Excavating Turkey's Hardest Rock at the Bahce-Nurdag Railway Tunnel

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ABSTRACT

Southeastern Turkey's Gaziantep province is characterized by complex fractured rock within the Eastern Anatolian Fault, and it is now the location of an important railway tunnel project. With a population of nearly 1.7 million, the province is overhauling its public transportation with a rail line between the towns of Bahçe and Nurdağı. The Bahce-Nurdag Railway Tunnel consists of two parallel 9.75 km tunnels being excavated by both NATM (850 m) and TBM (8.9 km).

Contractor Intekar Yapi Turizm Elektrik Insaat San. ve Tic. Ltd. Sti chose a Robbins Single Shield TBM, 8 m in diameter, to excavate two sections of tunnel. Mixed ground conditions prevail on the project, and range from abrasive, interbedded sandstone and mudstone with quartzite veins to highly weathered shale and dolomitic limestone. The TBM has thus far encountered some of the hardest rock ever tunneled in Turkey, measuring between 136 and 327 MPa UCS.

This paper will analyze TBM performance, as well as the performance and wear of disc cutters in the difficult ground conditions. It will discuss TBM design and project logistics including onsite TBM assembly in a remote area of Turkey. Finally, it will give recommendations as to proper TBM design and cutter usage in hard, abrasive rock based on the project results.

Key Words: Bahce Nurdag, Disc Cutters, Hard Rock, Turkey

1. INTRODUCTION

The 17 km long double-track railway project for owner Turkish State Railways (TCDD) will include the longest railway tunnels in Turkey once complete (10.1 km total length). The railway will bridge a gap of one of the busiest railway sections between Toprakkale and Malatya where trains can only proceed with the support of an additional loco (see Figure 1). With the new project, totalling € 65 million, the route between Bahçe and Nurdağı will be 15 km shorter, with gentler gradients (dropping from 27% to 15%), wider curves (minimum radius will increase from 500 m to 1,500 m) and proceed at faster speeds (from 40 km/h to 120 km/h).

It is planned to complete the tunnelling portion of the project by the end of 2019 and to open the new section of line to traffic by 2023.

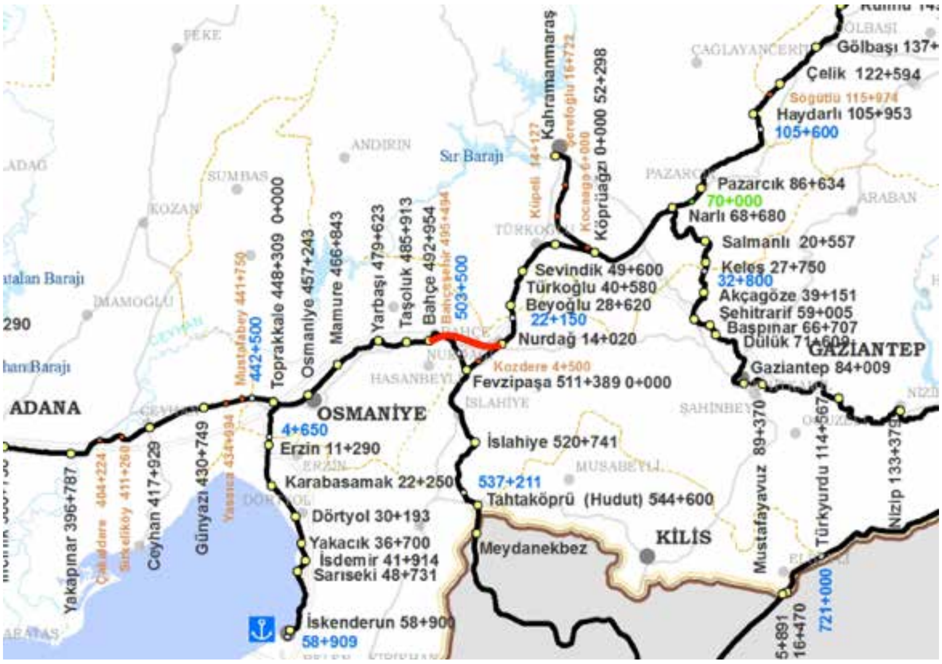

Figure 1. Bahce-Nurdag Railway Route Map (in red). Image Credit: railturkey.org.

