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Extreme Excavation in Fault Zones and Squeezing Ground at the Kargi HEPP in Turkey

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1. Summary

Multiple fault zones and squeezing ground requiring extensive bypass tunneling were just a few of the challenges to be overcome to successfully complete Turkey’s Kargı Kızılırmak Hydroelectric Project. Launched into poor geology in 2012, the 10 m Double Shield TBM experienced delays to the project that forced team members to find innovative solutions that included major in-tunnel modifications to the machine. In the first 2 km of boring a total of seven bypass tunnels were needed to free the TBM from collapsed ground. The cutterhead stalled on numerous occasions as the conditions varied widely from solid rock to running ground. Small and wide faults along the alignment added another level of complexity, as the excavation was located very close to the North Anatolian fault line in Turkey’s relatively recent rock formations.

Due to the delays, it was decided to take what was an originally 11.8 km TBM driven tunnel, and reduce it to 7.8 km with the final 4 km being excavated by drill and blast. The contractor, owner, consultants and Robbins engineers worked together to generate solutions to improve progress in the difficult conditions. A custom-built canopy drill and positioner was installed for the contractor to allow pipe tube support installation through the forward shield. Drilled to a distance of up to 10 m ahead of the cutterhead, 90mm diameter pipe tubes provided extra support across the top 120-140° degrees at the tunnel crown. Injection of resins and grouting protected against collapse at the crown while excavating through soft ground. As a result of successful use of the probe drilling techniques, the contractor was able to measure and back fill cavity heights above the cutterhead in some fault zones to over 30 m and in addition help detect loose soil seams and fractured rock ahead of the face.

This paper will go over the extreme challenges at the Kargı project, as well as the dramatic improvement in advance rates and the ultimately successful breakthrough in July 2014. A comparison will also be made with the site conditions and advance rates at the drill and blast tunnel to determine when each method of excavation is best used.

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2. Introduction

The Kargı Kızılırmak Hydroelectric Project is located on the Kızılırmak River, near the Beypazarı district of Ankara province in Turkey. The Kızılırmak (Turkish for "Red River"), also known as the Halys River (Ancient Greek) is the longest river in Turkey. The salient features of the project include a 13 meter high, 450 meter wide earth dam with a concrete spillway in the southern end and a water intake construction on the northern side. The dam creates an artificial lake with a highest water level of 405 meters above sea level. A head race tunnel diverts the water from the dam to the power house situated east of the village of Maksutlu. The water from the power house will flow into the Boyabat reservoir at 330 meters above sea level. Once online the project will generate 470 GWh of power annually, for project owner Statkraft, which is sufficient to supply approximately 150,000 homes.

2.1 TBM Supply

The Robbins Company supplied a 10 meter diameter Double Shield TBM and continuous conveyor system for excavation of the 11.8 kilometer head race tunnel to Turkish contractor Gülermak. Due to the expected variation in geology the planning for ground support regimes ranged from pre-cast segmental lining for the first 3.0 kilometers transitioning into ring beams, rock bolts and shotcrete as the tunnel moved into more competent geology. Several unique features were incorporated in the TBM design to facilitate installation of the various ground support regimes.

The Robbins 10 m diameter Double Shield was designed for mixed ground conditions (see Figure 1). Initial specifications included:

- 19-inch back-loading hard rock disc cutters
- 13 x 370 kW Variable Frequency Drive Motors
- Cutterhead Speed: 0 to 8.05 RPM
- Maximum Operating Cutterhead Thrust: 20,904 kN
- Cutterhead Torque: 9,864 kNm at 3.66 RPM
- Thrust Cylinder Stroke: 1900 mm

