TBM Excavation in Difficult Ground Conditions
Case Studies from Turkey

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Preface

The use of tunnel boring machine (TBM) tunneling has increased considerably in the past ten years in Turkey. It is planned to excavate 200 km of tunnels in the near future in Istanbul alone, and 100 km of tunnels in other parts of Turkey. Thirty new TBMs are predicted to start working in Istanbul during 2017.

The geology of Turkey is complex, and the country is in a tectonically active region; on a broad scale, the tectonics of the region are controlled by the collision of the Arabian Plate and the Eurasian Plate. The Anatolian block is being squeezed to the west. The block is bounded to the north by the North Anatolian Fault and to the south-east by the East Anatolian Fault. The effects of these faults are seen clearly on the performance of TBMs used in these regions.

This book is written with the intention of sharing the tunneling experiences gained during several years in difficult ground and complex geology. The methane explosion in an earth pressure balance (EPB) TBM chamber, the clogging of a TBM, the need to change disc cutters to chisel cutters, the need to change CCS-type discs cutters to V-type disc cutters, excessive disc cutter consumption, the optimum selection of TBM type in complex geology, magmatic inclusions or ‘dykes’, the effect of blocky ground on TBM performance, the mechanism of rock rupture in front of TBMs, TBM face collapses and blockages, the effect of opening ratio in EPB-TBMs in fractured rock, squeezing of the TBM or jamming of the cutterhead, probe drilling and the use of umbrella arching ahead of TBMs are discussed within this book.

We hope that the experiences shared in this book may help project designers and practicing engineers dealing with TBM drivages in complex geology in different parts of the world.

Istanbul, June 2016

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1 Introduction

A man who carries a cat by the tail learns something he can learn in no other way.

~Mark Twain

This book is written with the intention of sharing the experiences gained in difficult ground conditions with TBMs in Turkey.

Turkey is in a tectonically active region; at a large scale, the tectonics of the region are controlled by the collision of the Arabian Plate and the Eurasian Plate. The Anatolian block is being squeezed to the west. The block is bounded to the north by the North Anatolian Fault and to the south-east by the East Anatolian Fault. The effects of North and East Anatolian Faults on TBM performances in Kargi energy tunnel, Dogancay energy tunnel, Nurdagi railway tunnel and Uluabat energy tunnels are explained in detail giving the causes, effects and precautions to be taken in order to eliminate the problems created by two large sets of faults. Some information is also given about the most difficult tunnels (Ayas and Bolu) that have ever been excavated by drill and blast method.

We believe that the Selimpasa and Silvan tunnels also provide unique experience since one suffered a methane explosion in the EPB chamber and the other hit a natural gas reservoir completely destroying a TBM and its related accessories.

The clogging of a TBM, as is encountered in clay-containing ground, has extensive consequences for the construction process and can severely affect the performance of the machine, increasing the torque, thrust and specific energy and lowering the advance rates with the extra cleaning efforts needed. Chapter 10 is written with the intention of clarifying the subject by giving three examples of tunneling projects in Turkey: Suruc Tunnel plus Selimpasa and Zeytinburnu Ayvalidere, two wastewater tunnels that were studied in detail in this respect. Experimental studies performed in the soil conditioning laboratory indicated that regular application of foam selected by the contractor was adequate to solve the sticking and clogging problems in Selimpasa, while an anti-clay agent different from the one selected by the contractor was suggested for Zeytinburnu. The representatives in the two cases applied the laboratory results in the field. The field measurements validated the experimental studies and the net advance rates of the EPB-TBMs increased at least 1.3 to 1.5 times and the stoppages due to clogging problems were reduced to normal ranges.

One of the most difficult tunnels ever opened in Istanbul was Beykoz sewerage tunnel, which encountered a complex geology. The need to change disc cutters to chisel cutters, CCS-type discs cutters to V-type disc cutters, excessive disc cutter consumption and TBM squeezing problems were also experienced in this tunnel.

Istanbul has a very complex geology, and in the near future the majority of TBM tunneling projects of Turkey are planned to be carried out in this fast-growing city. Bearing in mind this reality, the main objective of Chapter 3 is to show how the optimum selection of TBM type for Istanbul, has gradually changed from open type TBM (Baltalimani Tunnel), to double shield TBM (Moda-Tuzla Tunnel), to slurry type TBM

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(Marmaray tunnels) and finally to EPB-TBMs over the past 25 years. This gradually progressing selection based on the complex geology of Istanbul is a typical example to the concept of 'learning costs'. A model of the performance prediction of EPB-TBMs is also given based on experiences and data collected in several metro tunnels as Uskudar–Cekmekoy and Mahmutbey–Mecidiyekoy metro tunnels.

As already explained, Turkey is widely affected by two major fault systems, the North Anatolian and East Anatolian Faults. These two fault systems and magmatic inclusions 'dykes', fracture the host rock creating problematic blocky ground for TBM excavations. This problem is explained in Chapter 7 which is aimed to explain the effect of blocky ground on TBM performance and the mechanism of rock rupture in front of the TBM. Typical examples are given from Kozyatagi–Kadikoy Metro tunnels.

The causes and effects of TBM blockages are explained for Kadikoy–Kozyatagi metro tunnels. Eleven different TBM face collapses and blockages which have occurred in very complex geology within the Kadikoy–Kozyatagi Metro tunnels are analyzed considering TBM parameters such as opening ratio, working modes and geological parameters. It is determined that the TBM excavation parameters fluctuate while approaching the collapse regions, and these parameters show an increasing or decreasing trend insite 'during collapse' region and it is concluded that this trend is a good indicator of face collapses, which will serve as a guide to foresee critical areas in front of TBM.

Squeezing of TBM or jamming the cutterhead is a nightmare for tunnel engineers, since it affects machine utilization time and realization of the project scheduled time. The salvation (rescue) of a jammed cutterhead can considerably reduce the mean advance rate. This problem was studied for Kargi, Uluabat and Dogancay tunnels, where the causes and effects of TBM squeezing are discussed with respect to remedial works needed for these three tunnels.