2. GEOLOGY: MECHANICAL AND PHYSICAL PROPERTIES

2.1. Geology

The excavation of the tunnel was planned to start from chainage 13+450 m and to terminate at chainage 3+700 m. The chainage from 13+450 m to 12+400 consists of Karadag Limestone of Mesozoic age, which is affected by the East Anatolian Fault (EAF), fracturing the rock formation to a great extent. High water ingress was expected in this area. Karadag Limestone discharges the water at the foot of the mountain on the Nurdagi side. Several springs are present along the EAF, which is a large strike slip fault about 550 km long extending from the Gulf of Iskenderun to the North Anatolian Fault with a strike of 60°E. This fault takes up most of the motion between the Turkish and Arabian plates. Due to technical difficulties and time necessary to provide the TBM, the first 1050 m in limestone was planned to be excavated by the New Austrian Tunnelling Method (NATM) (Bilgin et al, 2016) since a risk analysis showed that this area was risky to very risky for TBM excavation. The geologic cross section of this area, which was planned to be excavated by drill and blast method, is seen in Figure 2. However it should be pointed out that only 850m of this tunnel could be excavated by NATM.

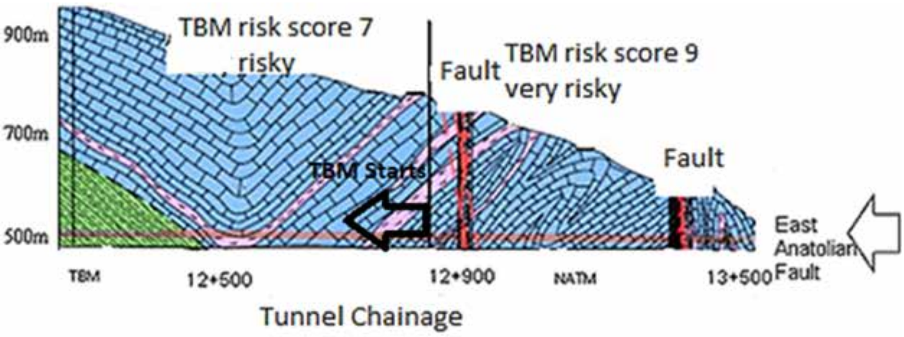

Figure 2. Cross section of the Nurdagi tunnel planned to be excavated by NATM.

The geological formation from chainage 12+400 m to 4 +850 m consists of middle-Ordovician-aged Kızlaç Formation of very massive inter-bedded meta-sandstone, meta-quartzite and meta-mudstone with very high strength and abrasivity characteristics. This section is planned to be excavated with a single shield hard rock TBM. However, the massive characteristic of the rock formation changes from chainage 4+850 m to 3+700 m, being affected by local faults and shear zones; in this zone RQD values are very low and high water ingress is also expected. This section is planned again to be excavated with NATM.

2.2. Mechanical and Physical Properties

The strength characteristics and the ratio of compressive strength to tensile strength play an important role in determining the optimum penetration of disc cutters, and thus, net penetration rates of TBMs. Compressive and tensile strength values of the rocks to be encountered in the Nurdagi Railway Tunnel route are given in Tables 1 and 2

