TBM Excavation in Himalayan Geology: Over 1,200 Meters per Month at the Bheri Babai Diversion Multipurpose Project

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ABSTRACT: A Double Shield TBM achieved in 17 months what was projected to have taken 12 years with Drill & Blast: The 12.2 km long Bheri Babai Diversion Multipurpose Project (BBDMP). Bored in Himalayan geology including sandstone, mudstone, and conglomerate, the excavation was able to achieve over 1,200 m advance per month on multiple occasions. Crews achieved this while traversing a fault zone and getting through one section that required a bypass tunnel constructed in just five days. The success of this tunnel is not only in breaking through a historically difficult mountain range, but also in changing the notion, to the people of Nepal, that drill and blast is the way to excavate mountainous rock tunnels. This paper highlights the BBDMP excavation using the first-ever TBM in Nepal, examining the geology and how the machine was able to get through fault zones, squeezing ground, and water inflows. The paper draws conclusions as to the role of geological conditions, TBM design, operation, and logistics in the completion of the excavation nearly one year earlier than projected.

KEYWORDS: Tunnelling, Nepal, Himalayas, TBM, Double Shield

1. INTRODUCTION

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 of land in the southern region of Nepal, benefitting an estimated 30,000 households. It will divert 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 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 could withstand squeezing ground, rock instability, possibly high ingress of water and fault zones. Maximum cover above the tunnel is 820 m.

2. JOBSITE & CONSIDERATIONS

2.1 Location

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.

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.

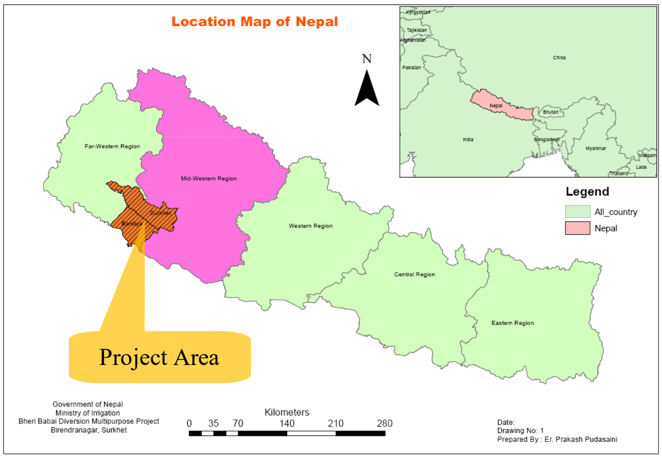


Figure 1 Map of Nepal and jobsite location

2.2 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, 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 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.

2.3 Geology

In order to connect the two river valleys, the TBM would 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. The alignment was known to contain at least one large fault zone. The flow rate of water expected to be encountered was 40 m³/sec (see Figure 2).

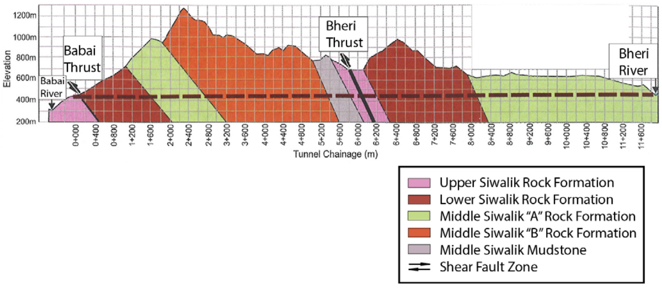


Figure 2 BBDMP Tunnel Alignment

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

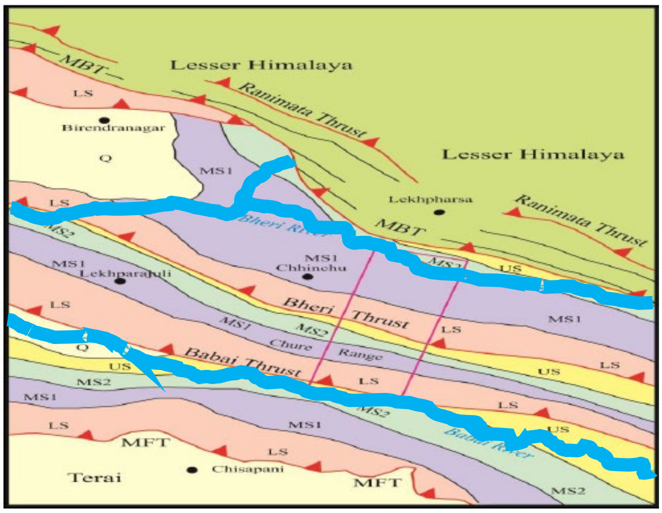


Figure 3 The geological formations along the tunnel alignment

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.