Cutter consumption is one of the most important cost items in mechanized tunneling due to replacement costs, cutting efficiency (penetration rate reduction with worn tools), and also man-hours spent on replacement. Yamanli II HEPP Tunnel, Buyukcekmece wastewater tunnel, Beykoz sewerage tunnel and Uskudar–Umraniye–Cekmekoy–Sancaktepe Metro Tunnels are detailed in this respect in Chapter 12.

Probe drilling ahead of a TBM is a time-consuming and tedious operation. If it is not interpreted correctly, it can give misleading results in complex geology. The research study summarized in this book shows that for correct interpretation of the drilling data, muck from the excavated area should be collected continuously for petrographic identification and strength tests. Two typical examples are Melen water tunnel and the Kargi Project. The experience gained in the umbrella arch in front of the TBM in the Kargi Project is also shared within this book.

11 Effect of high strength rocks on TBM performance

11.1 Introduction

The strength of rock mass is an important parameter in determining the thrust–torque values and the type of cutters for a TBM. Large diameter CCS type disc cutters with larger tip widths are preferred in high strength and abrasive rocks. Sometimes in complex geologies, a rock formation having unexpectedly high strength characteristics may suddenly appear in the tunnel route, limiting the penetration of the cutters, thus decreasing the advance rates in most cases to undesired values. The Beykoz sewerage tunnel in Istanbul is a typical example to this, a sudden mass of quartzite, a few hundred meters in length, affected the cutter penetration to an undesirable, even to practically zero level. In that case CCS disc cutters were replaced with V-type disc cutters, because, as explained in earlier chapters, for a limited thrust force the penetration is higher in V-type disc cutters compared with other types of disc cutter [1, 2, 3, 4].

Sometimes in very high strength rock formations, as encountered in the Nurdagi railway tunnel, it is essential to carry out full-scale laboratory cutting tests to predict the behavior of the cutters to obtain the optimum design parameters of a TBM [5].

In the light of the information given above, the in-situ observation obtained with a TBM in the Beykoz tunnel will be given first, and then full-scale laboratory cutting tests will be detailed for the Nurdagi tunnel.

11.2 Beykoz sewerage tunnel, replacing CCS disc cutters with V-type disc cutters to overcome undesirable limits of penetration for a maximum limit of TBM thrust

The sewerage tunnel excavated between Kavacik and Beykoz in the northern part of the Istanbul Bosphorus is part of an environmental protection project concerned with renewing the inadequate sewerage network around Beykoz and collecting the wastewater in a treatment plant and cleaning the polluted water of the Istanbul Bosphorus.

The ground conditions change from soft to hard formations, and excessive water ingress was expected in some areas. The total length of the tunnel is 7,253 m, tunnel excavation started from shaft AT2 on 9 January 2007 in open mode, and 4,267 m of the tunnel had been excavated by 26 January 2009. The general layout of the tunnel and previous works carried out are given in Guclucan et al. [1, 2, 3].

Figure 11.1 shows the relationship between penetration index in kN/mm of penetration and torque penetration index in kNm/mm. These relationships are only valid for disc cutters used in chainages 0–800 and 2,300–2,900 m and may be used to explain the performance of the TBM in relevant geological conditions.

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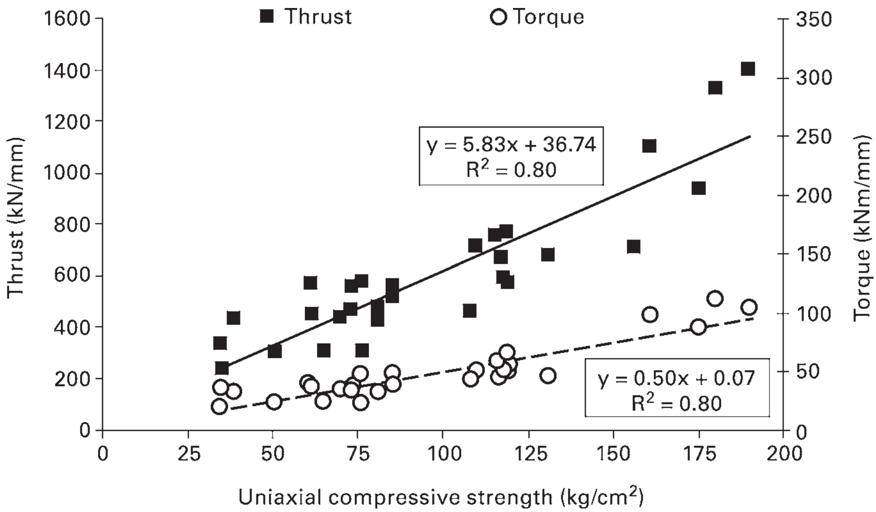

Figure 11.1 The change of TBM penetration index and torque per unit penetration for disc cutters [4].

Quartzite veins of 50 m in thickness and having compressive strength of 110–225 MPa were faced after chainage 2,550 m, which caused very low disc penetration of around 1 mm/rev with excessive dust problems. It was therefore decided to change all discs with 76° edge angle V-type disc cutters, except the eight central CCS type disc cutters. Penetration index in kN/mm (the ratio of disc thrust to the penetration per revolution) is seen for both CCS disc cutters and V-type disc cutters in Figure 11.2. It is clear from this figure that for a unit penetration, V-type disc cutters work with less thrust compared to CCS disc cutters. However, this advantage disappears when the abrasivity of the rocks is considered. Therefore, the V-type disc cutter was changed to CCS disc cutters when passing to limestone formation.

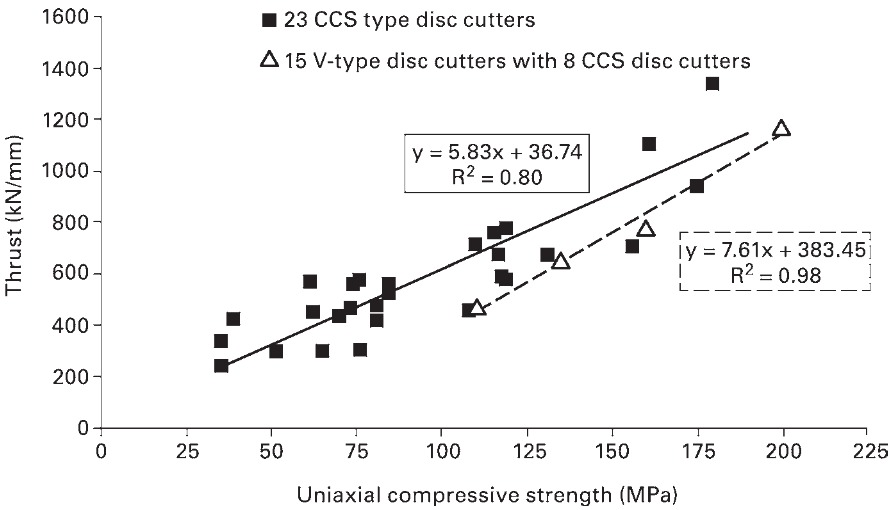

Figure 11.2 The variation of penetration index with compressive strength for CCS and V-type disc cutters [4].