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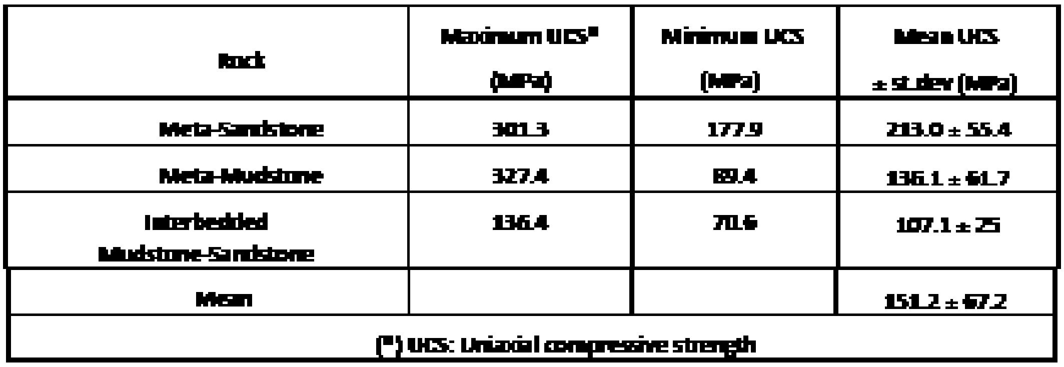
A series of Schmidt Hammer tests (N-type) were carried out in the field during the site visit. The mean values obtained in the field for meta-sandstone are 56.4 ± 5.6, for meta-mudstone 34.8 ± 9.7 and for limestone is 56.1 ± 4.8.

Basic parameters affecting tool consumption of a TBM are the abrasivity, strength and geological discontinuities of the formation to be excavated. After petrographic analysis carried out on the rock samples, the meta-sandstone and the meta- siltstone are classified as very abrasive with quartz content varying from 48 to 68%.

The sandstone is composed mainly of quartz with minor feldspar, opaque and rock fragments. The grains are cemented by chlorite. A thin chlorite cement holds the grains together. The sandstone can be classified as quartz arenite. The mean quartz content is 68% with grain sizes varying between 0 and 0.3 mm.

The mudstone (siltstone) consists of angular quartz grains embedded in a voluminous matrix of sericitic muscovite, opaque, chlorite, feldspar and quartz. It shows a distinct cleavage defined by the parallel orientation of the mica grains. The mean quartz content is around 48% with grain sizes between 0.05 and 0.1 mm.



Rock	Maximum UCS* (MPa)	Minimum UCS (MPa)	Mean UCS ± st.dev (MPa)
Meta-Sandstone	301.3	177.9	213.0 ± 55.4
Meta-Mudstone	327.4	89.4	136.1 ± 61.7
Interbedded Mudstone-Sandstone	136.4	70.6	107.1 ± 25
Mean			151.2 ± 67.2
(*) UCS: Uniaxial compressive strength			

Table 2. Tensile strength of the rocks in the tunnel route

Rock	Maximum UTS* (MPa)	Minimum UTS (MPa)	Mean UTS ± st.dev (MPa)
Meta-Sandstone	27.2	11.63	17.8 ± 2
Meta–Mudstone	19.2	17.6	18.8 ± 1.1
Mean			18.1 ± 1.5
(*) UTS: Uniaxial tensile strength			

3. FULL-SCALE LABORATORY TESTS AND ESTIMATION OF TBM PARAMETERS

Two block samples of meta-sandstone and meta-mudstone were subjected to full-scale laboratory rock cutting experiments (Bilgin et al., 2017). A constant cross-section disc cutter with a tip width of 1.2 cm and ring diameter of 13 inches (330 mm) was used in the experiments. A testing program with a constant cutter (line) spacing of 80 mm including relieved and unrelieved cutting patterns was set and depth of cut was varied (3, 5, 7 mm). The sample surface was cut several times to condition the surface similar to the real case of a tunnel face. Normal, rolling and side forces were recorded, muck samples were collected and their weights were measured during each cut. Force values were reduced by a custom-made macro program. The meta-mudstone sample was cut parallel to the bedding planes. Based on the experimental results, optimum line spacing to penetration ratio was determined for the TBM to be used in the tunnel. As a basic rule of rock cutting mechanics, specific energy--defined as the energy consumed per unit volume of the excavated rock--is optimum for a given s/d (cutter spacing / cutting depth) ratio. In optimum conditions, the energy spent to excavate a unit volume of rock is minimal. Cutter spacing is a constant value of a TBM cutterhead, which dictates that for a given rock formation the predetermined cutting depth in the laboratory will determine the optimum thrust values of the excavating machine. In the light of these main rules, an intensive laboratory full-scale cutting test program was planned to obtain the relationships between cutting depth and cutter force values, specific energy and s/d ratio for two rock samples. The cutting test results are discussed in Bilgin at al. 2017 and summarized in Table 3.

