Mechanized tunnelling in the influence zone of North Anatolian and East Anatolian Faults

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"A good university doesn't just teach knowledge but the ability to think."
Lino Guzzella, President of ETH Zurich

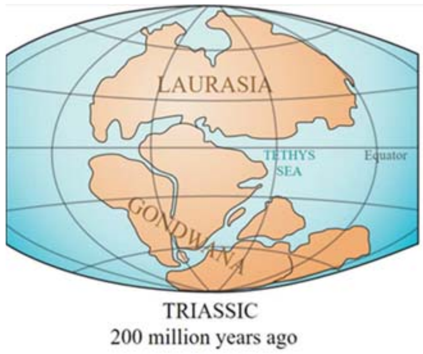
Tectonic PROBLEMS

The geology of Turkey is very complex and major North and East Anatolian Fault Zones including minor faults associated to these faults zones create tremendous problems, *like squeezing the TBM, excessive water ingress, TBM face collapses. SEGMENT COLLAPSES-LOOSING TBM AND TUNNEL*

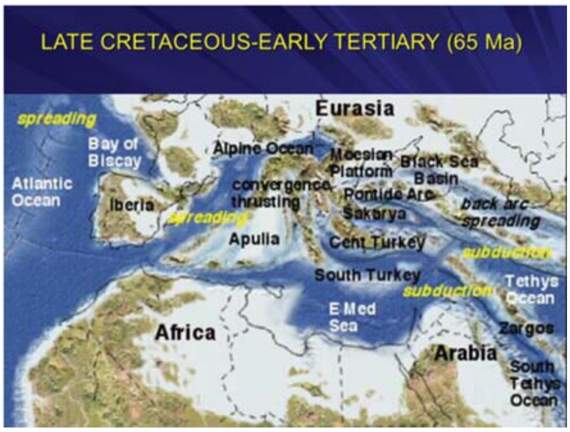
Fig.1 North and East Anatolian Faults

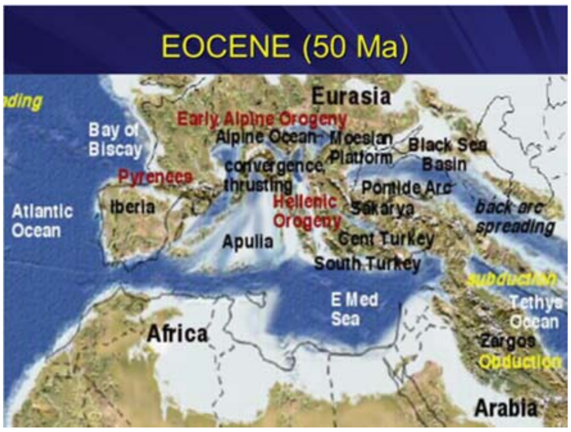
Understanding North Anatolian and East Anatolian Faults / Pangea-Laurasia-Gondwana

Pangaea or Pangea was a supercontinent that existed during the late Paleozoic and early Mesozoic eras. It assembled from earlier continental units approximately 335 million years ago, and it began to break apart about 175 million years ago



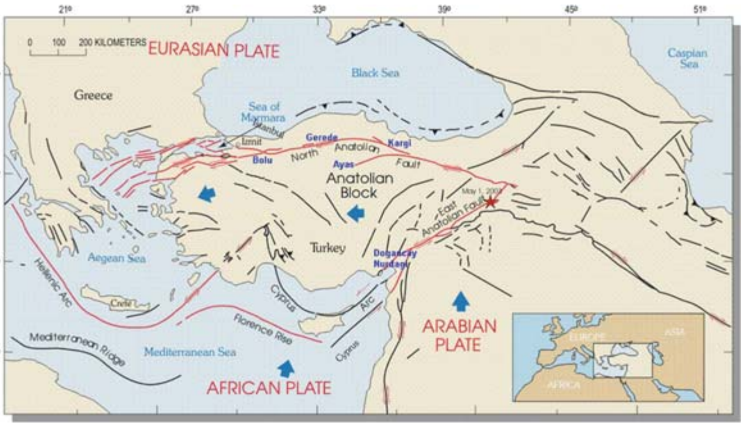
How did North Anatolian and East Anatolian Faults Formed ?





Reference: Neotectonics and Seismicity of Turkey Prof.Dr.Okan Tüysüz, 2005 İTÜ Avrasya Institute

How did North Anatolian and East Anatolian Faults Formed ?



