TBM Excavation in Difficult Ground Conditions
Case Studies from Turkey

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This book is dedicated to our lovely wives
Ayfer Bilgin, Nurten Copur and Nurgul Balci
and our beloved children
Damlanur Bilgin, Serkan and Busra Copur and Cem Eren Balci
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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Hanifi Copur
Cemal Balci
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# Table of contents

**Preface** ............................................................................................................................ VII  
**Acknowledgements** ........................................................................................................ IX  
**About the Authors** ........................................................................................................... XI  
**1 Introduction** ................................................................................................................ 1  
**2 Geology of Turkey and Istanbul, expected problems, some cuttability characteristics of the rocks** ........................................................................................................................................ 3  
2.1 Introduction .................................................................................................................. 3  
2.2 Geology of Turkey ...................................................................................................... 3  
2.3 Geology of Istanbul .................................................................................................. 4  
2.4 TBM performance in different projects in Istanbul .................................................. 6  
2.5 Description of geological formations in Istanbul, physical and mechanical properties ........................................................................................................................................ 8  
2.5.1 The stratigraphy of Istanbul and description of geologic formations ............... 8  
2.5.2 Typical frequency of RQD and GSI in the geological formations in Istanbul ........................................................................................................................................ 16  
2.5.3 Physical and mechanical properties of rocks taken from different geological formations ........................................................................................................................................ 28  
2.5.4 Schmidt hammer tests carried out in station tunnels in Uskudar–Umranıye metro line ........................................................................................................................................ 37  
2.6 Full-scale linear rock cutting tests with disc cutters in rock samples collected from different projects in Istanbul ........................................................................................................................................ 40  
2.6.1 Description of laboratory full-scale linear rock cutting test ................................ 41  
2.6.2 Testing methodology and test results .................................................................... 43  
2.6.3 Comparison of laboratory full-scale linear rock cutting test results with in-situ cutter performance – the effect of rock discontinuities .................................................. 52  
2.7 Conclusions ................................................................................................................ 68  
**References** ..................................................................................................................... 70  
**3 Difficult ground conditions dictating selection of TBM type in Istanbul**  
3.1 Introduction ................................................................................................................ 73  
3.2 Case study of open TBM in complex geology (1989), in Baltalimani tunnel: Why open type TBM failed ........................................................................................................................................ 73  
3.2.1 Collapse between chainage 0+920 and 0+935 km ............................................. 78  
3.2.2 Collapse between chainage 0+965 and 0+982 km ............................................. 79  
3.2.3 Collapse between chainage 1+148 and 1+155 km ............................................. 80  
3.2.4 Collapse between chainage 1+220 and 1+235 km ............................................. 80  
3.3 Double shield TBM in the Istanbul–Moda collector tunnel, 1989/90 ....................... 80  
3.4 Double shield TBM working without precast segment, difficulties in difficult ground: Tuzla-Dragos tunnel in Istanbul ........................................................................................................................................ 80  
3.5 Difficulties in using slurry TBMs in complicated geology, Marmaray tunnel project ........................................................................................................................................ 84
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>Difficulties in single-shield TBM working in open mode in complex geology: An example from Kadikoy–Kartal metro tunnel</td>
<td>86</td>
</tr>
<tr>
<td>3.7</td>
<td>Eurasia tunnel excavated by a large diameter slurry TBM</td>
<td>88</td>
</tr>
<tr>
<td>3.8</td>
<td>Conclusions</td>
<td>88</td>
</tr>
<tr>
<td>4</td>
<td><strong>Difficult ground conditions affecting performance of EPB-TBMs</strong></td>
<td>91</td>
</tr>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>91</td>
</tr>
<tr>
<td>4.2</td>
<td>Factors affecting performance of EPB-TBMs</td>
<td>92</td>
</tr>
<tr>
<td>4.3</td>
<td>Performance prediction of EPM TBMs in difficult ground conditions</td>
<td>93</td>
</tr>
<tr>
<td>4.3.1</td>
<td>A model to predict the performance of EPB-TBMs in difficult ground conditions</td>
<td>94</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Estimation of optimum specific energy from full-scale laboratory cutting experiments</td>
<td>95</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Estimation of optimum field specific energy</td>
<td>95</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Estimation of machine utilization time</td>
<td>98</td>
</tr>
<tr>
<td>4.3.5</td>
<td>Numerical example to estimate daily advance rate of an EPB-TBM</td>
<td>99</td>
</tr>
<tr>
<td>4.3.6</td>
<td>Comparison of predicted and realized EPB-TBM performance values</td>
<td>100</td>
</tr>
<tr>
<td>4.3.7</td>
<td>Verification and modification of the model for silty-clay and sand in the Mahmutbey–Mecidiyekoy metro tunnels</td>
<td>103</td>
</tr>
<tr>
<td>4.4</td>
<td>Conclusions</td>
<td>106</td>
</tr>
<tr>
<td>5</td>
<td><strong>Selection of cutter type for difficult ground conditions</strong></td>
<td>109</td>
</tr>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>109</td>
</tr>
<tr>
<td>5.2</td>
<td>Comparative studies of different type of cutters for Tuzla–Dragos tunnel in Istanbul – test procedure and results</td>
<td>109</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Efficiency of chisel cutters as against disc cutters</td>
<td>111</td>
</tr>
<tr>
<td>5.3</td>
<td>The inefficient use of tungsten carbide studded disc cutters in the Marmaray–Istanbul project</td>
<td>114</td>
</tr>
<tr>
<td>5.4</td>
<td>Conclusions</td>
<td>115</td>
</tr>
<tr>
<td>6</td>
<td><strong>Effects of North and East Anatolian Faults on TBM performances</strong></td>
<td>117</td>
</tr>
<tr>
<td>6.1</td>
<td>Introduction</td>
<td>117</td>
</tr>
<tr>
<td>6.2</td>
<td>Kargi tunnel</td>
<td>117</td>
</tr>
<tr>
<td>6.3</td>
<td>Gerede tunnel</td>
<td>118</td>
</tr>
<tr>
<td>6.4</td>
<td>Dogancay energy tunnel</td>
<td>120</td>
</tr>
<tr>
<td>6.5</td>
<td>Nurdagı railway tunnel</td>
<td>122</td>
</tr>
<tr>
<td>6.6</td>
<td>Uluabat energy tunnel</td>
<td>123</td>
</tr>
<tr>
<td>6.7</td>
<td>Tunnels excavated by drill and blast methods</td>
<td>126</td>
</tr>
<tr>
<td>6.7.1</td>
<td>Ayas Tunnel: the most difficult tunnel in Turkey affected by North Anatolian Fault</td>
<td>126</td>
</tr>
<tr>
<td>6.7.2</td>
<td>Bolu tunnel</td>
<td>127</td>
</tr>
<tr>
<td>6.8</td>
<td>Conclusions</td>
<td>127</td>
</tr>
</tbody>
</table>
Table of contents