11.3 Nurdagi tunnel, full-scale cutting tests to obtain optimum TBM design parameters in very high strength and abrasive rock formation

The geology and outline of the Nurdagi tunnel is summarized in Chapter 6. Cuttability of the two block samples (meta-sandstone and meta-mudstone) representing the tunnel route are determined by full-scale linear cutting tests in ITU Laboratories, using a disc cutter aimed at selecting a suitable TBM, defining its basic specifications and predicting its excavation performance for the Bahce–Nurdagi tunnel crossing. Also, some tests were performed to determine some of the physical and mechanical properties of the block samples by using chunk samples obtained from the block samples. The full-scale linear cutting tests were performed by using a constant cross-section disc cutter with a diameter of 13″ (330 mm) and a tip width of 1.2 cm at 80 mm of cutter (line) spacing and different depths of cut (3, 5, 7 mm). The normal and rolling forces acting on the disc cutter and specific energy values were measured, optimum cutting geometry is identified and size distribution and coarseness index values of the chip samples were identified for defining the efficiency of the excavation process.

Based on experimental results, optimum cutting geometry (optimum line spacing to depth of cut (s/d) ratio) was determined for the TBM to be used for excavation of the tunnel, its preliminary net cutting rate was predicted by using specific energy method, and some nomograms were developed for predicting its daily advance rates.

Uniaxial compressive strengths of the meta-sandstone and meta-mudstone samples were found to be 223 MPa and 118 MPa, and their Cerchar abrasivity index values were found to be 3.87 (high abrasive) and 1.84 (low abrasive), respectively.

Optimum cutting geometry was obtained at cutter (line) spacing to depth of cut (s/d) ratio of 16, and at this geometry, the optimum specific energy was found to be

11.08 kWh/m^3 for meta-sandstone sample. The thrust force that should be applied to the disc cutter at optimum cutting geometry was found to be 198.65 kN.

Optimum cutting geometry was obtained at s/d ratio of 16, and at this geometry, the optimum specific energy was found to be 1.59 kWh/m^3 for the meta-mudstone sample. The thrust force that should be applied to the disc cutter at optimum cutting geometry was found to be 38.6 kN.

Some nomograms were developed aimed at predicting preliminary net excavation (cutting) rates and daily advance rates for the meta-sandstone and meta-mudstone samples by using the specific energy method with some assumptions (especially for hard rock TBMs). Based on selected TBM and tunnel conditions, a preliminary performance can be estimated. It was also seen that the excavation rates in meta-mudstone could be higher by as much as twice that in meta-sandstone.

Instantaneous (net) cutting rate of a mechanical miner is that achieved only during excavation, excluding stoppages. Net cutting rates of mechanical miners can be predicted using the model given below (Eq. 11.1), which is based on linear cutting tests [6, 7].

$$ICR = k \cdot P_{net}/SE_{opt} \tag{11.1}$$

where ICR is the instantaneous (net) cutting rate (m^3/h), P_{net} is the cutterhead power of the mechanical miner while cutting at optimum conditions (kW), SE_{opt} is optimum specific energy obtained from full-scale linear cutting tests (kWh/m^3) and k is the energy transfer coefficient (which can be taken as 0.8–0.9 for hard rock TBMs).

Optimum specific energy values are 11.08 kWh/m^3 for meta-sandstone and 1.59 kWh/m^3 for meta-mudstone. It is assumed that any variation of disc cutter diameter would not affect these values. Assuming k value of 0.85, the relationship between ICR and P_{net} shown in Figure 11.3 can be obtained. ICR values for meta-mudstone are divided by 2 in this graph (worst case), since a TBM would excavate in both parallel and perpendicular to bedding planes in reality. By using this graph, ICR can be estimated by using installed cutterhead power reduced by an efficiency factor (or estimating deterministically). However, estimated ICR values should be corrected for fractures-joints or for RQD, which increase ICR. Net cutting rate (as IPR in m/h) can be estimated by dividing ICR by tunnel cross-section area (Figure 11.3).

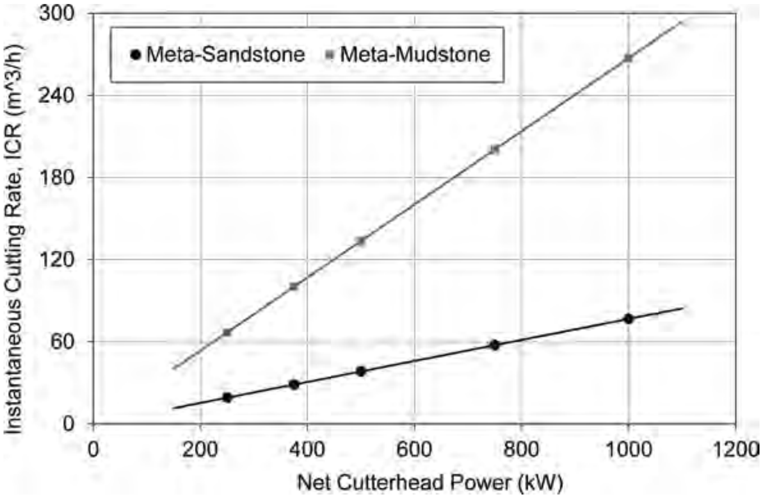

Figure 11.3 Relationship between instantaneous cutting rate and net cutterhead power for Nurdagi project based on laboratory rock cutting tests [5].