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Reference: Bilgin, N., Çopur,H., Balcı,B TBM Excavation in Difficult Ground Conditions, Case Studies from Turkey, Wiley, Ernst and Son, 2016

Problamatic tunnels opened by NATM in the influence zones of North Anatolian and East Anatolian Fault Zones

Ayaş Tunnel.

The construction of the railway tunnel between Beypazari and Istanbul (Arifi ye–Sincan, started in 1976, length of 10.064 km). The lined inner diameter of the tunnel is 9.60 m. The tunnel was excavated by the NATM and about 230 million USD has been spent on the tunnel construction and it is still not finished. The main reason is the highly complicated geology and the difficult ground conditions. Ayas Tunnel was the longest railway tunnel planned in Turkey, it is abandonned now.

Bolu tunnel

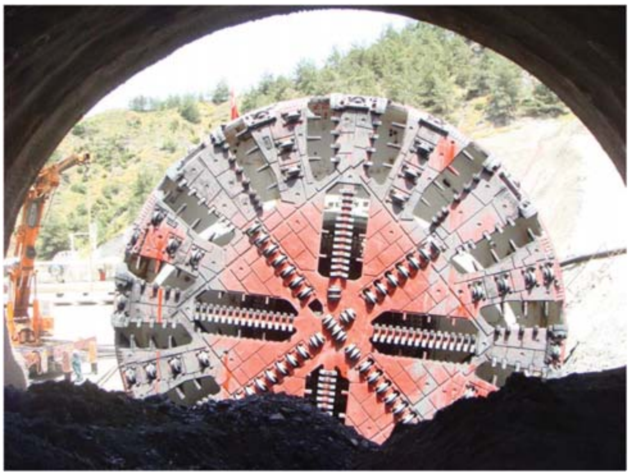
This tunnel is within the Trans-European Motorway project, and tunnel exaction started on 16 April 1993. The total cost of the tunnel is about 300 million USD. It has twin 17 m wide bores, carrying three lanes of traffic in each direction. The tunnel crosses the North Anatolian Fault. The 12 November 1999 the Duzce earthquake (MW = 7.2) caused substantial damage to the tunnel and viaducts, which were under construction at the time of the earthquake. Excavation of the tunnel in the Ankara to Istanbul direction was completed by the beginning of August 2005, using NATM

KÖSEKÖY- BİLECİK HIGH SPEED TUNNEL

The excavation of T26 Tunnel started with NATM method in 2010. The tunnel is on the North-East of Turkey. Due to geological problems, shear zones, fault zones and low RQD values, the daily advance rates were very slow. Karakaya formation is the main formation in tunneling area with Pazarcik melange. **Karakaya formation** contains fault zones in several places, this formation has similarities with Karakaya Formation found in **Ulabat Energy Tunnel**. **Graphitic schist is moderately weathered to fresh and very weak to weak and is extremely sheared along the foliation surface.**

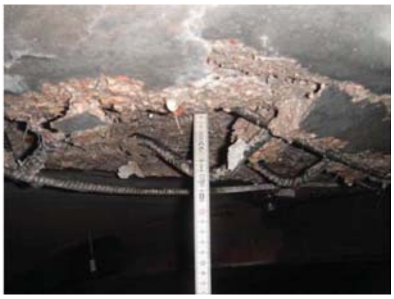
PROBLEMS IN GRAPITIC SHISTS / KÖSEKÖY HIGH SPEED TUNNEL

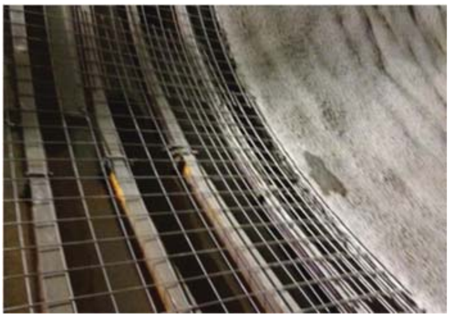
Mixed ground conditions with **ophiolites, graphitic schists** and mélanges with boulders including over excavation were the main difficulties leading to squeezing and blocking of the TBMs or even **causing complete failures of the segments and abandoning of the tunnel**. **Remedial works** are sometimes complex and tedious :**reducing the size of openings, minimal waiting, control of over excavation, lubrication between shield and rock, umbrella arch, increasing torque and thrust and sometimes rescue galleries are necessary.**



