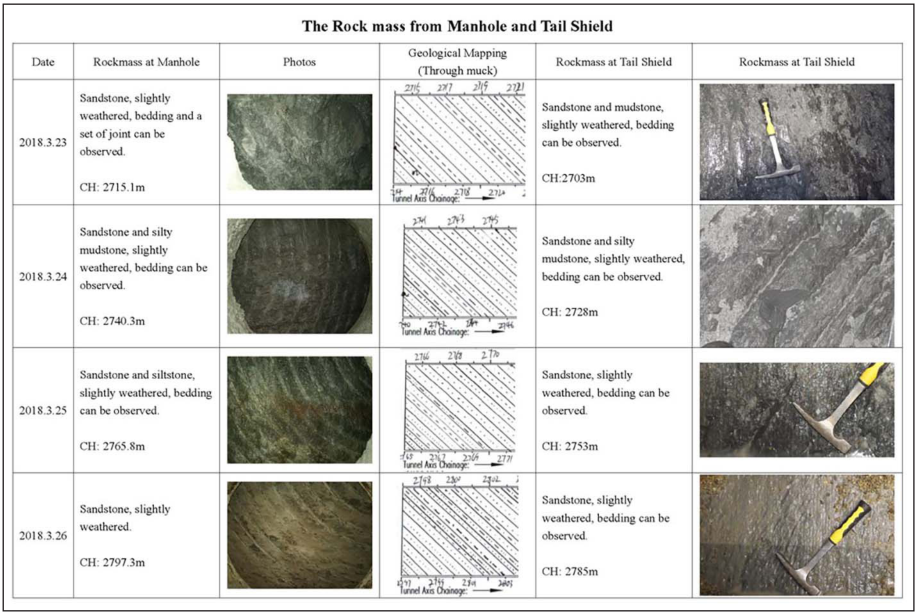
Figure 8. Hexagonal segment lining model

Figure 9. Completed lined tunnel section for BBDMP

As is the case in most long tunnels, logistics were a key to keeping advance rates high. Coordination of trains and continual supply of components is needed to keep up with the fast pace of ring builds. In addition a geologist on site conducts daily face mapping so that operational parameters and other measures can be adjusted accordingly (see Figure 10). This type of mapping is critical in mountainous tunnels where the expected geology may differ from the geological report. The geologist also analyzes the geology at the tail shield. Lastly, favorable geology has been a big factor, with less water than expected in fault zones.

SUCCESSFUL FUTURE PLANS

The success of the BBDMP, a national pride project, is paramount for the country as well as the TBM industry. It is expected to help aide the food crisis in the mid-western region of Nepal by increasing agricultural yields and invigorating socio-economic



The Rock mass from Manhole and Tail Shield

Date	Rockmass at Manhole	Photos	Geological Mapping (Through muck)	Rockmass at Tail Shield	Rockmass at Tail Shield
2018.3.23	Sandstone, slightly weathered, bedding and a set of joint can be observed. CH: 2715.1m			Sandstone and mudstone, slightly weathered, bedding can be observed. CH:2703m	
2018.3.24	Sandstone and silty mudstone, slightly weathered, bedding can be observed. CH: 2740.3m			Sandstone and silty mudstone, slightly weathered, bedding can be observed. CH: 2728m	
2018.3.25	Sandstone and siltstone, slightly weathered, bedding can be observed. CH: 2765.8m			Sandstone, slightly weathered, bedding can be observed. CH: 2753m	
2018.3.26	Sandstone, slightly weathered. CH: 2797.3m			Sandstone, slightly weathered, bedding can be observed. CH: 2785m	

Figure 10. Typical face mapping reports from the onsite geologist

development in the region. Even though the project has yet to be completed, the current success of this project has proven the tunneling method to those involved and the government is planning more TBM projects. This will open up the future for areas of infrastructure such as construction in the country, water diversion and irrigation, hydropower generation, transportation and more. More than 100 km of tunneling are planned for Nepal in the next five years, of which more than 50% is considered feasible for TBM excavation. Many projects that would previously have recommended Drill & Blast only are now considering TBMs as an option.