A suitable machine utilization factor (AR) should be estimated to predict the daily advance rates. The machine utilization factor determines the percentage of the time used just for excavation (excluding stoppage time) over a whole shift time (stoppages + excavation time); it varies from project to project. By assuming a net cutterhead power of 750 kW for meta-sandstone and 375 kW for meta-mudstone, a machine utilization factor of 50%, and 24 hours of daily working time, the variation of daily advance rate with tunnel diameter is obtained, as given in Figure 11.4.

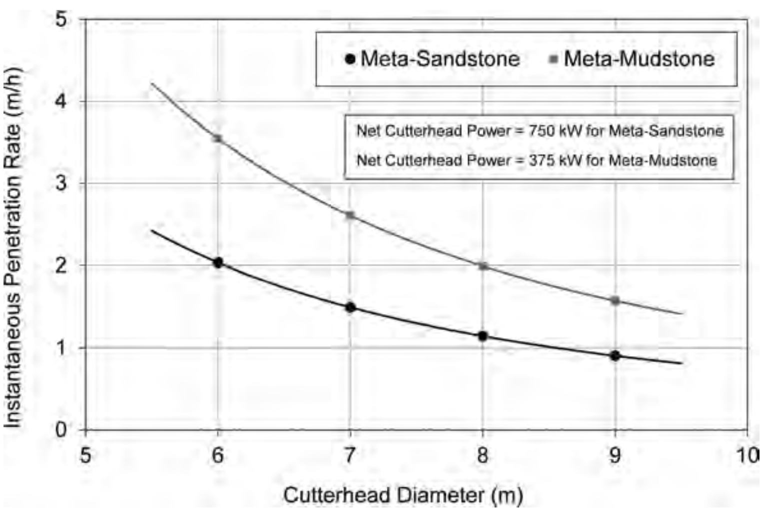

Figure 11.4 Relationships between instantaneous cutting rate and net cutterhead power for Nurdagi project based on laboratory rock cutting tests [5].

A single-shield TBM has been designed and manufactured based on site investigations and full-scale laboratory cutting test results. The TBM is now in the process of excavating the tunnel. Performance of the TBM is being collected currently; predicted and actual performance values will be the subject of a coming research topic.

11.4 Beylerbeyi–Kucuksu wastewater tunnel, TBM performance in high strength rock formation

This section is summarized based on [8]. The Beylerbeyi–Kucuksu wastewater tunnel aligned along the Istanbul Strait having a length of 4,344 m and finished diameter of 2.2 m was constructed by Unal Akpinar Construction Inc. for the owner Istanbul Water and Sewage Authority (ISKI).

Palaeozoic aged geological units are found between Beylerbeyi and Kucuksu. Lithology basically includes limestone, laminated mudstone with interbedded siltstone, sandstone, carbonated-laminated-fossiliferous shale interbedded with limestone. These units are cut sometimes by andesite and diabase dykes having thicknesses of up to several meters and significantly fractured contact zones and high strength. Physical and mechanical properties of the formations along the alignment are summarized in Table 11.1. As seen, the general strength of the formations is not very high, but from time to time very hard and massive rock zones were encountered.

Table 11.1 Some of the properties of the rock masses [9].

Formation	Dolayoba formation (limestone)	Kartal formation (shale)	Tuzla formation (nodular limestone)	Dykes
UCS (MPa)	34.0 ± 14.0	32.4 ± 18.0	34.0 ± 13.5	76.0 ± 26.6
BTS (MPa)	6.3 ± 3.0	5.2 ± 2.4	5.5 ± 2.8	7.8 ± 2.7
E_S (GPa)	5.2 ± 3.5	5.3 ± 3.8	4.26 ± 3	4.55 ± 1.62
v_S (—)	0.27 ± 0.15	0.32 ± 0.13	0.28 ± 0.14	0.26 ± 0.11
RQD (%)	70–90	25–50	60–80	25–70
RMR	66	45	50	59
Q	8	1	2	10

UCS: Uniaxial compressive strength, BTS: Brazilian (indirect) tensile strength, E_S: Static elasticity modulus, v_S: Static Poisson's ratio, RQD: Rock quality designation, RMR: Rock mass rating class, Q: Q class.

The EPB-TBM used for excavation is a new machine manufactured by Herrenknecht and designed to work in closed and open modes and for mixed ground conditions. Its basic characteristics are summarized in Table 11.2. A photograph of the cutterhead after the second revision during the construction is presented in Figure 11.5.

Figure 11.5 General view of cutterhead of EPB-TBM [8].

Table 11.2 Technical features of Herrenknecht (M1801M) EPB-TBM.

Total length (TBM + backup)	62 m
Excavation diameter	3,251 mm
Shield diameter	3,195 mm
Number of push cylinders	12
Stroke of push cylinders	1,700 mm
Total thrust capacity	10,688 kN
Maximum torque (continuous)	620 kNm
Maximum torque (intermittent)	780 kNm
Variable rotational speed	0–9.2 rpm
Installed power	400 kW
Cutterhead power	315 kW
Number of disc cutters	6 single + 9 double
Diameter of disc cutters	12″ (305 mm)
Number of scrapers + buckets	18 scrapers+6 buckets
Nominal diameter of screw conveyor	500 mm
Rotational speed of screw conveyor	0–27 rpm

Monthly advance rates and general performance nomograms for formations having certain characteristics are presented in Figures 11.6–11.11, considered as helpful for decision-makers. Advance per revolution in fractured/jointed limestone was almost 60% higher than massive limestone, while thrust force was almost 30% higher in the massive zone. While 29% of TBM utilization time was achieved, the TBM-related delays took almost 32% of the whole delays. Cutterhead maintenance and revisions had the highest share of around 25% of the TBM related stoppages.