13.7 m diameter
Single shield TBM

THE COLLAPSE OF SEGMENTS IN KÖSEKÖY RAILWAY TUNNEL





KÖSEKÖY HIGH SPEED TUNNEL

Face collapses, over excavation and jamming of the cutterhead started at chainage 216+300m in May 2012 and continued thereafter. TBM manufacturer decided to close some of the openings within the cutterhead. After several problems occurred during TBM excavation, **the thrust of the TBM was increased from 84464 kN to 170000kN (breakout) and the torque was increased from 24083 kN.m (overload) to 36000 kN.m.** Face collapsing continues frequently depending on the weak zones developed within shear zones, slowing down tremendously advance rates.

Köseköy Hİgh Speed Tunnel

After several discussions between the consultants, the machine manufacturer and the contractor, bentonite and foam were decided to be used to stop face collapses. With several modifications made to TBM, 2 bars of mean face pressure could be obtained. Segments started cracking in May 2012 and tunnels started collapsing gradually damaging the TBM. For the sake of safety all tunneling activities were stopped thereafter. Limited information about this tunnel is given in this speech since the international dispute is still continuing between the machine manufacturer and the contractor.

The Effect of closing openings in Köseköy T26 High Speed Tunnel, single shield TBM, D=13,7m

$$SE = 2 \cdot \pi \cdot N \cdot T/NPR$$

SE = Spesific enrgy, kWh/m3
N = Rotational speed rpm
T = Torque, kNxm
NPR = Net penetration rate m3/h

Example
Ring 147
N=2.8/60 revolution per second
T=14600 kNxm
Excavation area 3.14x13.7x13.7/4= 147.4m2
TBM penetration=107 mm/min
NPR= 0.107x60x147.4 = 907m3/h
SE=2xπx2.8x14600/(60x907)
SE= 4.7 kW(m3)

In the area where the openings were opened
Date 19.09.2011, Ring 146-150, SE = is 3.57 kWh/m^3.
Bentonite application in the area where the openings were half closed.
Date 3-11 2011, Ring 155-165, SE = 12.6 kWh/m^3.
The openings are half closed, bentonite is not applied
Date 17.11.2011, Ring 190-199, SE = 7.5 kWh/m^3.
Result of closing the openings : High energy consumption, High disc consumption

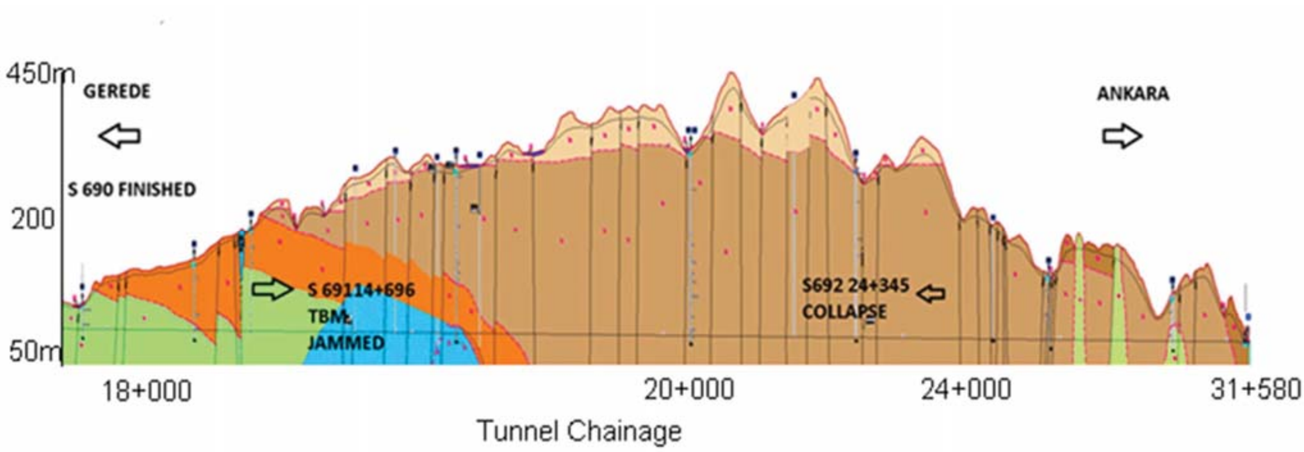
LESSONS LEARNED

1. A good side and geotechnical investigation is a necessity
2. Understanding the interaction between machine and the ground is a key point in the sucess
3. Proper machine selection and design are necesseary.
4. Experiences of the contractor and the tunnel crew are the fondamental key point in the success