References .......................................................................................................................... 128

7 Effect of blocky ground on TBM performance and the mechanism of rock rupture .................................................................................. 129
7.1 Introduction .................................................................................................................. 129
7.2 Mechanism of rock rupture and face collapse in front of the TBM in the Kozyatagi–Kadikoy metro tunnels in Istanbul ........................................ 131
7.2.1 Kozyatagi and Kadikoy metro tunnels and problems related to blocky ground ......................................................................................... 131
7.2.2 Mechanism of rock rupture and face collapse in front of the TBM .......... 134
7.2.3 Other factors affecting the efficiency of tunnel excavation on the Kozyatagi–Kadikoy metro line .............................................................. 138
7.3 Conclusions .................................................................................................................. 140

References .......................................................................................................................... 141

8 Effects of transition zones, dykes, fault zones and rock discontinuities on TBM performance ................................................................................. 143
8.1 Introduction .................................................................................................................. 143
8.2 Beykoz sewerage tunnel ............................................................................................... 143
8.2.1 Description of the project ........................................................................................ 143
8.2.2 Geology of the area ................................................................................................. 144
8.2.3 Description of the TBM .......................................................................................... 146
8.2.4 Effect of rock formation on chip formation and machine utilization time ..... 147
8.2.5 Effect of dykes on tunnel face collapse and TBM blockage ............................... 149
8.2.6 Effect of transition zones on TBM performance .................................................. 150
8.2.7 Effect of fault zones on TBM performance ............................................................ 152
8.3 Kartal–Kadikoy metro tunnels, methodology of understanding critical zones ................................................................................................. 153
8.3.1 Geology and physical and mechanical properties of rocks ...................... 154
8.3.2 Mechanism of face collapse and TBM blockages ............................................ 155
8.3.3 Change of TBM performance in problematic areas ...................................... 161
8.4 Conclusions .................................................................................................................. 163