Table 3. TBM recommended and actual parameters.

Parameter	Recommended Value	TBM Manufacturer Val
Disc number and diameter	53, 19"	53, 19"
Maximum load per disc	311	311 kN
Disc spacing	80	77.6 mm
Total power	3250 kW	10x330 kW
Cutterhead torque	4500 kNm	4588 kNm at 6.9 rpm
Exceptional torque	N/A	14453 kNm at 0-3.3 rpm

mmended thrust based on disc bearing capacity	16483 kN	16503 kN
Maximum thrust	N/A	18543 kN

4. MACHINE DESIGN

The design of the Bahce-Nurdag Single Shield TBM was optimized for variable geology and for the results obtained by laboratory testing. A high-speed segment erector and hoist with mechanical pickup were designed to build segment rings of 350 mm thickness in a 5+1 arrangement. The system allowed for pea gravel injection and grouting through the segments for backfill. 360 degree probe drill coverage was provided to allow for systematic probing of ground conditions and grouting if necessary (see Figure 4 - TBM General Assembly).

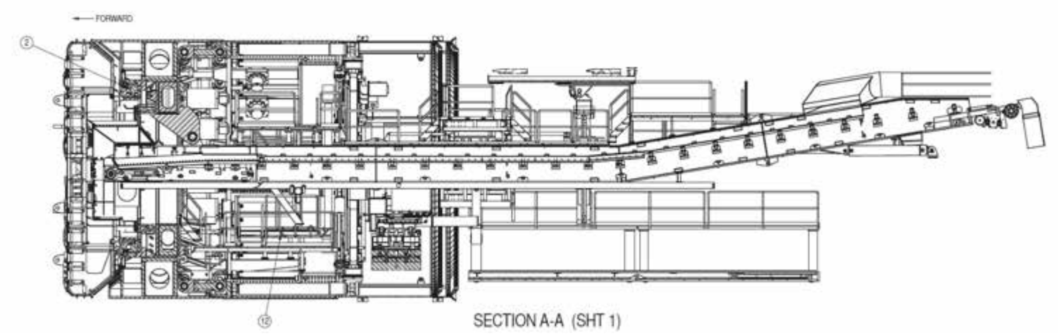


Figure 4. TBM General Assembly Cutaway View.

4.1. Emergency Sealing System

In the case of a large inrush of water or mud, the uniquely designed Single Shield TBM can engage an emergency sealing system consisting of muck chute closure doors. Since the conveyor is a belt conveyor and is not enclosed like a screw conveyor, it must be sealed off at the front. The bulkhead has a large sealing gate just above the belt conveyor. These are pressure relieving gates. These gates can also be used in a semi-EPB mode: As the pressure builds in the cutting chamber, the gate is opened by the pressure, and material spills onto the belt. As the pressure is relieved, the gates then automatically close, again sealing off the chamber.

In extreme cases, the gates can be sealed and the probe/grout drills can be used to forward drill and grout for ground consolidation and to seal off the water (see Figure 5 – A generalized schematic of the emergency sealing system).