<u>OUTHERWISE YOU MAY ABANDON THE TUNNEL</u>

GEREDE TUNNEL-EXCESSIVE WATER

The purpose of the project is to supply drinking water to Ankara, via a tunnel having a length of **<u>31.6 km and a final diameter of 4.4 m. The geology of the Gerede tunnel consists mainly of volcanic units.</u>** The tunnel was intended to be completed by using three double-shielded TBMs of 5.5 m diameter. Tunnel excavation began in 2010 simultaneously in three points: entrance portal, shaft and output portal, with S-690, S-691 and S-692 TBMs**<u>. The TBM S 690 excavated a length of 9588 m and the first part was finished.</u>** However, this has been one of the most problematic TBM tunneling operations in Turkey



GEREDE TUNNEL

The second drive, which started from the intermediate shaft towards Ankara, was excavated in downstream direction by the S-691 DS TBM. **The TBM became stuck in smectite clay**, which has a tremendous swelling characteristic. **Swelling stresses started breaking the segments,** and the broken segments were then supported by steel arches. **It is thought that the smectite zone is behaving like a pillar zone, protecting the tunnel from the highly stressed pressurized water reservoir ahead of the tunnel** and so the machine was removed from this side, and to continue from the Ankara side to take advantage of the dip of the tunnel for water removal. The third drive, which was being excavated by the S-692 DS, upstream of the Ankaran side, has been constantly hindered by the complex existing geological conditions of heavily altered and weathered volcano-clastic rocks under very high water tables, which even caused one 12-month stoppage and required a bypass tunnel. The S-692 shield was trapped at chainage 24+344.86 km after the tunnel suffered a collapse in July 2014. The pressure deformed the telescopic shield and about 20 m of segmental lining, as can be seen in following Figure causing **a huge water and material inflow, estimated to be around 1250 m3 in 15 minutes**

Gerede tunnel

The Machine was destroyed, the area was collapsed. A new TBM was ordered in 2015, a bypass tunnel was excavated by a new TBM