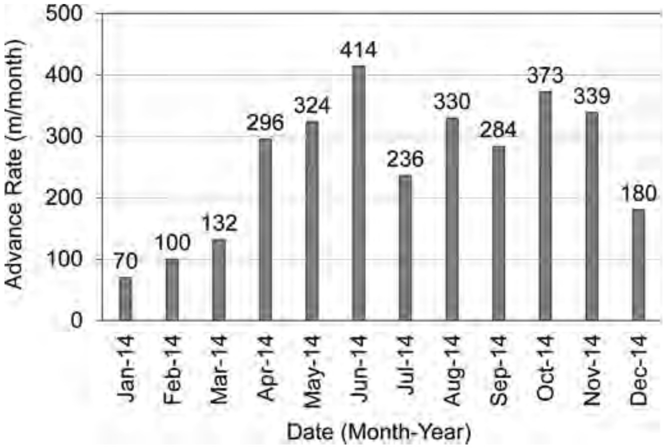

Figure 11.6 Monthly advance rates in Beylerbeyi–Kucuksu wastewater tunnel [8].

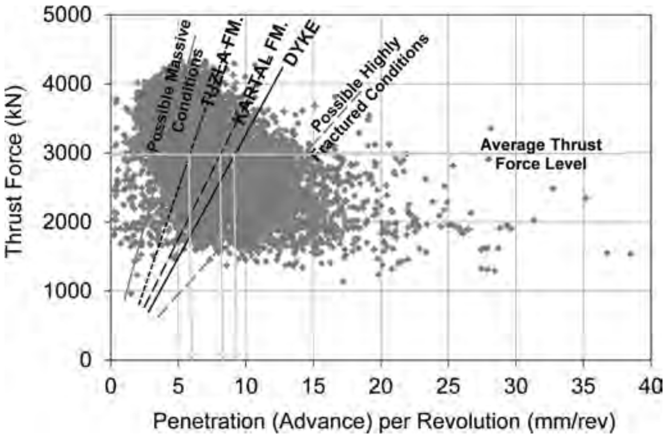

Figure 11.7 Relationship between advance per revolution and thrust force in the Beylerbeyi–Kucuksu wastewater tunnel [8].

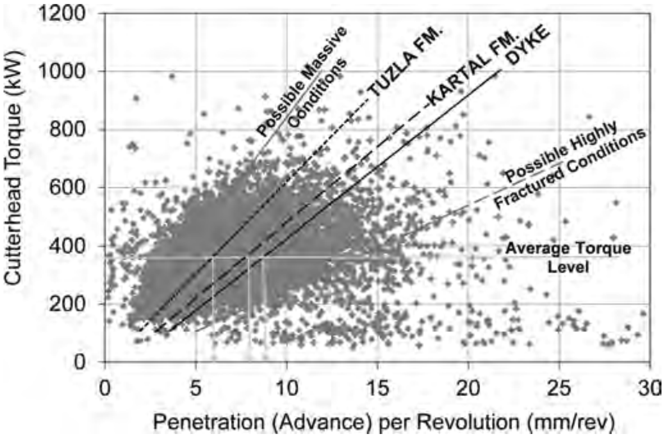

Figure 11.8 Relationship between advance per revolution and cutterhead torque in the Beylerbeyi–Kucuksu wastewater tunnel [8].

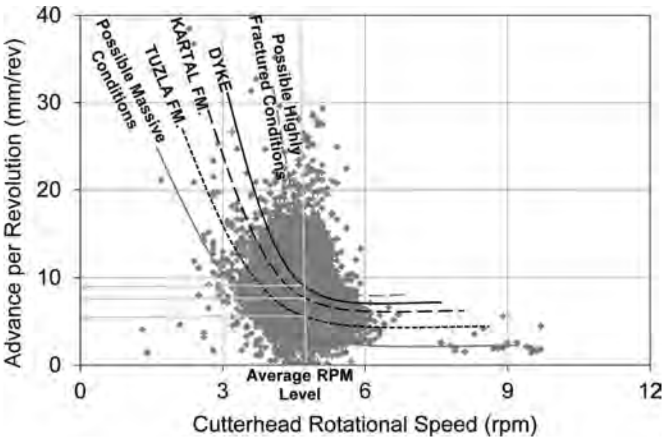

Figure 11.9 Relationship between cutterhead speed and advance per revolution in the Beylerbeyi–Kucuksu wastewater tunnel [8].

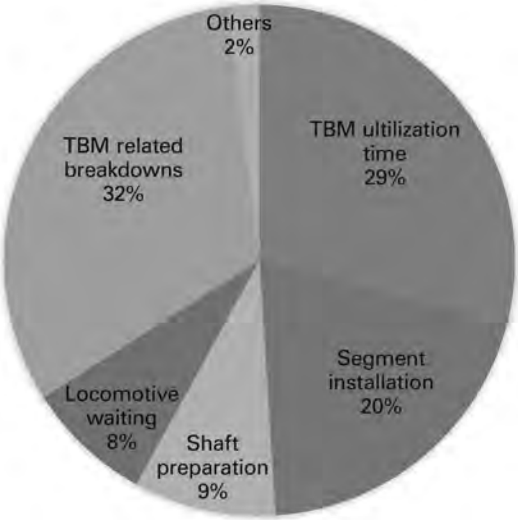

Figure 11.10 Job time utilization distributions in the Beylerbeyi–Kucuksu wastewater tunnel [8].

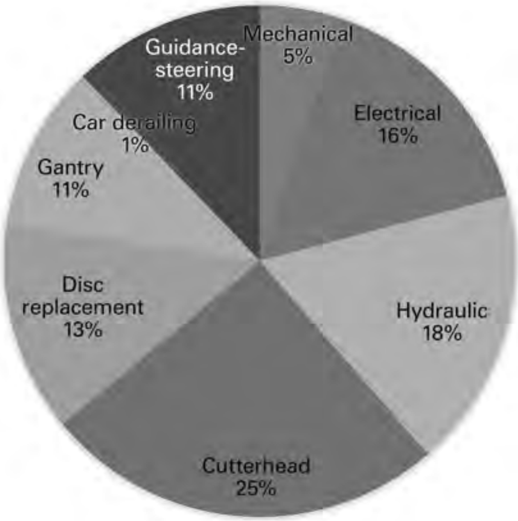

Figure 11.11 Distribution of TBM related stoppages in the Beylerbeyi–Kucuksu wastewater tunnel [8].