References .......................................................................................................................... 165

9 Squeezing grounds and their effects on TBM performance ................................................................................................................................. 167
9.1 Introduction .................................................................................................................. 167
9.2 Basic works carried out on squeezing ground ......................................................... 167
9.3 Uluabat tunnel ............................................................................................................ 168
9.3.1 Description of the project ....................................................................................... 168
9.3.2 Geology of the project area .................................................................................... 169
9.3.3 Description of the TBM used and the general performance ...................... 171
9.3.4 Effect of TBM waiting time on squeezing ......................................................... 176
9.3.5 Effect of bentonite application on TBM squeezing ........................................ 178
9.3.6 Conclusions ............................................................................................................ 179
9.4 Kargi Tunnel ............................................................................................................... 179
9.4.1 Squeezing of the cutterhead and related problems ....................................... 179
9.4.2 Effect of Q values on squeezing of TBM ...................................................... 184
9.4.3 Discussions and conclusions on TBM swelling in Kargi project............. 185

References ........................................................................................................... 186

10 Clogging of the TBM cutterhead ................................................................. 189
10.1 Introduction .................................................................................................. 189
10.2 What is clogging of a TBM cutterhead and what are the clogging materials? ........................................................................................................... 189
10.3 Testing clogging effects of the ground .......................................................... 189
10.4 Mitigation programs to eliminate clogging .................................................. 191
10.5 Clogging of TBMs in Turkish projects ....................................................... 192
10.5.1 Suruc Project .......................................................................................... 192
10.5.2 Selimpasa sewerage tunnel in Istanbul .................................................... 196
10.5.3 Zeytinburnu Ayvalidere-2 wastewater tunnel project ......................... 201
10.6 Conclusions ............................................................................................... 207

References ........................................................................................................... 208

11 Effect of high strength rocks on TBM performance ...................................... 211
11.1 Introduction .................................................................................................. 211
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 .............................................................................. 211
11.3 Nurdagi tunnel, full-scale cutting tests to obtain optimum TBM design parameters in very high strength and abrasive rock formation ........................................................................................................... 213
11.4 Beylerbeyi–Kucuksu wastewater tunnel, TBM performance in high strength rock formation ................................................................. 216
11.5 Tuzla-Akfirat wastewater tunnel, TBM performance in high strength rocks ........................................................................................................... 221
11.6 Conclusions ............................................................................................... 222

References ........................................................................................................... 223

12 Effect of high abrasivity on TBM performance ............................................ 225
12.1 Introduction .................................................................................................. 225
12.2 Determination of the abrasivity .................................................................. 229
12.3 Empirical prediction methods for disc cutter consumption ....................... 232
12.3.1 Colorado School of Mines (CSM) model for CCS type 17-inch single-disc cutters ........................................................................................................... 232
12.3.2 Norwegian Institute of Technology (NTNU) model ............................... 233
12.3.3 Maidl et al. (2008) model for CCS type 17-inch single-disc cutters ....... 238
12.3.4 Frenzel (2011) model for CCS type 17-inch single-disc cutters ............ 238
12.3.5 Gumus et al. (2016) model for CCS type 12-inch monoblock double-disc cutters of an EPB-TBM ................................................................. 238
12.4 Examples of cutter consumptions on TBMs in Turkey ............................. 239
12.4.1 Tuzla-Akfirat wastewater project in Istanbul ......................................... 240
12.4.2 Yamanli II HEPP project in Adana ........................................................ 250
12.4.3 Beykoz wastewater project in Istanbul .................................................. 260
# Table of contents

12.4.4 Buyukcekmece wastewater tunnel in Istanbul .............................................. 262
12.4.5 Uskudar–Umrianiye–Cekmekoy–Sancaktepe metro tunnel in Istanbul .... 264
12.5 Conclusions ........................................................................................................ 269

References .................................................................................................................. 271