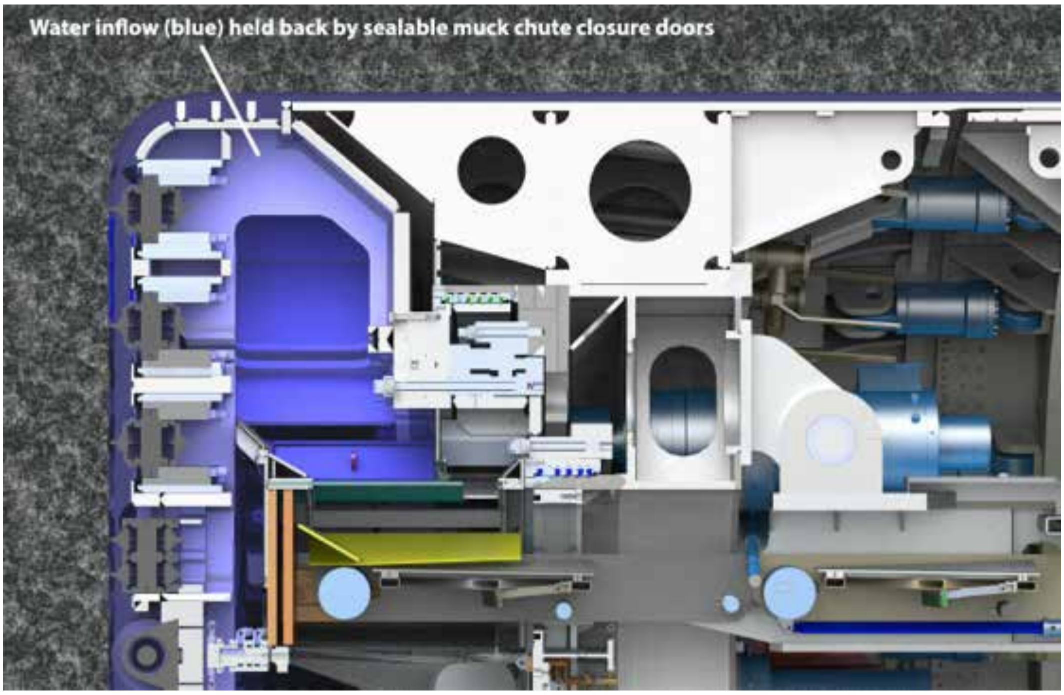


Figure 5. Water inflow (blue) can be sealed off inside the muck chamber with closure doors.

5. ONSITE FIRST TIME ASSEMBLY (OFTA)

Onsite First Time Assembly, or OFTA, was deemed the most efficient method of TBM assembly due to the remoteness of the site and proximity to a conflict area (the jobsite is about 48 km from the Syrian border). OFTA is a method developed by Robbins that allows for the TBM to be initially assembled at the jobsite rather than in a manufacturing facility, saving the contractor up to three months on the delivery schedule and millions in USD (see Figure 6).

While several villages were nearby and roadways gave good access, the logistics of shipping internationally was challenging. Crews often had to wait for small items such as cables, lights, and hydraulic fittings that could not be sourced in Turkey. Customs clearances were difficult to obtain and resulted in delays of international shipments. Despite this, the machine was completed in early 2016, and following a ceremony in January, was walked forward to the entrance of a 500 m long starter chamber. Once the tail shield was flush with the portal entrance, an invert thrust frame was installed that allowed the machine to build full starter rings, complete with pea gravel and grout backfill, up to the launch face.

Figure 6. Onsite First Time Assembly of the Single Shield TBM.

6. TBM EXCAVATION

6.1. Challenges at Startup

The machine was launched in March 2016. As only 13 bore holes could be drilled along the tunnel route due to high overburden and field difficulties, it was obvious that the East Anatolian Fault, as explained in section 2, was a limiting factor for the efficient excavation of any type of TBM. Prior to selecting the TBM, a risk analysis was carried out, and it was found that from the tunnel portal up to chainage 12+850 m the use of a TBM would be very risky and from this point up to chainage 12+500 m the use of a TBM would be risky. It was recommended to excavate the first 1250 m by NATM, (Bilgin et al., 2016 & 2017). However, as seen from Figure 7 the tunnel face was very fractured with high water inflows and only an advance rate of 1 m per day could be reached. Due to this fact only 850 m of tunnel were excavated by NATM before the arrival of the TBM. The TBM started excavation at chainage 12+854 m. Surprisingly, the rock formation from 12+450 m up to 11+450 m was very weak graphitic schist with a high water ingress. A water ingress of 400 l/s was encountered between chainages 12+420 m and 12+450 m. Within 1000 m of this weak zone, the TBM became stuck several times due to face collapses and the squeezing effect of the graphitic schist. Two bypass galleries were excavated at ring 1071 chainage 11+840m and ring 9250 chainage 12+075 m

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The cumulative advance of the TBM in meters, in relation to the time of excavation, is seen in Figure 8. Despite very bad ground conditions, the TBM succeeded in excavating 1050 m in 270 days, which averages to 4 m a day.