Average daily advance rate of 9.3 m/day, monthly advance rate of 256.5 m/month, and penetration per revolution of 7.1 mm/rev were achieved. Average thrust force was 2994 kN reciprocating to average 173 kWh of cutterhead power and 356 kNm cutterhead torque at an average 4.7 rpm rotational speed. Average cutter life was realized around 158 m^3/cutter ring (20 m/cutter ring), which was quite low. It was seen that advance per revolution in fractured or jointed limestone was almost 60% higher than the massive limestone, while the thrust force was almost 30% higher in the massive zone. While 29% of TBM utilization time was achieved, TBM related delays took almost

32% of job time. Cutterhead maintenance and revisions had the highest share of TBM related stoppages at 25%.

This performance could be considered quite low, mostly because the ground conditions encountered are classed as difficult ground conditions for the EPB-TBM used in the Beylerbeyi–Kucuksu wastewater tunnel, since it is considered that a larger diameter TBM equipped with larger diameter single disc cutters would excavate these rocks without any significant problem. Since the EPB-TBM used in the Beylerbeyi–Kucuksu wastewater tunnel had a small diameter and were designed for mixed ground conditions, it had a limited thrust and power for the rocks excavated. The disc diameter of 12″ limited the applied load/thrust on the cutters and thus the penetration rate. It is also known that applied thrust on double discs is split into two halves, reducing its penetration capability into rock face and increasing tool consumption rates.

11.5 Tuzla-Akfirat wastewater tunnel, TBM performance in high strength rocks

The detailed information about Tuzla-Akfirat wastewater tunnel is given in Chapter 12 of this book. Very hard and abrasive rock zones up to 200 MPa uniaxial compressive strength were encountered in this tunnel [10]. This project saw uniaxial compressive strength values of over 50 MPa, which can be considered as difficult ground conditions for an EPB-TBM with diameter of 3,151 m designed for mixed ground conditions and equipped with small diameter double disc cutters. The relationship between advance per revolution and uniaxial compressive strength of the rocks encountered along the tunnel alignment is presented in Figure 11.12. It is seen that the advance rate of the TBM decreases below 2 mm/rev when excavating rocks having compressive strength values over 50 MPa.

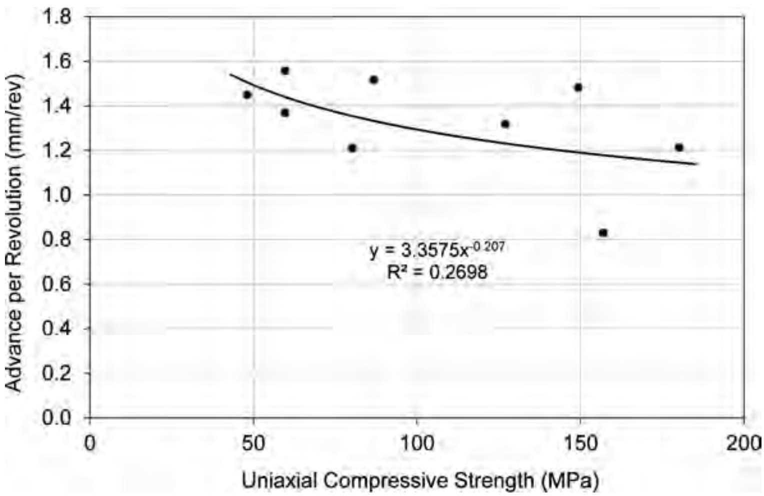

Figure 11.12 Relationship between uniaxial compressive strength of the rocks and advance per revolution in the Tuzla-Akfirat wastewater tunnel [10].

14 Probe drilling ahead of TBMs in difficult ground conditions

14.1 Introduction

This chapter summarizes the results of probe drilling carried out ahead of TBMs in Melen and Kargi projects in a very complex geology. Melen water tunnel was excavated under the Istanbul Bosphorus within sedimentary rocks that are cut frequently by andesitic dykes, fracturing the surrounding rocks and creating a potential risk for water ingress into the tunnel. Probe drillings with petrographic analysis and strength tests were used with samples collected from the TBM muck. This analysis made it possible to identify some critical normalized probe drilling rate values for predicting potential weak zones created by andesitic dykes. These studies gave a sound basis for further interpretation of TBM and geological data for the tunnel. The second set of probe drilling analyses was from the Kargi tunnel. The North Anatolian Fault highly affected the tunnel excavation by fracturing the rock formations. Although the change in normalized probe drilling data was a good indicator of fractured zones, the diversity of rock formations made it difficult to interpret the data. On the basis of the probe drilling results at Kargi, an umbrella arch was used to strengthen the rock mass for easing tunneling operations and to stop the jamming of the TBM cutterhead. A summary of the probe drilling in Melen and Kargi has already been published, Bilgin and Ates [1]. More detailed information about this will be given here.

14.2 General information on probe drilling and previous experiences in different countries

Probe drilling is a technique used ahead of TBMs in difficult geological conditions as an indicator of water ingress into a tunnel, gas potential ahead of a tunnel, fault and transition zones. However, probe drilling rate is also related to the type of drill rig and drilling parameters such as feed, percussion and rotation pressures, in other words to the thrust and the torque of the drill rig. Drilling rate measurements should be carried out under constant, percussive and rotary pressures in order to make a meaningful comparison of the changing situations ahead of a tunnel. Before evaluating the measurements, drilling rate values should be normalized using thrust or rotary pressures in order to have comparable values. However, it should be emphasized also that in difficult ground conditions and in large diameter tunnels more than one probe drill hole will be necessary. In such cases, the interpretation of the drilling results with TBM operational parameters such as thrust and torque values may be a useful guide for predicting potential hazards ahead of the tunnel.

Tunnel face collapses and sudden and unexpected water ingress in a tunnel are always associated with fractures or other geological singularities such as faults. Schunnesson [2] developed a model for predicting RQD of rock mass ahead of the tunnel using the percussive drilling parameters. He concluded that the ability to predict RQD, based on drill parameters, offers a unique opportunity to utilize RQD not only for characterization of the entire tunnel section, but also to provide detailed knowledge of the structural geometry of the rock mass within the tunnel section. Schunnesson [3] also concluded that a major problem in such attempts is the analysis of the data. The monitored

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'raw' data is significantly affected by the operator, who often adjusts the drill settings in order to achieve the best drilling result. Furthermore, the advanced control systems on modern drill rigs adjust drill parameters (thrust and torque pressures) independently to avoid drilling problems and damage to the drill string, and as a result he concluded that drilling data should be normalized according to thrust and torque pressure values. Another problem in interpreting the drilling data is the wear of drill bits, which decreases drilling rates to a considerable extent in abrasive rocks. The drilling rate is also affected by the energy absorption of the drill string within long holes.