13 **Effect of methane and other gases on TBM performance** .................................... 273
13.1 Properties of methane .......................................................................................... 273
13.2 Selimpasa wastewater tunnel, methane explosion in the pressure chamber of an EPB-TBM ........................................................................................................ 275
13.2.1 Introduction to the Selimpasa wastewater project ........................................ 275
13.2.2 Occurrence and causes of methane explosion in the Selimpasa wastewater tunnel ........................................................................................................... 278
13.2.3 Consequences of methane explosion in the Selimpasa wastewater tunnel 279
13.2.4 Precautions against methane and excavation performance in the Selimpasa wastewater tunnel .............................................................................. 280
13.3 Gas flaming in the Silvan irrigation tunnel .......................................................... 284
13.4 More gas-related accident examples for mechanized tunneling ...................... 287
13.5 Conclusions ........................................................................................................ 290

References .................................................................................................................. 291

14 **Probe drilling ahead of TBMs in difficult ground conditions** .............................. 293
14.1 Introduction ........................................................................................................... 293
14.2 General information on probe drilling and previous experiences in different countries ........................................................................................................ 293
14.3 Melen water tunnel excavated under the Bosphorus in Istanbul ...................... 295
14.4 Methodology of predicting weak zones ahead in the Melen water tunnel 297
14.4.1 Data analysis and results .................................................................................. 300
14.5 Kargi energy tunnel ............................................................................................ 308
14.5.1 General information on the Kargi project ....................................................... 308
14.5.2 Probe drilling operations ................................................................................. 309
14.5.3 Analysis of probe drilling data in the Kargi project ....................................... 309
14.6 Conclusions ........................................................................................................ 316

References .................................................................................................................. 318

15 **Application of umbrella arch in the Kargi project** ............................................. 321
15.1 Introduction ........................................................................................................... 321
15.2 General concept of umbrella arch and worldwide application ......................... 321
15.3 Methodology of using umbrella arch in the Kargi project .................................. 322
15.4 Criteria used for umbrella arch in the Kargi project and the results .................. 325
15.5 Conclusions ........................................................................................................ 330

References .................................................................................................................. 331

16 **Index** .................................................................................................................. 333
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.
(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 in site ‘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.
2 Geology of Turkey and Istanbul, expected problems, some cuttability characteristics of the rocks

2.1 Introduction

Recent studies have revealed that tunnels were excavated under hundreds of Neolithic settlements all over Europe, and the fact that so many tunnels have survived 12,000 years indicates that the original networks must have been huge, from Scotland to Turkey. Some experts believe that the network was a way of protecting man from predators, while others believe that some of the linked tunnels were used like motorways are today, for people to travel safely regardless of wars or violence or even weather above ground [1]. There are several underground cities from Roman Imperial Times, and even older in Cappadocia, Nevsehir in Turkey, the historical underground cities are linked with a network of tunnels. Tunneling activities in Turkey have been carried out for centuries since then.

There are currently 1,700 hydropower projects, with more than 800 tunnels being excavated. Turkey is a mountainous country necessitating continuous road tunneling activities, all over the country. The national target up to 2023 is 330 km of road and highway tunnels and 78 km of railway tunnels. The need for metro tunnels in big cities is increasing, reflecting the growing population; the length of metro lines in Istanbul was 141 km in 2013 and it is expected that this will reach to 400 km by 2019. The length of utility tunnels to be built in the near future in Istanbul is expected to be around 85 km. Altogether, it is predicted that Turkey will invest more than 35 billion USD in tunneling projects in the near future, and the majority of tunnels will be driven using tunnel boring machines (TBM). The anticipated problems are directly related to the complexity of the geology of Turkey, including frequent face collapses, squeezing of TBM, high water inflow and excessive cutter wear. In this book a brief summary of the geology of Turkey, and Istanbul in particular, will first be given, describing the main geological formations with physical, mechanical and cuttability characteristics. It is hoped that the information given in this chapter will help to make rational decisions in designing and executing the tunneling projects.

2.2 Geology of Turkey

Turkey’s varied landscapes are the product of a wide variety of tectonic processes that have shaped Anatolia over millions of years and which continue today, as evidenced by frequent earthquakes and occasional volcanic eruptions. Turkey’s terrain is structurally complex. Nearly 85% of the land is at an elevation of more than 450 m, the median altitude of the country being 1,128 m. It is hard to explain the complexity of the geology of Turkey within the limited length of this book, but the following paragraph taken from a well-known paper published by Okay [2] explains the complexity of the geology.