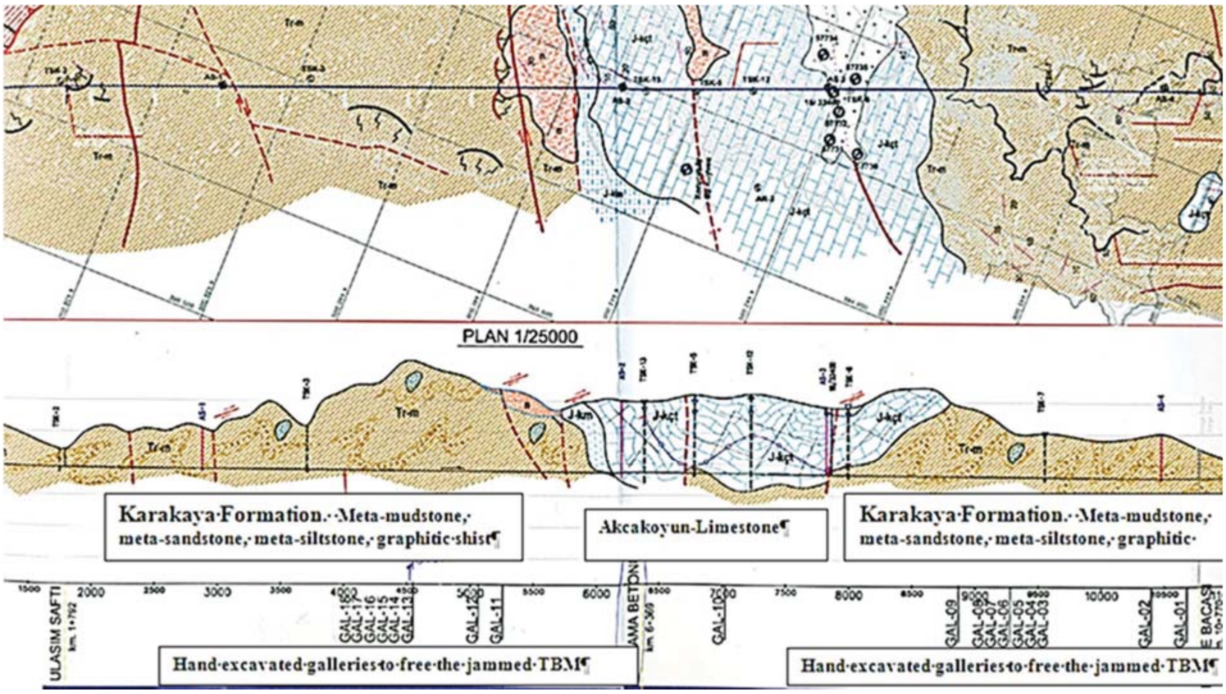
Uluabat Tunnel

The working area is situated on the southern part of Uluabat-Bursa (Apolyont) Lake, Turkey. **The tunnel, with a length 11.4 km**, started to be excavated with a **5.05 m diameter EPB-TBM from chainage June 2006, and terminated in March 2010.** The geology is consisted of Karakaya formation of Triassic age with meta- detritic rocks such as fi ne grained meta-claystone, meta-siltstone, meta-sandstone and graphitic schists. During the tunnel excavation, the TBM was jammed several times due to the highly squeezing characteristics of the **Karakaya formation**. **Eighteen rescue galleries were constructed to free the trapped TBM, and 192 days were spent in TBM rescue operations.** Detailed study of the TBM performance data showed that overburden, RMR, Q values, the increase of machine thrust for a given tunnel length and time, the variation in the torque/thrust ratio can all be used as a reliable basis to alert the practicing engineers to implement some mitigating measures, such as using bentonite injection around the TBM shield

ULUABAT TUNNEL

The working area is situated on the southern part of Uluabat-Bursa (Apolyont) Lake, Turkey. **The tunnel, with a length 11.4 km, started to be excavated with a 5.05 m diameter EPB-TBM** from chainage 11+465 km in June 2006, and terminated in March 2010, at chainage 1+792 km. The tunnel route within chainages 11+465 to 7+750 km and 6+000 to 1+792 km consisted of **Karakaya formation** of Triassic age with meta-detritic rocks such as fine grained meta-claystone, meta-siltstone, meta-sandstone and graphitic schists.

ULUABAT TUNNEL



Uluabat Tunnel and Squeezing FormatIons

MITIGATION MEASURES TO OVERCOME TRAPPED TBM IN ULUABAT TUNNEL

For a first initiation, the fixed **overcut was increased from 35 mm eventually to 95 mm on the radius.** However, this was not found sufficient in some area and the **bentonite injection was utilized in critical points**. This was accomplished by pumping a bentonite mixture between the shield skin and the ground, with the aim of reducing frictional forces. The bentonite mixture was delivered to the shield in a mixing car, to keep it fluid. **Injection through 2 inch diameter ports, six in total**, was done . Delivery pressure depended on the proximity of the ground at the injection points, and varied between **0.2 bar and 2.5 bars** when ground squeezing had reduced the clear-ance gap (overcut). Two to three cubic meters of the thin bentonite solution was used for each advance.