3. MACHINE DESIGN

The 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).

Figure 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).

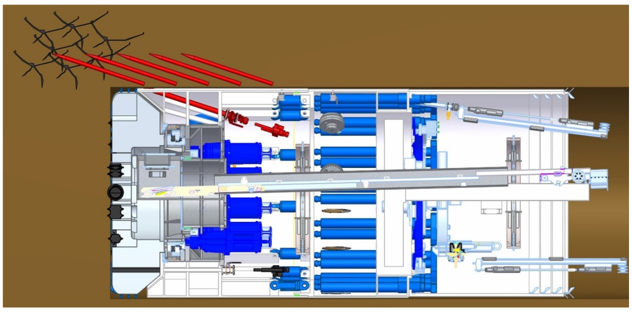


Figure 5 Forepole Drilling

4. 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.

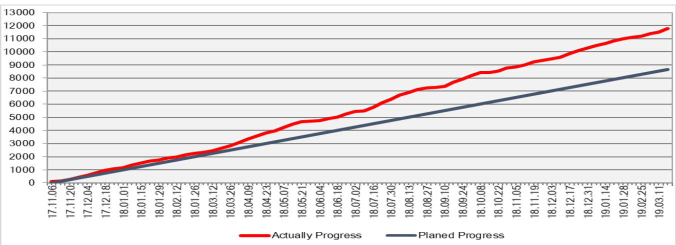


Figure 6 Accumulative Excavation Rates vs. Planned Rates

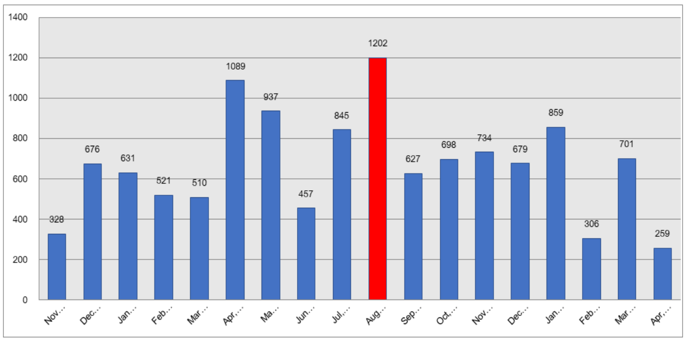


Figure 7 Average Monthly Excavation Record

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.

5. EXCAVATION CHALLENGES & RESOLUTIONS

Despite a smooth excavation for the majority of tunnelling, there were several challenges that the crew was able to navigate successfully:

- 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. Since this section was mainly composed of sandstone and the rock strength was relatively high, the contractor thought it was unnecessary to carry out grouting for water plugging, but adopted the methods of slow excavation, enhanced pumping and drainage, and intensified back-filling and plugging.

- 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 contractor adopted the methods of slow excavation, enhanced pumping and drainage, and intensified back-filling and plugging. As the section was in sandstone stratum with excellent stability, and the ingress of water through fissures in the rock, it was determined that there were minimal risks of the TBM being stuck or buried. The resolution was to slowly bore through the water without any drilling or grouting to stop the water (see Figure 8).

- 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 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 geological conditions of the tunneling face were soft on the left-hand side and harder on the right-hand side, so the machine alignment became difficult to control. The TBM started to shift and reached a 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 then 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.

Figure 8 Water Ingress on January 6, 2018

8. CONCLUSIONS

8.1 Overall Project Conclusions

On reflection, there have been multiple reasons for the extremely good performance at this tunnel site. The result is especially impactful in Nepal, where resources are not abundant and transportation routes are not well developed, to show that a tunnel can be completed seven months ahead of schedule. The project has set a milestone in Nepal's infrastructure as the country's first TBM-driven tunnel and laid the foundation for future planning by the Government of Nepal to better the country's economy and overall quality of life. There are several points that ensured the BBDMP's fast progress:

- *Full study of the geological conditions and targeted design for the TBM*. Prior to the production of the TBM, 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 diameter ratio of 0.65, split bearing gear rings, etc.
- *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.
- *Strict control of the construction organization.* The TBM's rapid tunneling was based on good equipment maintenance and tunneling management. Pursuing only tunneling speed and forcibly extending tunneling time would get half the result with twice the effort. It would not only fail to maintain stable production for a long time, but also increase the cost and manpower of subsequent equipment maintenance, and could even lead to serious equipment damage and safety 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 tunneling.
- *Logistical resource allocation*. The supporting resources for TBM construction were in great demand. After winning the bid, the contractor provided relevant logistics and support for the TBM's rapid excavation through a professional scheme. For long-distance transportation in the tunnel, the contractor set up three groups of turnout platforms in the tunnel and increased the number of diesel locomotives to ensure rapid excavation under the premise of long-distance transportation. Moreover, the material transportation capacity of each diesel locomotive was increased to one time for two segment rings to reduce the transportation times. The contractor also equipped a 4*90kW series variable frequency fan to continuously convey air in the tunnel, and together with the booster fan and dust removal fan on the TBM equipment, this formed an effective air supply circulation system, which ensured a comfortable construction environment for the workers in the tunnel.
- *Use of diversified materials.* The remoteness of the project meant there were limited resources, so the project team 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 team 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 the site on schedule and reduce downtime.

- *Use of technological innovations.* In view of the large convergence and deformation possible in the soft rock structure of the Siwalik strata, the contractor developed a "five-step grouting method" to fill the gaps behind the segments. Through rapid backfilling behind the segments, the segmental lining structure can bear uniform stress in the circumferential direction, reducing the dislocation and breakage of the segment. In the TBM tunneling stage, the filling rate behind the segment reached 91.6%, significantly more than other similar projects that showed a 75% of the filling rate. The method thus saved subsequent grouting time and construction cost, and fully matched the TBM construction progress.

- *Good safety and risk awareness.* During TBM construction, 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. No safety accident occurred during the construction of the whole project.

8.2 Reflections on Fast Advance

There were multiple reasons for the extremely good performance at this tunnel site. The site staff made it a high priority to maintain the machine daily, 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. Besides the two exceptions previously discussed, this method was successful.

The use of hexagonal segments may be another contributing factor (see Figures 9-10). 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.

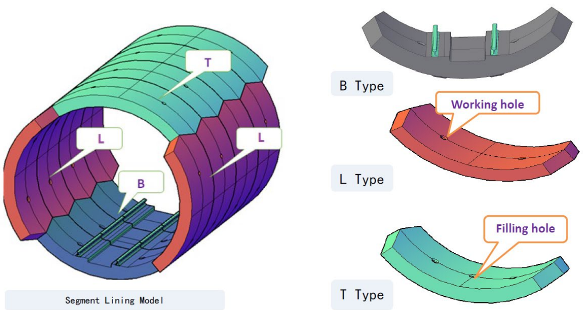
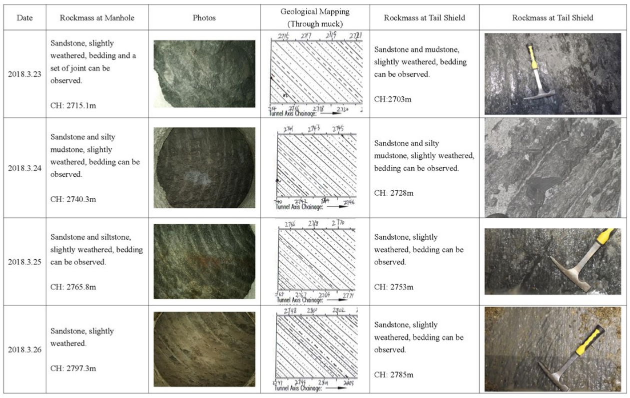


Figure 9. Hexagonal segment lining model

Figure 10. 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 was needed to keep up with the fast pace of ring builds. In addition a geologist on site conducted daily face mapping so that operational parameters and other measures could be adjusted accordingly (see Figure 11). This type of mapping is critical in mountainous tunnels where the expected geology may differ from the geological report. The geologist also analyzed the geology at the tail shield. Lastly, favorable geology was a big factor, with less water than expected in fault zones.



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		Tunnel Axis Chainage:	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		Tunnel Axis Chainage:	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		Tunnel Axis Chainage:	Sandstone, slightly weathered, bedding can be observed. CH: 2753m	
2018.3.26	Sandstone, slightly weathered. CH: 2797.3m		Tunnel Axis Chainage:	Sandstone, slightly weathered, bedding can be observed. CH: 2785m	

Figure 10. Typical face mapping reports from the onsite geologist

The success of the BBDMP, a national pride project, was critically important for the country as well as the TBM industry. It will 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. 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.

9. REFERENCES

Panthi, KK. 2019. A TBM First in Nepal. Tunnelling Journal, October / November 2019, pp. 36-40.