Figure 7. General view of tunnel face in the risky area for TBM. Note high water inflows.

6.2. TBM Performance

The TBM was very successful in very hard and abrasive rock formations after chainage 11+400m (see Figure 8). Mean daily advance rates changing from 10 to 16 m can be seen in Table 4. Typical values for March 2015 are given in hard interbedded meta sandstone and meta mudstone as 11.8 m per day.

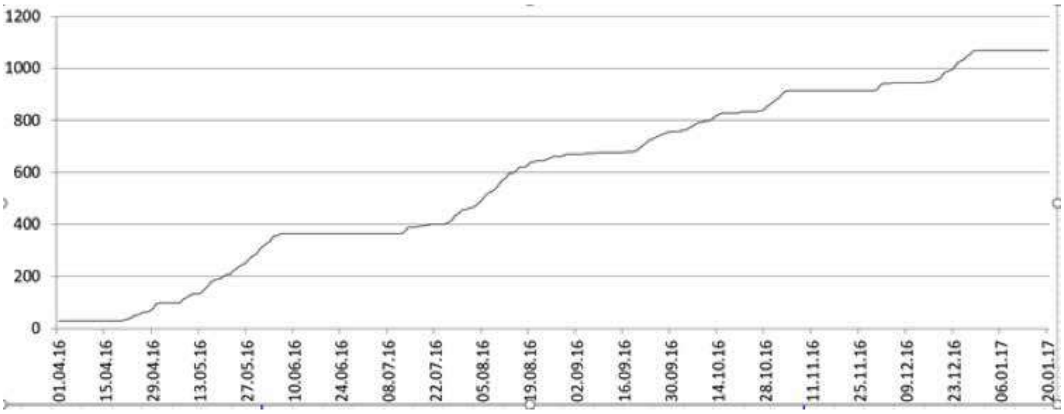
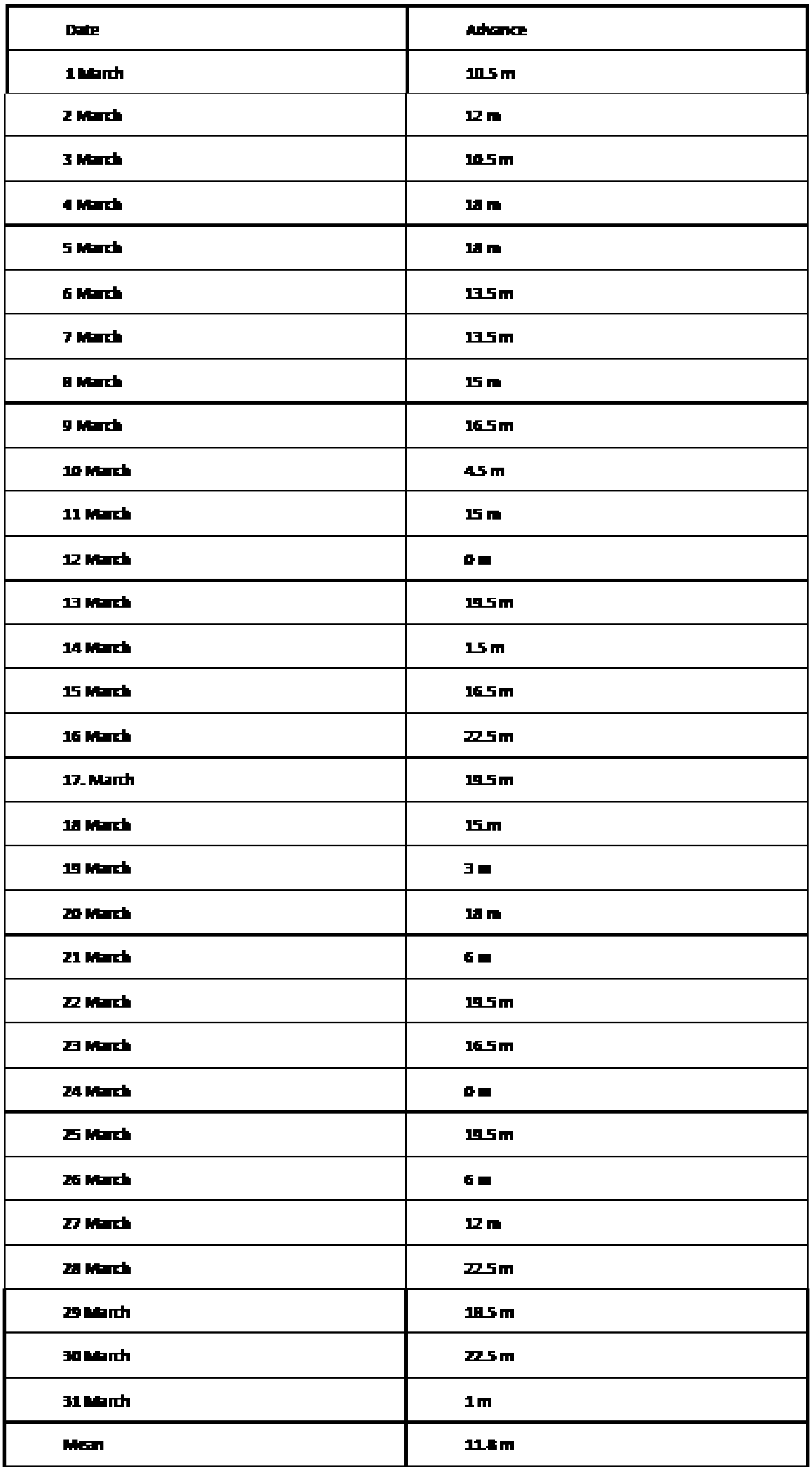