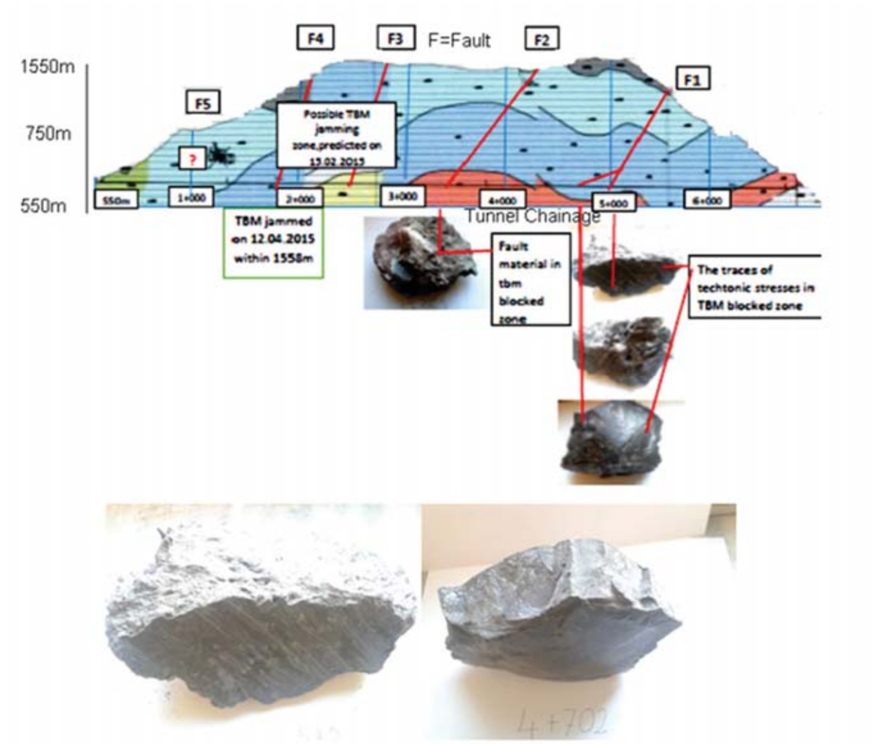
MITIGATION MEASURES TO OVERCOME TRAPPED TBM IN ULUABAT TUNNEL

Steel plates of 20 mm in thickness were welded to the TBM skin surface around injection ports to facilitate the injection. The aim was to produce a groove to permit bentonite injection; **since excessive ground squeezing sealed the injection ports so strongly that bentonite could not be pumped even at pressures in excess of 10 bars.** The exception to this statement occurred when the TBM was stopped for a long time, and the ground squeezed down even around the raised plates, consequently sealing the outlet. The jamming of the shield was not encountered between the chainages where the bentonite was applied, due to the reduction of friction between the shield and the rock**. It is also important to note that welding of steel plates of 20 mm to the TBM skin surface around injection ports facilitated the injection**.

TBM SQUEEZING IN DOĞANÇAY TUNNEL DUE TO TECTONIC STRESSES

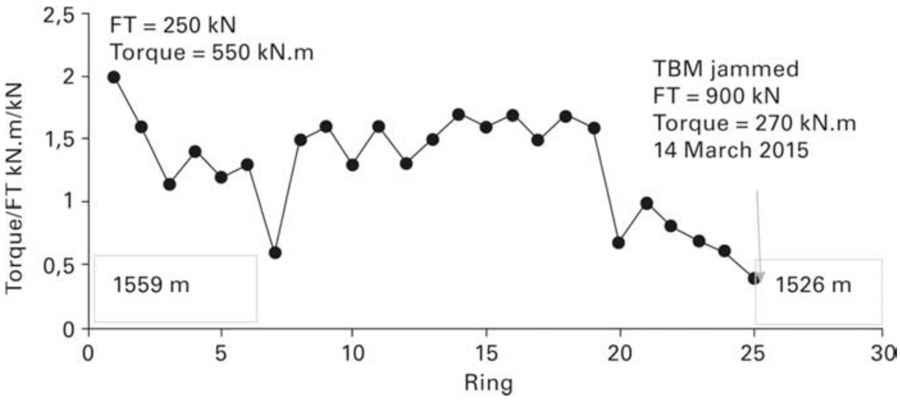
The Dogancay tunnel is located in the North East of Turkey, affected by North Anatolian Fault, and it is a part of a hydroelectric project licensed by Enerji Sa. The **tunnel length is 6655 m, and the excavation started in September 2012 and ended in July 2015** (5.5 m/day). The tunnel was excavated by a **double-shield Herrenknecht having a diameter of 4.1 m.** The tunnel route contains limestone, **shale, siltstone, claystone**, sandstone and quartzite. **The overburden** within 3 km of the tunnel route is **around 1,000 m** and only two boreholes could be opened in the tunnel route prior to starting the excavation. Tectonic stresses squeezed the TBM several times, causing considerable delays in tunnel drivage. T he followingFigure shows the general layout of the tunnel route with the main faults (F1, F2 etc.)