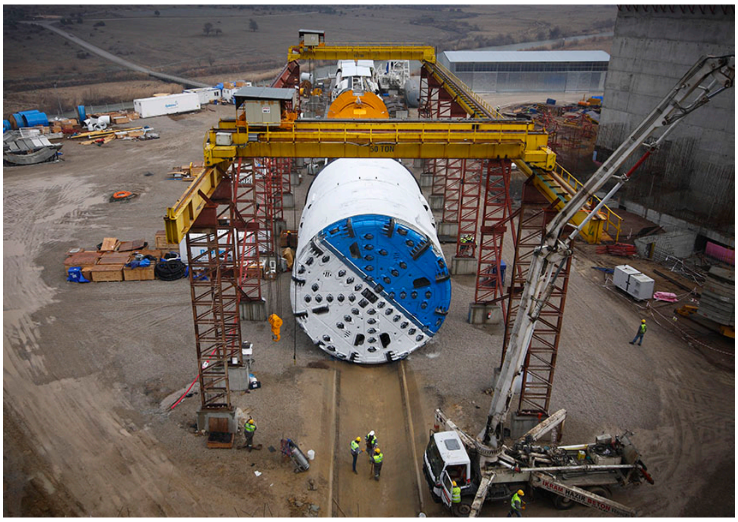

Fig.1 *Double Shield TBM at launch in Turkey*

2.2 Geology

The project area is located within the Northern Anatolian Fault System (NAFS), which is primarily responsible for earthquakes in Turkey. The tunnel was driven through a mountainside with up to 600 m of overburden. The expected geology along the tunnel alignment consisted of Kırazbası complex Kargı ophiolites (including sandstone, siltstone and marl) for the initial 2,300 meters, followed by 1000 meters of Kundaz metamorphites (including marble, metalava and metapelite), and the remaining 8,500 meters consisted ofBeynamaz Volcanites (including basalt, agglomerates and andesite). The anticipated strength of the rock was up to 140 Mpa. Multiple fault zones and transition zones added to the complexity of the geological conditions but the geological base line report did not indicate that severe problems would be encountered (See figures 2-3).