“Geologically Turkey consists of a mosaic of several terranes, which were amalgamated during the Alpide orogeny. The relics of the oceans, which once separated these terranes, are widespread through the Anatolia; they are represented by ophiolite and
accretionary complexes. The three terranes, which make up the Pontides, namely the Strandja, Istanbul and Sakarya terranes, have Laurasian affinities. These Pontic terranes bear evidence for Variscan and Cimmeride orogenies. Their Palaeozoic and Mesozoic evolutions are quite different from the Anatolide-Taurides. The Pontides and the Anatolide-Taurides evolved independently during the Phanerozoic and they were first brought together in the Tertiary. In contrast to the Pontic terranes, the Anatolide-Tauride terrane has not been affected by the Variscan and Cimmeride deformation and metamorphism but was strongly shaped by the Alpide orogeny. It was part of the Arabian Platform and hence Gondwana until the Triassic and was reassembled with the Arabian Platform in the Miocene. The Anatolide-Tauride terrane is subdivided into several zones mainly on the basis of type and age of Alpide metamorphism. The southeast Anatolia forms the northernmost extension of the Arabian Platform and shares many common stratigraphic features with the Anatolide-Tauride terrane. The final amalgamation of the terranes in the Oligo-Miocene ushered a new tectonic era characterized by continental sedimentation, calc-alkaline magmatism, extension and strike-slip faulting. Most of the present active structures, such as the North Anatolian Fault, and most of the present landscape are a result of this neotectonic phase.”

As Bozkurt and Mittwede [3] stated, Anatolia forms a superb laboratory for the study of subduction, ophiolite obduction, continent-continent collision, metamorphism, the relationship between lithospheric deformation and magmatism, fold and thrust belts, suture zones, active strike-slip faulting, active normal faulting and associated basin formation.

All the complexity of the geology as explained above makes it really difficult to excavate tunnels in some parts of Turkey and this book is aimed at summarizing the possible difficulties that may occur during TBM excavation, with possible solutions given based on past experience.

2.3 Geology of Istanbul

Palaeozoic, Mesozoic and Cenozoic formations are recognized in Istanbul as seen in Figure 2.1 [4].
2.3 Geology of Istanbul

Figure 2.1 The geology of Istanbul [4].
The oldest rocks are Palaeozoic rocks consisting of quartz, quartz arenite and arcose. From the Ordovician to the middle of the Carboniferous there is a concordant rock sequence outcropping several thousand meters thick. This sequence mainly consists of variable facies of clastic and carbonate rocks. Some of the main characteristics of the Palaeozoic sequence are horizontal and vertical transitions, alternations of different rocks and lenticular structures. Palaeozoic rocks cover large areas of Istanbul. Rocks of Ordovician, Silurian and Devonian age outcrop mostly on the Asian side, and Carboniferous rocks are located mostly on the European side. Andesitic and diabasic dykes are also present. Triassic formations are represented by conglomerate, sandstone, dolomite, dolomitic limestone and clayey limestone, and Cretaceous units by sandstone, shale, and limestone interbedded with lavas and pyroclastic rocks. The Mesozoic rocks, in turn, are covered by Tertiary units. These units are generally fossiliferous limestone, clayey limestone or marl, and uncemented or loosely cemented sand, silt and clay. Halic and Bosphorus sediments, old and new alluvium and artificial fill cover the other units in Istanbul. Halic and Bosphorus sediments generally consist of black clay, sand and silt. The thickness of these materials is 5–13 m on the Marmara Sea coasts, and 60–70 m on the Halic (Golden Horn) coasts. Old and new alluvium can be seen in the Baltalimani, Istinye and Bebek Valleys on the European side, and close to the Kurbagali, Maltepe-Cevizli and Buyuk Rivers on the Asian side. They consist of uncemented gravel, sand and clay which originate from other units in the area. The thickness of the alluvium is 8–20 m, and artificial fill 2–40 m thick can be seen on the Historical Peninsula (Eminonu). This consists of gravel, sand, silt, clay, rubble, brick and tile fragments [5].

2.4 TBM performance in different projects in Istanbul

Some typical examples of TBM performance in different projects are given in Tables 2.1, 2.2 and 2.3. As seen from these tables main daily advance rates vary in different geologic formations. The main expected problems are frequent changing of the strata, dykes, ancient water wells etc. Sometimes in earth pressure balance (EPB) TBM applications, excessive ground deformations may cause damage to the surrounding buildings as experienced in the Otogar–Esenler metro tunnels, which caused an extra cost of 35.6 million USD of the project [4].