Doğançay Tunnel



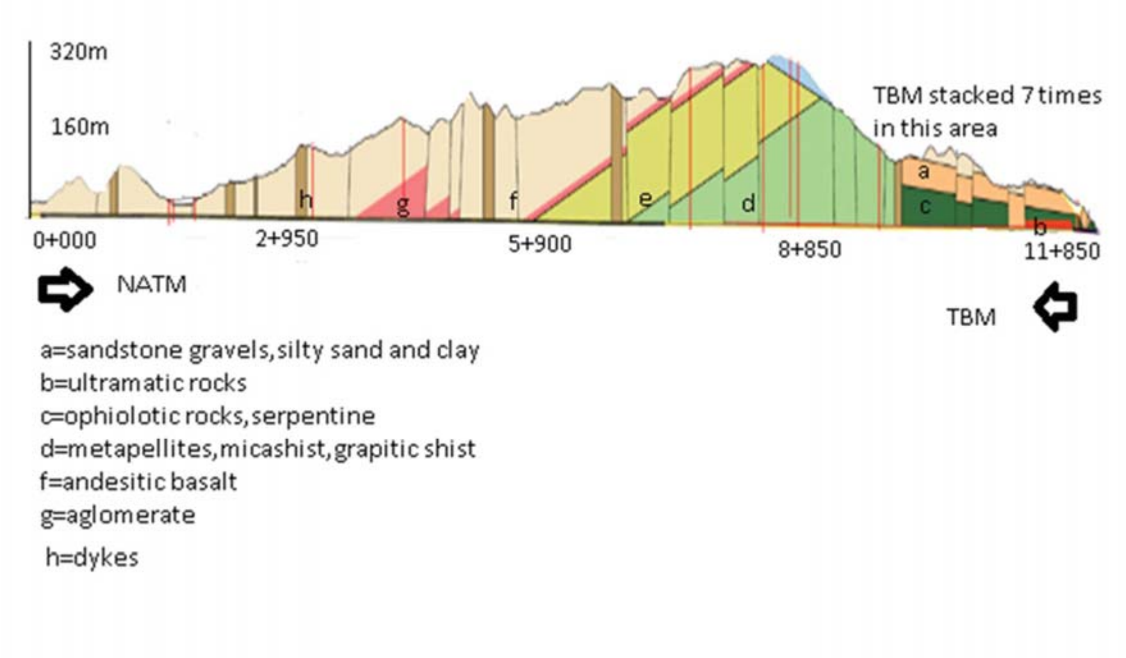
DOĞANÇAY TUNNEL

The ratio of torque to thrust force is a good indicator of the squeezing of a TBM. The following Figure shows the variation of this ratio between 12.04.2015 and 14.04.2015. As can clearly be seen from this figure the ratio started at 2, and dropped to 0.5 by the 7th ring, then later increased up to 1.5 and dropped again to 0.5, and the TBM was jammed within the 25th ring.

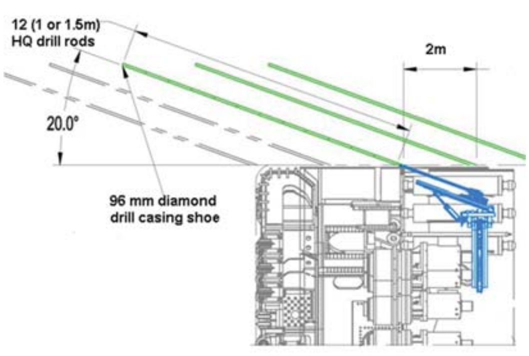


Kargi Hepp Tunnel AFFECTED BY EAST ANADOLIAN FAULT-Probe drıll

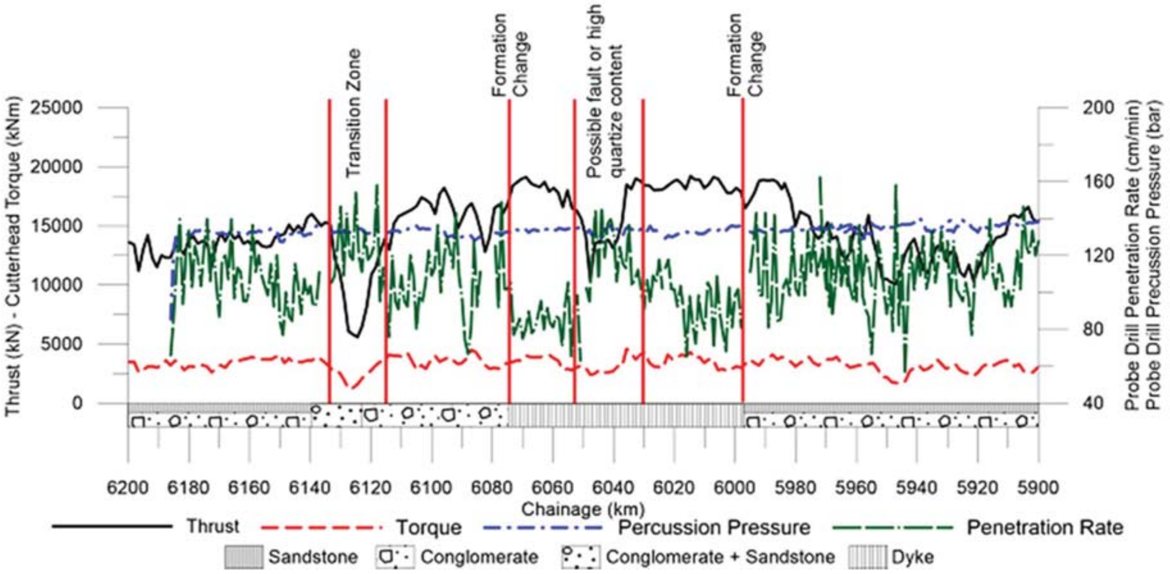
Kargi Hydropower project is situated in the region of Kizilirmak River between the town of Osmancik and the Boyabat reservoir. **The excavation of an 11.8 km tunnel has been recently finished, 7.8 km of the tunnel was excavated with a double shield Robbins TBM of 9.84 m diameter, and 4 km of the tunnel was opened with NATM.** However due to geological difficulties, and North Anatolian Fault Zone the ground became blocky in character, TBM stuck several times and galleries were opened in different places to rescue the trapped cutterhead. **To overcome the difficulties in continuing the project, systematic probe drilling and umbrella arch (UA) were selected as remedial works.**