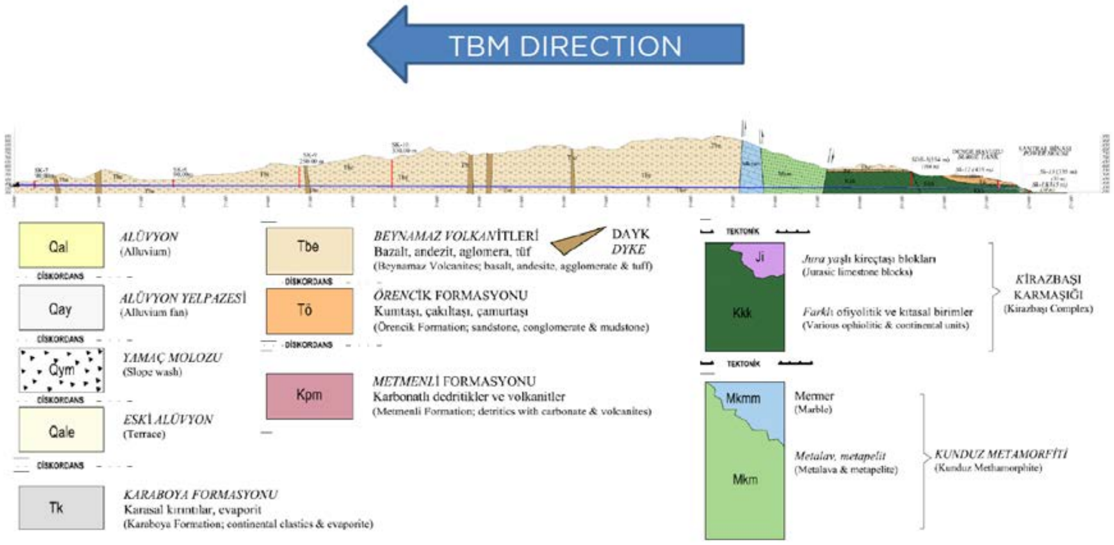

Fig. 2 Original geology along tunnel alignment

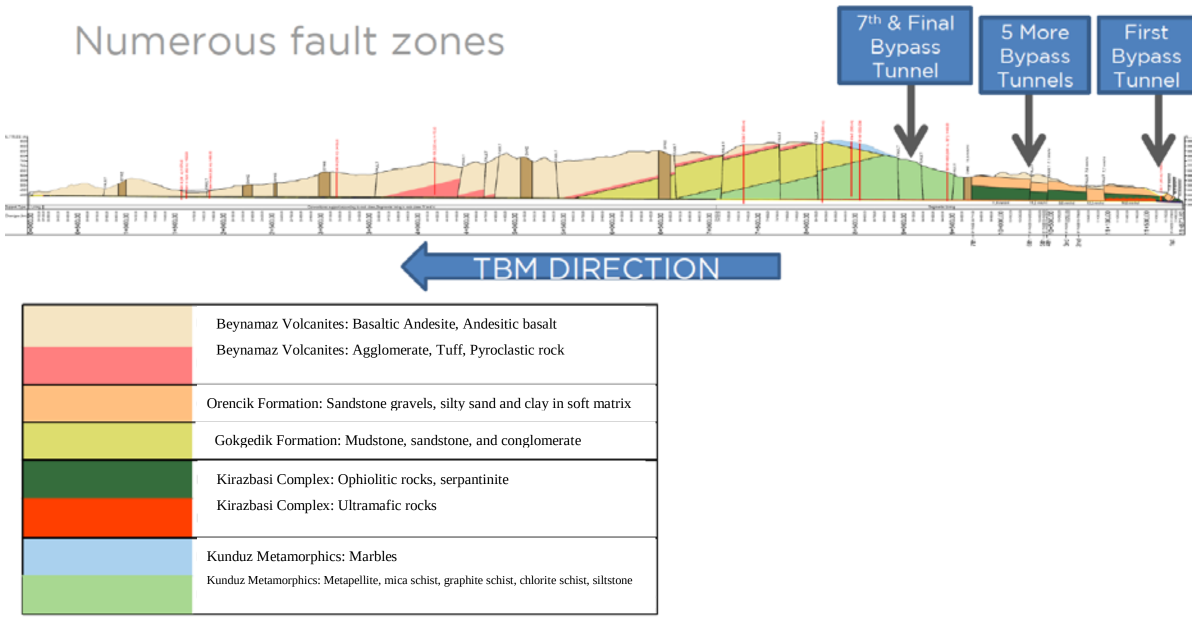

Fig. 3 Final Geology along tunnel alignment

3. Adverse Geology From Start Up

Shortly after the machine was launched adverse ground conditions were encountered. The geology consisted of blocky rock, clay, and running sand. As a countermeasure that was immediately put into place to avoid the cutterhead becoming stuck in the blocky and loose material, crews began boring half strokes and half resets. This ensured that there was always the option of rapidly retracting the cutterhead in the event that torque reached critical levels. During the first 80 m of boring through these difficult ground conditions the cutterhead stalled on numerous occasions but each time the forward shield was retracted and the cutterhead was freed. However after boring up to chainage 88 m the machine encountered a section of extremely loose running ground with high clay and sand content. A collapse occurred in front of and above the cutterhead and the cathedral effect resulted in a cavity forming that extended more than 10 m above the crown of the tunnel.

3.1 Trapped Cutterhead

The weight of the collapsed material trapped the cutterhead and even after retracting the forward shield, attempts to restart the cutterhead failed. The next course of action was to clear the cutterhead of loose material and make a further attempt at restarting the cutterhead but this also proved to be unsuccessful. It became clear that the only solution would be consolidation of the ground above and in front of the machine. This was carried out by injection of polyurethane resins via lances inserted through the cutter housings and muck buckets; however, injection locations were restricted to the available openings; hence, the consolidation was not as comprehensive as desired and subsequent attempts to restart the cutterhead proved to be unsuccessful.

3.2 Bypass tunnel

After assessing all the available options it was decided that a bypass tunnel would be required. Robbins Field Service assisted Gülermak with bypass tunnel design and work procedures to free the cutterhead and stabilize the disturbed ground. Blasting techniques were ruled out due to concern over further collapses caused by blast induced vibration; hence, the excavation was undertaken using pneumatic hand held breakers. The bypass tunnel was constructed by utilizing timber heading techniques.

Upon completion of the bypass tunnel, further stabilization of the collapsed material above the machine and the ground ahead of the machine was carried out. The injection process this time was far more comprehensive due to the vastly improved access provided by the bypass tunnel. The area around the cutterhead was able to be cleared of material and the cutterhead was freed, allowing boring to recommence.

At this point in time it was believed that the collapse was an isolated event and that the geology would improve as the overburden increased; however, material for a second bypass tunnel was stored at site. Unfortunately this measure proved to be prudent planning. Although the machine passed through several weak zones successfully, a further six bypass tunnels were required to free the cutterhead during the first 2.1 kilometers of boring.

3.3 Improved bypass tunnel methodology

Robbins and Gülermak analyzed the bypass tunnel excavation methodology and implemented improvements that resulted in a reduction in the time taken for bypass operations from 28 days to 14 days. One of the main aspects of the improved procedures was the implementation of breaking out for the bypass tunnel through the telescopic shield area of the TBM rather than the accepted norm of breaking out from the tail shield. This modification resulted in reducing the length of each bypass tunnel by over four meters. It also facilitated the installation of gangways that extended from the portal of the bypass tunnel to the TBM conveyor. Wheel barrows were used to transfer the excavated material from the bypass tunnels, across the gangways and subsequently tipped directly onto the TBM conveyor via a purpose-built muck chute. Details of the design of the bypass tunnel can be seen in figure 4.