One of the most interesting probe drilling operations in TBM applications was carried out in the Lesotho Highlands water project, in delivery tunnel north. Probe drilling was carried out within a double-shield TBM with probe holes being 115 m long and 65 mm in diameter. They were angled at 5.5° to the roof of the tunnel. Probe holes, in addition to providing an indication of groundwater ahead of the face, also yielded information on the geology. For example, in the Ash River tunnel, they indicated the location of dykes, some of which were associated with groundwater. These required grouting: in the case of the Elim Dyke (20 m in width) the initial water ingress was as much as 400 1/min at 9 bar pressure. It took approximately 15 days to reduce these water inflows to 6 l/min. Around 120 m^3 of cement grout, with anti-washout and non-shrink additives, was injected in three concentric arrays of grout-holes at 15 m centers, which started about 50 m in front of the dyke, De Graaf and Bell [4].

Experience gained from mechanical ground probing in the Gotthard base tunnel contributed also to the development of probe drilling methodology applied in front of a TBM. The critical and most interesting working phase was the approach to the Piora basin, formed of sugar-grained dolomite, mixed with water at a pressure of up to 150 bar. The drilling installation, mounted on the TBM, was equipped with a sophisticated preventer system, composed by a 'blow-out preventer', as used in oil prospecting technology. The equipment was set to connect to a water pressure of up to 150 bars. The bores were put above the TBM crown, with variable inclination of 2–5°. During the driving of the fifth borehole in advance, at station 5,553 m, the sugar-grained, porridge-like dolomite of the Piora basin was met and the dolomite–water mixture poured into the tunnel through the 42 m long borehole, with 98 mm diameter, at high pressure, initially of more than 90 bars. Some parts of drilling equipment were thrown up to 30 m and water ingress reached a maximum outflow of 400–500 l/sec. The granulometric composition of the material corresponded to a fine to middle grained sand, Henke [5]. Flurry and Priller [6] reported also that in most cases core drilling was inevitable in this project.

Probe drilling operations used in the Arrowhead tunnels in USA were also very effective. Arrowhead tunnels project consists of two 5.7 m excavated-diameter tunnels, 9.6 km east and 8 km west tunnels. The tunnels were bored using two TBMs. The Arrowhead west tunnel, the more difficult of the two, took four years to bore. At one point, a flash flood temporarily submerged the TBM. The TBM in the east tunnel encountered water-bearing strata of metamorphic and granitic rock. The presence of the water, coupled with the depth of the tunnel below the surface, up to 700 m, forced the tunneling team to deal with water pressures in the tunnel heading in excess of 14 bars.

Also, much like the west, the TBM had to traverse branches of the San Andreas Fault. The tunnel was completed in May 2008. The automated probe drill monitoring system was proven to be a useful tool for evaluating ground conditions ahead of the TBM. The drill pressure data was analyzed, usually within a couple of hours after the completion of probing, Duke and Arabshahi [7].

Two important comprehensive studies on TBM drives in complex geology, on probe drilling and treatment of rock in front of a tunnel face are published by Barla and Pelizza [8] and Peila and Pelizza [9]. A report on this subject, edited by a group of contributors and published by AFTES [10] is also worth mentioning.

Steele et al. [11] concluded that the rock mass strength was affected by the weathering grade and discontinuity intensity of the rocks. A classification made by using the probe drilling specific energy provided indicative correlation with the weathering grade and localized zones of weak rocks. However, they emphasized that in a given rock mass a reduction in energy occurs with increased length of drill rode. They reported that the energy loss, referred to as the 'Trod' coefficient is ideally needed to be established from site-specific records to determine the energy loss over drilling length. Drilling rate was found to be decreased with drilling distance by about 2.5 cm/min per drilled (m) length.

14.3 Melen water tunnel excavated under the Bosphorus in Istanbul

The Melen tunnel is a water tunnel in Istanbul, crossing the Istanbul Bosphorus strait at a depth varying from 0 to 146 m, situated between Beykoz and Sariyer on the Asian and European sides, respectively. Probe drilling for advance exploration every 40 m allowed proper determination of geological structure, boundaries of unstable areas and inflow of water. The construction of tunnels started in February 2008 and finished in April 2009. Injections of cement grout and polymer compositions in front of the heading and behind the lining were applied to stop the water ingress.

The Melen water tunnel passes through Kartal formation, which is an alteration of calcareous shale, clayey limestone, sandy limestone and sandstone. RQD values change from 0 to 90%. There are minor and major faults in the area with andesite dykes. These magmatic intrusions or dykes are high strength rocks with compressive strength going up to 140 MPa. However, these intrusions are sometimes fractured and weathered, with varying thickness, from a few meters up to 50 m, making the contact zones very fractured and filled with fine materials. The presence of dykes, and the small intrusions cutting the Paleozoic sedimentary rocks in Istanbul region, is known from previously published data on TBM tunneling [12]. These andesitic rocks, are generally considered to be of Cretaceous age. Figure 14.1 shows the geological profile along the alignment. Potential problems in fractured dykes and blocky ground include high water inflows, difficulties with mucking and the installation of segmental lining, the annulus grouting and instability in front of the TBM [13, 14].

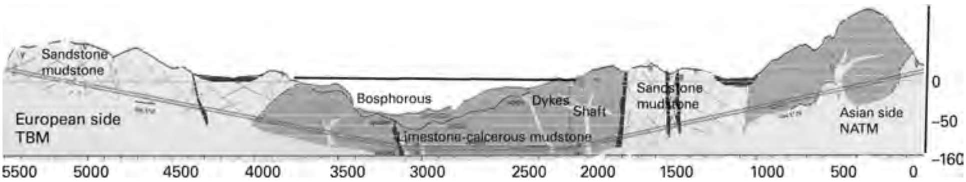

Figure 14.1 Geological cross-section of the Melen tunnel.