For an efficient tunneling operation in Istanbul it is essential to understand the behavior of TBMs in different geological formations. That is why detailed information of each stratum will be given within this chapter.
### Table 2.1 Some of the completed metro tunnels [4].

<table>
<thead>
<tr>
<th>Line</th>
<th>Kozyatagi–Kadikoy</th>
<th>Otogar–Kirazli</th>
<th>Basaksehir–Ikitelli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology</td>
<td>Kartal formation</td>
<td>Gungoren formation</td>
<td>Gungoren formation</td>
</tr>
<tr>
<td>TBM Type</td>
<td>2 Herrenknecht open mode + EPB</td>
<td>Herrenknecht + Lovat EPB</td>
<td>2 Lovat (EPB)</td>
</tr>
<tr>
<td>Cutterhead diameter, m</td>
<td>6.57</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Total power, kW</td>
<td>2,000</td>
<td>1,622</td>
<td>2,100</td>
</tr>
<tr>
<td>Cutterhead torque, kNm</td>
<td>5,200 at 1.6 rpm</td>
<td>4,450 at 2.5 rpm</td>
<td>6,600 at 1.7 rpm</td>
</tr>
<tr>
<td></td>
<td>1,515 at 5.5 rpm</td>
<td>4,350 at 1.95 rpm</td>
<td>4,400 at 2.1 rpm</td>
</tr>
<tr>
<td>Max. thrust, kN</td>
<td>42,575</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Best daily advance, m</td>
<td>19.6</td>
<td>25</td>
<td>29</td>
</tr>
<tr>
<td>Mean daily advance, excluding main stoppages, m</td>
<td>7.2; 7.7</td>
<td>11.3; 11.1</td>
<td>—</td>
</tr>
</tbody>
</table>

### Table 2.2 Some of recent TBM applications in sewerage projects in Istanbul [4].

<table>
<thead>
<tr>
<th>Line</th>
<th>Beykoz–Kavacik</th>
<th>Ambarli</th>
<th>Baltalimani Sariyer</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBM</td>
<td>Robbins</td>
<td>Herrenknecht</td>
<td>Herrenknecht</td>
</tr>
<tr>
<td>Diameter, m</td>
<td>3.175</td>
<td>4.6</td>
<td>2.915</td>
</tr>
<tr>
<td>Total power, kW</td>
<td>400</td>
<td>—</td>
<td>620</td>
</tr>
<tr>
<td>Torque, kNm</td>
<td>527 at 4.3 rpm</td>
<td>3,117</td>
<td>725</td>
</tr>
<tr>
<td></td>
<td>254 at 8.5 rpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. thrust, kN</td>
<td>9,950</td>
<td>16,625</td>
<td>3,750</td>
</tr>
<tr>
<td>Best daily advance, m</td>
<td>23</td>
<td>28</td>
<td>24.8</td>
</tr>
<tr>
<td>Mean daily advance, incl. main stoppages, m</td>
<td>7.0</td>
<td>13.7</td>
<td>11.5</td>
</tr>
</tbody>
</table>
Table 2.3  Some of tunnels completed within Marmaray Project [4].

<table>
<thead>
<tr>
<th>Line</th>
<th>TBM type</th>
<th>Thrust (kN)</th>
<th>Torque (kNm)</th>
<th>Cutting power (kW)</th>
<th>Mean advance rate (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-1</td>
<td>EPB CAT</td>
<td>6,250</td>
<td>2,045</td>
<td>2,100</td>
<td>—</td>
</tr>
<tr>
<td>H-2</td>
<td>EPB CAT</td>
<td>6,250</td>
<td>2,045</td>
<td>2,100</td>
<td>13.5 m</td>
</tr>
<tr>
<td>H-3</td>
<td>Slurry, Hitachi-Zosen</td>
<td>7,500</td>
<td>4,767– 10,582</td>
<td>2,000</td>
<td>5.1 m</td>
</tr>
<tr>
<td>H-4</td>
<td>Slurry, Hitachi-Zosen</td>
<td>7,500</td>
<td>4,767– 10,582</td>
<td>2,000</td>
<td>7.50 m</td>
</tr>
<tr>
<td>H-5</td>
<td>Slurry, Hitachi-Zosen</td>
<td>7,500</td>
<td>4,767– 10,582</td>
<td>2,000</td>
<td>4.6 m</td>
</tr>
<tr>
<td>H-6</td>
<td>Slurry, Hitachi-Zosen</td>
<td>7,500</td>
<td>4,767– 10,582</td>
<td>2,000</td>
<td>3.9 m</td>
</tr>
</tbody>
</table>

H-1 and H-2 are excavated Miocene aged Bakirkoy and Gungoren formation. Marl, consolidated clay and sand lenses, H-4-6 re-excavated in Trakya formation interbedded sandstone, marl, siltstone and diabase dykes.