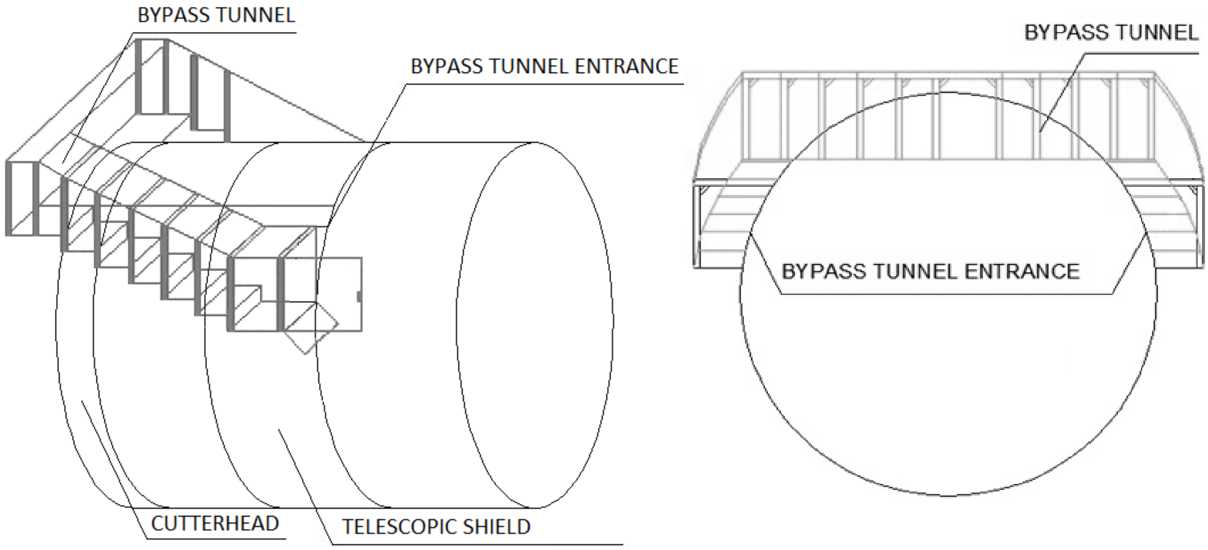

Fig.4 Bypass tunnel

3.4 Pipe roof canopy

The possibility of installing ground support such as fore-poles or a pipe roof canopy ahead of the tunnel face was investigated as a means of supporting loose and fractured ground. After consultation between Robbins and Gülermak a custom design canopy drill was delivered to site and installed in the forward shield for installation of a tube canopy (See figure 5). The space in the forward shield area is limited; hence the extension section of each tube is only 1.0m in length. However the advantages of drilling closer to the tunnel face more than compensates for the time spent adding extensions to the tube length. The location of the canopy drill reduces the length of each canopy tube by more than 3 meters when compared to installation using the main TBM probe drills.

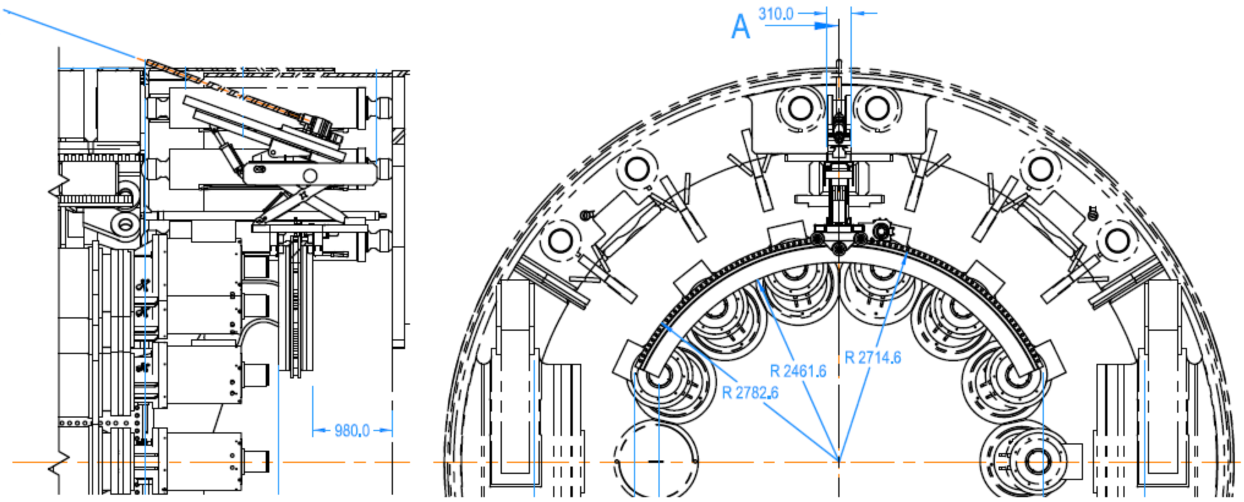

Fig. 5 Custom canopy drill

Apart from the obvious savings in drilling time, the extra 3 meters of drilling length can result in a significant increase in hole deviation. The diameter of the canopy tubes is 90 mm, each canopy typically extends up to 10 m from the tunnel face and the drill positioner, carriage and slew ring provide 130 degrees of coverage A total of nine canopies were installed between chainage 2135 m and chainage 2276 m.