There is no systematic published data on the distribution and the orientation of these andesitic dykes, but Ozgorus and Okay [15] concluded in their recent studies that the distribution of the strikes is highly scattered with a few prominent directions with two possibilities. The first is that the Istanbul dykes constitute a local dyke swarm related to a yet unexposed pluton at depth. The second possibility is that the Istanbul dykes are from a regional dyke swarm. The contact between the main sedimentary rock and the dykes are weak, weathered and fractured. Problems expected are face collapses in front of TBM, jamming of the cutterhead, damage of the cutterhead and high water ingress [12]. A typical TBM cutterhead that jammed in the Beykoz–Istanbul tunnel due to a weak zone between dykes and the main rock is illustrated in Figure 14.2 [12]. These types of zones are very critical when excavating under sea, due to expected high water ingress. The description of dykes and their influences on probe drilling were the main objectives of the first pioneering studies, Anagnostou et al. [13].

Figure 14.2 TBM cutterhead jammed in the Beykoz–Istanbul sewerage tunnel within dyke zone.

14.4 Methodology of predicting weak zones ahead in the Melen water tunnel

In the tender document it was indicated that continuous probe drilling of diameter not less than 51 mm should be used ahead of the tunnel faces to locate gas or water-bearing areas and to detect changes in the geological conditions. Grouting was kept mandatory if water ingress from a single or multiple probe holes exceeded 5 l/min per drilled hole. Routine probe drilling was suggested to be carried out using rotary percussive drilling equipment. It was also demanded that additional core rotary drilling should be carried out if it was asked for by the engineer for extra geological characterization.

Drilling parameters and TBM operational parameters, including muck size, are affected directly by the rock mass properties. Figure 14.3 gives a typical example of the effect of geological discontinuities on muck size during TBM excavation in Kartal formation.

The methodology used in this study for predicting the weak zones ahead of the tunnel is summarized in Figure 14.4.

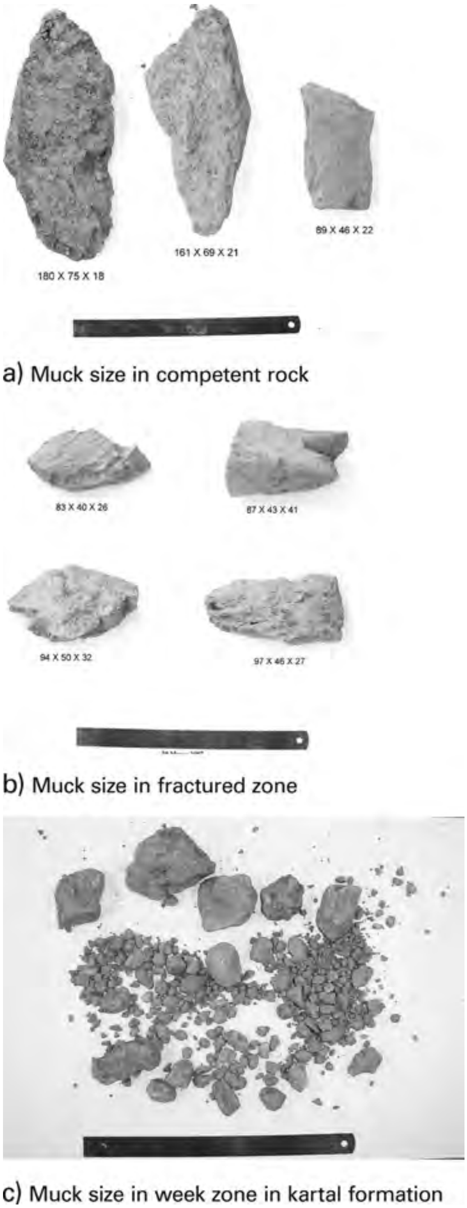

Figure 14.3 Effect of discontinuities on muck size.

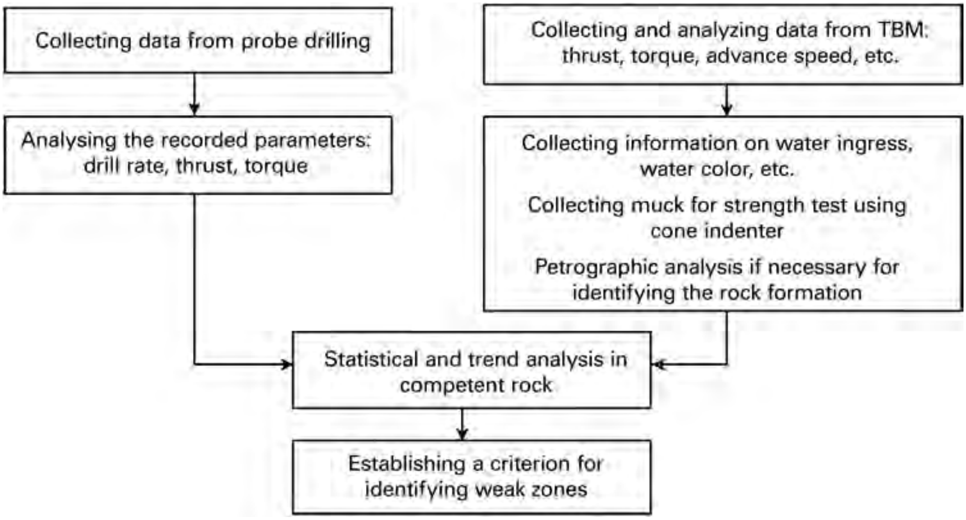

Figure 14.4 Methodology of using probe drilling in the Melen project.

At the beginning of the tunnel excavation extensive pioneering probe drilling operations were carried out between chainages 4+400 and 4+940 km to establish a criterion for further assessment of the probe drilling operations. The results presented in this study cover only the results of the site investigation within the chainages mentioned above. Later TBM crew took over the probe drilling operations, and first results of the data analysis were reported by Bakir et al. [16, 17]. Drilling parameters such as torque and thrust pressures and drilling rates were continuously recorded during probe drilling operations using an automated data acquisition system. Figure 14.5 shows the probe drilling equipment used in the Melen project.

Figure 14.5 Probe drilling equipment used in the Melen project.

To have consistent comparable results for data processing, drilling rate values were normalized in cm/min per drill thrust bar and in cm/min per drill torque (dividing

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