2.5 Description of geological formations in Istanbul, physical and mechanical properties

2.5.1 The stratigraphy of Istanbul and description of geologic formations

The stratigraphy of Istanbul is summarized in Figure 2.2 [6]. Some of the geological formations are described below from old to young units [7].
2.5 Description of geological formations in Istanbul, physical and mechanical properties

<table>
<thead>
<tr>
<th>TIME</th>
<th>LITHOLOGY</th>
<th>EXPLANATIONS</th>
<th>FOSSIL CONTENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CENOZOIC</td>
<td>Post-Eocene deposits</td>
<td>Eocene and younger sediments</td>
<td></td>
</tr>
<tr>
<td>Paleoc.-</td>
<td>L. Eoc.</td>
<td>Cretaceous sediments and volcanics</td>
<td></td>
</tr>
<tr>
<td>MESOZOIC</td>
<td>Upper Cretaceous</td>
<td>Triassic sediments</td>
<td></td>
</tr>
<tr>
<td>Triassic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carboniferous</td>
<td></td>
<td>Trakya Fm. Sandstone-shale, limestone interbeds and lenses</td>
<td>Forams in limestone</td>
</tr>
<tr>
<td>Permian</td>
<td>Sub-volcanic intrusions</td>
<td>Baltalimani Fm. Chert</td>
<td>Radiolaria</td>
</tr>
<tr>
<td>Ordovician</td>
<td>Permain Granitoids</td>
<td>Tuzla Fm. Nodular limestone</td>
<td>Conodont, Ostracoda</td>
</tr>
<tr>
<td>Silurian</td>
<td></td>
<td>Kartal Fm. Fossiliferous shale</td>
<td>Brachiopoda (Spirifer, Strophodonta, Strophomena, Atrypa, Orthis, Leptaena) Corals (Pleuroidium, Halyites, Zaphrentis) Trilobite, Nutiloid (Orthoceras, Cyrtoceras, Gyroceras)</td>
</tr>
<tr>
<td>Devonian</td>
<td></td>
<td>Dolayoba Fm. Fossiliferous limestone</td>
<td>Brachiopoda, Corals (Halyites, Favosites, Syringophora) Bryozoa (Fanestella) Crinoide</td>
</tr>
<tr>
<td>Carboniferous</td>
<td></td>
<td>Gozdaag Fm. Shale with quartzite lenses</td>
<td>Brachiopoda, Conularia, Graptolite</td>
</tr>
<tr>
<td>Precambrian</td>
<td></td>
<td>Aydos Fm. Quartz arenite</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kurtkoy Fm. Sandstone, conglomerate, shale</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.2 Stratigraphy of Istanbul [6].
2.5.1.1 Kurtkoy formation

This formation, having a thickness of 150 m in some parts of Istanbul, is composed of purple-colored conglomerate, sandstone and mudstone. A general view of Kurtkoy formation is seen in Figure 2.3 [6].

![Shale and sandstone within Kurtkoy formation](image)

2.5.1.2 Aydos formation

Aydos formation is situated in the upper level of the Kurtkoy formation. It is frequently fractured with rough surfaces filled with clay. The rocks within this unit have high strength values in most places not weathered; however, in some places, due to a shear zone, the rocks are highly fractured and weathered. It is laminated in different thicknesses, having colors ranging between white and pink-purple, consisting of quartz arenite, highly rich in feldspar with interbedded shales and siltstones. The rocks are very abrasive and have a range of high strength values. Typical view of Aydos formation is seen in Figure 2.4 [6].
2.5 Description of geological formations in Istanbul, physical and mechanical properties

2.5.1.3 Gozdag formation

Gozdag formation is found in the upper level of Kurtkoy formation, having a thickness of 700 m in some places, consists of laminated shale layers, and in upper levels shales having medium thickness sandstone layers. Typical view of Gozdag formation is given in Figure 2.5 [6].