3.5 Squeezing Ground

The time dependency of ground behavior is due to the creep and consolidation processes taking place around the tunnel (Anagnostou & Kovári 2005). In many cases the convergence can be a gradual process taking place over a period of days, weeks or even months. On several stretches of the Kargı tunnel, rapid convergences occurred in the space of a few hours. The geology at the time of these rapid convergences consisted of Serpentine with high content of swelling clay. The convergence was of a radial nature, and distributed relatively evenly around the profile of the TBM.

Probe drilling ahead of the tunnel face identified the majority of the areas considered to be at risk from squeezing conditions. As it is generally accepted that there is a direct relationship between TBM advance rates and problems caused by squeezing ground, it was essential that TBM downtime was minimized while boring through these stretches. On the occasions that squeezing ground had been identified all outstanding maintenance works, repairs and replacement of worn cutters was completed before boring through the zone of concern commenced. Inevitably, even after taking these precautions there were unscheduled stoppages. On many occasions the only successful means of restarting the machine after stoppages in convergence zones was to utilize single shield mode boring. In this mode the TBM gripper shoes are retracted, the main thrust cylinders are closed up and the auxiliary thrust cylinders are utilized to propel the machine forward by thrusting off the segmental lining. The typical thrust force for standard boring operations using the main thrust cylinders on the Kargı machine is approximately 21,000 kN. On several occasions thrust force up to 136,000 kN was applied through the auxiliary thrust system before the machine could be freed from squeezing ground. Generally after boring one or two meters in single shield mode the TBM was freed and it was possible to return to double shield mode. On several stretches of tunnel the rate of convergence coupled with the comparative softness of the ground caused the gripper shield to act as a plough and force muck into the telescopic shield area. The buildup of material became so severe that a mucking system had to be installed in the telescopic shield area. The system consisted of two electric hoists mounted on a running beam that allowed muck kibbles to be placed, lifted, and emptied directly onto the TBM conveyor.

Another measure utilized to combat the effects of the squeezing ground was the application of a polymer based biodegradable lubricant to the extrados of the TBM shields. Eight injection ports were installed around the perimeter of the forward shield and lubrication was injected when boring through convergence zones. It is difficult to quantify the advantage obtained as there was very little consistency in ground conditions and associated thrust pressures; however, it is clear that the application of lubrication reduced the frictional forces between the shields and converging ground.

3.6 Gear Reducers

To further mitigate the effects of squeezing ground or collapses, custom-made gear reducers were ordered and retrofitted to the cutterhead motors. They were installed between the drive motor and the primary two-stage planetary gearboxes. During standard boring operations the gear reducers operate at a ratio of 1:1, offering no additional reduction and allowing the cutterhead to reach design speeds for hard rock boring. When the machine encounters loose or squeezing ground the reducers are engaged, which results in a reduction in cutterhead speed but the available torque is increased. Figure 6 shows the torque curves for both standard and reduced gearing. After the installation of the canopy drill and the increase in available cutterhead torque, the TBM traversed several sections of adverse geology including stretches of severe convergence without becoming trapped.