Figure 8. The cumulative advance of TBM in meters in relation to the excavation date.

Table 4. Daily advance rates in some areas.



Date	Advance
1 March	10.5 m
2 March	12 m
3 March	10.5 m
4 March	18 m
5 March	18 m
6 March	13.5 m
7 March	13.5 m
8 March	15 m
9 March	16.5 m
10 March	4.5 m
11 March	15 m
12 March	0 m
13 March	19.5 m
14 March	1.5 m
15 March	16.5 m
16 March	22.5 m
17. March	19.5 m
18 March	15 m
19 March	3 m
20 March	18 m
21 March	6 m
22 March	19.5 m
23 March	16.5 m
24 March	0 m
25 March	19.5 m
26 March	6 m
27 March	12 m
28 March	22.5 m
29 March	18.5 m
30 March	22.5 m
31 March	1 m
Mean	11.8 m

To date, typical mean cutter consumptions have been as follows:

- 4.83 m/disc in quartzite
- 4-9.4 m/disc in meta sandstone
- 12.7 m/disc in interbedded meta sandstone and meta mudstone

Current excavation is going well of December 2017, with the machine having finished nearly 50% of the tunnel length.

7. CONCLUSIONS

Difficult to extreme geology, limited access to the project area and challenging working conditions on site make the Bahce-Nurdag Railway Tunnel Project a remarkable and special one in the industry. An intelligent combination of two tunnelling methods, excavation by NATM and fully mechanized tunnelling with a Hard Rock Single Shield TBM, was selected to provide for the most efficient and safe tunnel excavation. For the sake of optimal TBM design, intense studies of the rock properties were taken in advance and this has proven the correct approach. Well proven features were added to the design of the TBM for crossing difficult and varying ground formations. Delivery to site did not allow shipment of big bulk items and onsite first assembly was successfully employed to overcome this given restriction. The machine's performance in the extreme and difficult ground formations right after start and where TBM employment was qualified as risky to very risky demonstrated the approach taken was the right one. TBM excavation was worth the efforts made in special design and detailed studies of the rock formations. - This performance is proof of modern TBM design and machine performance in ground formations where in the past employment of mechanized excavation methods was not possible or would not be practical over NATM. The industry is well on its way to design and deliver TBM for almost all ground formations – limitations are steadily decreasing and very soon will have disappeared completely.

8. ACKNOWLEDGEMENTS

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