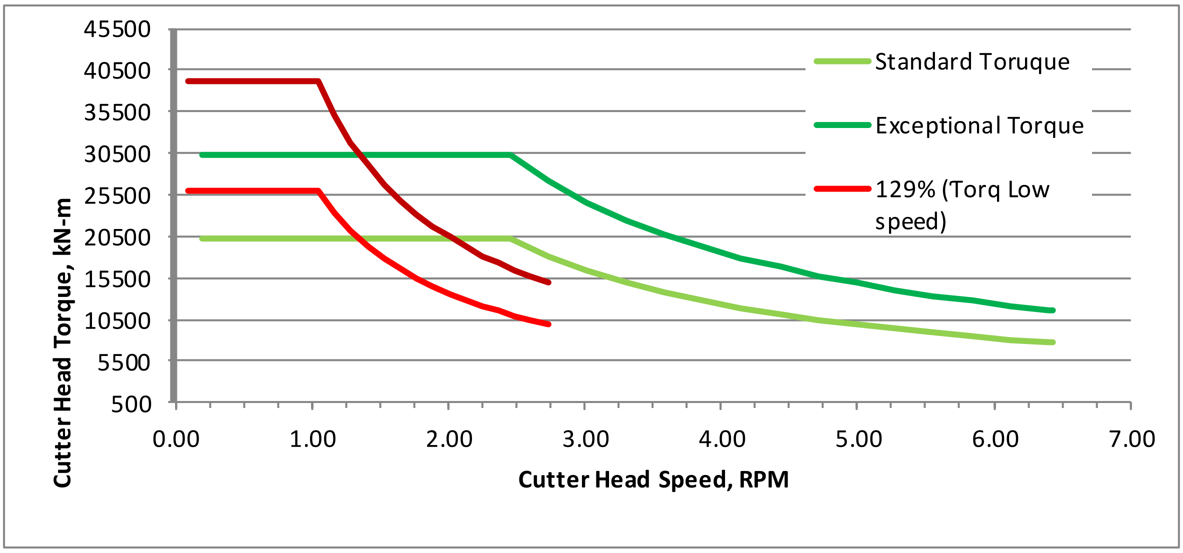

Fig. 6 Cutterhead torque curves

4. Comparison Of TBM Operations Against Drill & Blast Operations

Due to the delays resulting from adverse geological conditions, it was ultimately decided to reduce the length of the TBM driven tunnel to 7.8 km and drive the remaining 4 km of tunnel from the inlet portal by utilizing drill and blast methodology.Drill and blast operations commenced from the inlet portal in July 2012 and the tunnel was driven utilizing NATM support techniques. It was expected that advance rates in the drill and blast section would be relatively high due to the competent rock of the Beynamaz Volcanites along this section of the alignment.

4.1 Support Regimes

The original planning for the TBM tunnel was to use a precast segmental lining for only the initial 3 km of boring but due to the unexpected geological conditions it was decided to continue with the segmental lining for the whole length of the TBM drive. The support regimes utilized in the drill and blast section are shown in Table 1.

***Table 1.** Rock class and supports regimes*

Rock Class	Length	Shotcrete Thickness	Lattice Girders Per Running Meter	Rock Bolts Per Running Meter
II	770 m	6 cm	0	4 x 3 m
III	3,100 m	15 cm	0	6 x 4 m
IV	130 m	30 cm	1	8 x4 m

4.2 Production Rates

The chart in Figure 7 shows the comparative advance rates per month for both the drill and blast and TBM operations. From the launch of the TBM in March 2012 up until the end of July 2013 the TBM encountered 2,228 meters of extreme geological conditions, which required seven bypass tunnels and nine pipe roof canopies; hence, a direct comparison between the drill and blast operations and TBM operations is not possible for this period.

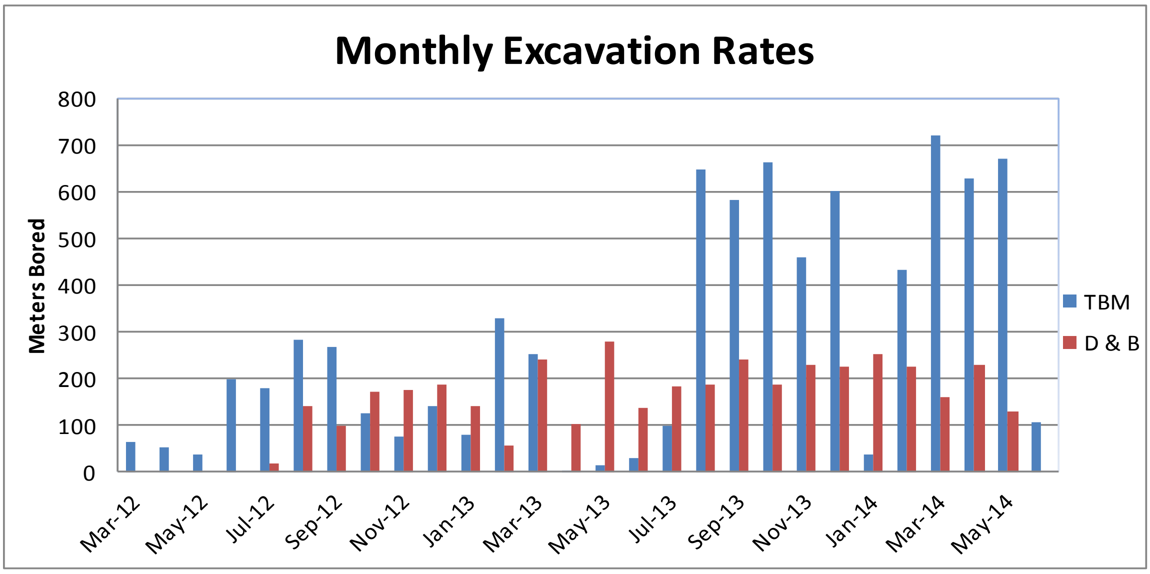

Fig. 7 Monthly production rates

It wasn't until the beginning of August 2013 that the TBM encountered geology of a very similar nature to that of the drill and blast operations. Analysis of the monthly production rates from August 2013 through to the breakthrough in June 2014 clearly shows that the TBM operations achieved far superior advances rates to that of the drill and blast operations and regularly achieved production rates of over 600 meters per month, with a best month of 723m.

To provide a clearer comparison of the performance of the TBM operations against the drill and blast operations the chart in Figure 8 shows the comparative advance rates while boring through the Beynamaz Volcanites. It can be seen that the drill and blast operations took twenty three months to complete 4,000 m of tunnel whereas it took less than 8 months for the TBM operations to complete the same length of tunnel. During this period the TBM production rates could have been higher still, but the segment plant was unable to produce enough rings to meet the high advance rates. Based on these production rates it would have taken approximately 32 months for the drill and blast operations to achieve the same production as the TBM achieved in 8 months.

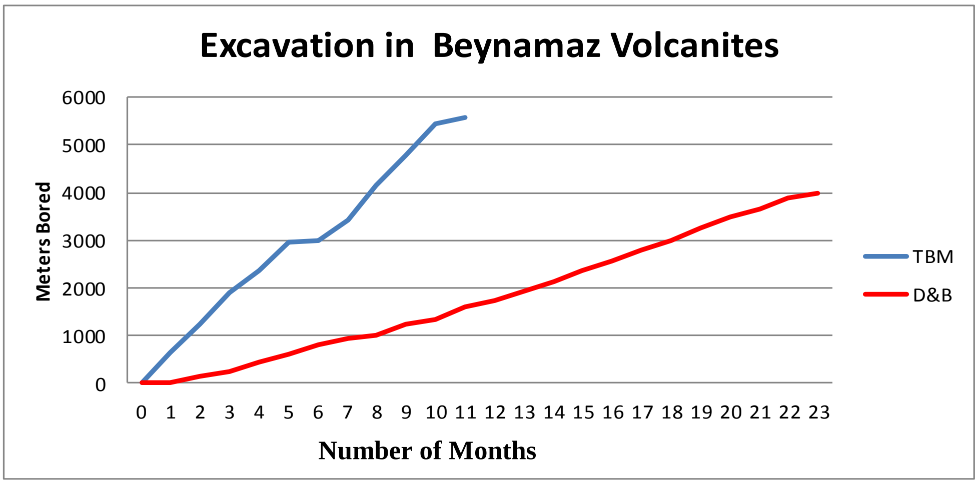

Figure 8. *Advance rates in Beynamaz Volcanites*

Although a direct comparison cannot be made between the TBM and drill and blast operations for the extreme conditions faced by the TBM during the first 2,228 m of boring, a comparison can be made of the performance while boring through various geological conditions faced on the project. Table 2 shows the average comparative advance rates for both the TBM and drill and blast operations in various ground conditions and includes the performance of the TBM both before and after the modifications were carried out.

The comparison in good stable rock is relatively straight forward due to the TBM not having encountered any good stable rock prior to the modifications. It can also be assumed that the modifications would have had little effect on the machine's performance in good stable ground. In this case the data show that the drill and blast operations achieved approximately 35% of the production rates of the TBM operations.

The comparison in fairly stable rock shows a substantial improvement of almost 96% in the TBM's performance after the modifications had been carried out. This can be mainly attributed to the gear reducers providing an increase in CHD torque, which prevented the CHD from stalling when overloaded with loose blocky material. The drill and blast operations managed to achieve approximately 28% of the production rates of the modified TBM in these ground conditions. The data also shows that the reduction in the TBM's performance in fairly stable rock compared to that of good stable rock was only 3.5 meters per day, which is equivalent to 16%, whereas the reduction in the drill and blast performance was 2.5 meters per day, which is equivalent to 32%. The reduced production in the drill and blast tunnel was mainly due to the shortened round length and additional support requirement per running meter. In this case the poorer geological conditions had a greater impact on the drill and blast operations than that of TBM operations.

Table 2. *Advance rates in various ground conditions*

Advance Rates in Various Ground Conditions			
	TBM (Before Modifications)	**TBM (After Modifications)**	**D&B**
Good Stable Rock	N/A	22.5 m/day	8 m/day
Fairly Stable Rock	9.7 m/day	19 m/day	5.5 m/day
Non-self-supporting rock	4.7 m/day	8.5 m/day	1.5 m/day
Running/squeezing ground	1.3 m/day	1.8 m/day	N/A

The comparison in non-self -supporting rock again shows a substantial increase of over 80% in the production rates of the TBM after the modifications where carried out. This increase can be attributed to the custom built pipe roof drill, the increase in CHD torque and the mucking system that enabled faster clearance of the buildup of loose material in the telescopic shield area of the TBM. The drill and blast operations managed to achieve only 18% of the production rates of the modified TBM in non-self-supporting rock. Although reduced round length was a factor, the most significant factor was the time taken for installation of temporary and permanent ground support. Permanent ground support included installation of lattice girders, shotcrete lining with a thickness of up to 30 cm, and eight rock bolts of 4.0 m length per running meter of tunnel. Temporary support consisted of forepoles. The data also shows that the TBM achieved 55% less production in non-self-supporting rock than in fairly stable rock, whereas the production in the drill and blast operations was reduced by 73%. This again indicates that that deteriorating geology had a greater impact on the drill and blast operations than that of TBM operations.

The comparison in running/squeezing ground conditions shows an increase of 29% in the production rates of the TBM after the modifications where carried out. Again this increase can be attributed to the pipe roof drill, increase in CHD torque and faster clearance of the buildup of material in the telescopic shield area. The application of lubricants via the injection ports around the extrados of the TBM shields also contributed to the overall performance of the TBM while boring through squeezing ground. The reduction in the TBM's performance in running/squeezing ground compared to that of non-self-supporting rock was substantial at 6.7 meters per day which is equivalent to 79%.

The drill and blast operations did not encounter any running or squeezing ground so an actual comparison of the reduction in production rates due to deteriorating geology cannot be made; however the author of this paper has experience of NATM tunneling in squeezing and running ground hence experience gained on a previous project will be used for the sake of comparison. The methodology utilized for excavation when running/squeezing ground conditions were encountered on the Pir Panjal rail tunnel project in Kashmir, India is shown in figure 9 (This methodology is generally accepted in the industry). A top heading utilizing a temporary invert was driven first, followed by a bench excavation and installation of a permanent invert. Lattice girders and forepoling is required and a central core or buttress is left unexcavated at the center of the face to provide additional support. Full-column grouted face bolts are installed for face support. Each sector of the face from sector 1 through to sector 8 is excavated individually as shown in the numerical sequence. This involves removal of the face bolt bearing plates, followed by excavation. Once the single sector of excavation is complete the face bolts are cut off close to the newly excavated face before, installation of mesh, new bearing plates and shotcrete can be applied. After the completion of all eight sectors the temporary invert is excavated and shotcreted.

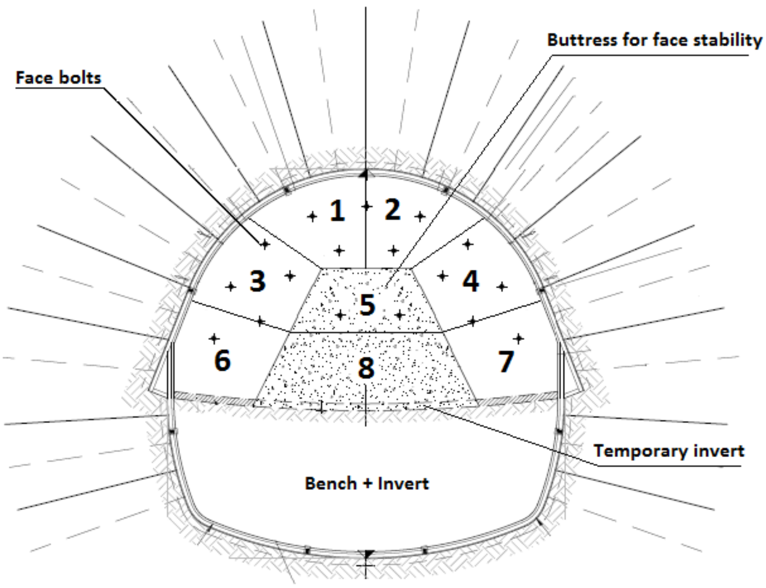

Fig. 9 *NATM excavation in running/squeezing ground*

Typical round lengths for this type of excavation are approximately 1.0 m and the completion of a single round of the top heading in 36 hours is considered to be good progress. This of course still leaves the bench section to excavate and support which may also require sectored excavation. The bench can be excavated as a stand-alone activity approximately 100 meters from the top heading but it will inevitably cause a certain amount of disruption to the top heading excavation. Even if we ignore the time required for the bench excavation the average expected advance rate for this type of excavation is approximately 0.7 meters per day which is a reduction of 0.8 meters per day or 53% of the production achieved with NATM in the non-self-supporting ground. In this case the adverse geological conditions would have a greater impact on the TBM operations than that of the drill and blast operations; however, the overall production rates of the TBM still remain over 2.5 times higher than that of the estimated rate for the drill and blast operations.

5. Conclusions

There is great deal of reluctance on the part of contractors to utilize TBMs on projects that face difficult or unknown geological conditions. This is mainly because there is a history of projects suffering substantial delays due to TBMs being unable to cope with adverse geological conditions. It is because of these problematic projects and the lessons learned that modern day TBMs are far better equipped than their predecessors to deal with adverse geological conditions. The additional technical features that were retrofitted to the Kargi TBM improved the machines performance in all ground conditions and had these features been installed during the manufacturing process it is safe to assume that the number of required bypass tunnels would have been reduced. Analysis of the Kargi project goes a long way towards answering the question: ‘When is it suitable to utilize a TBM?’ The TBM substantially outperformed the drill and blast operations in all comparable geological conditions and achieved production rates in running and squeezing ground that were better than the drill and blast operations achieved in relatively straight forward non-self-supporting rock.

6. References

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