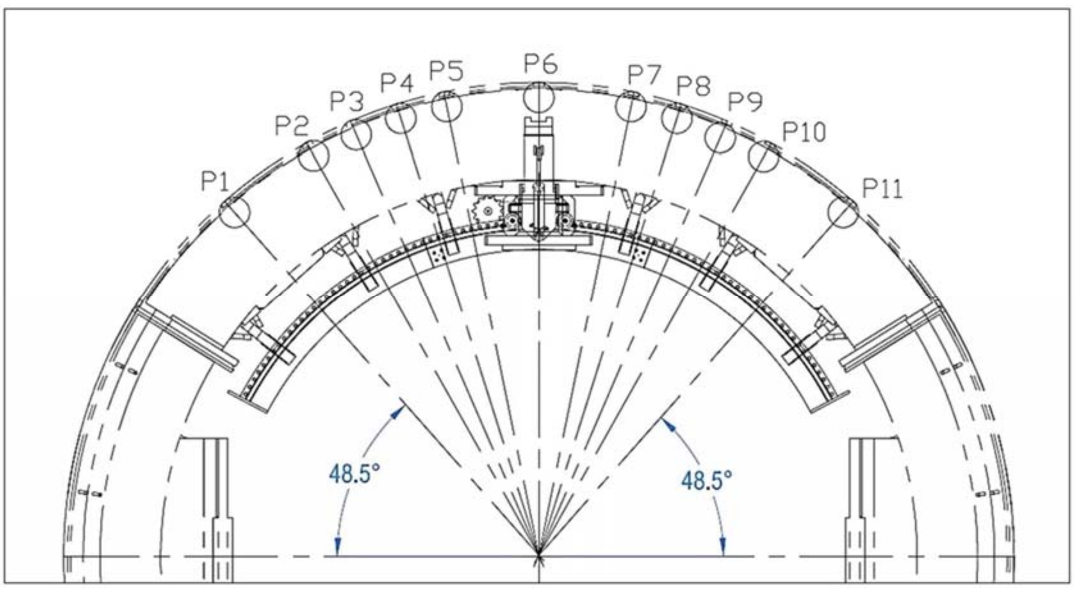
Eleven ports existed in the front shield of TBM. Drillings for UA started approximately 3 meters behind the cutter-head. Drill pipes having diameter of 3 inches were used for UA. At the be-ginning of the operation the holes were drilled with a drilling bit attached to drill pipes. After removing the drill bit**, a string of perforated pipes for injection**, was placed into drill hole. **Injection was done up to 120 bars pressure**, depending on injection materials properties. For injection fast setting **micro fine Portland cement (Rheocem 650)** was used. Moreover along with micro cement, **two component polyurethane injection resin (MasterRoc MP 355 and Geofoam) were also used.** For filling very large voids, two component urea-silicate (MasterRoc MP 367) injection was realized. Generally 15 meters of drill holes having an approximate of 20° angle were realized with 4 meter overlaps be-tween drills. It was seen that one umbrella arch drill, permits to support approximately 4 ring excavations, which is 6 meters in length .



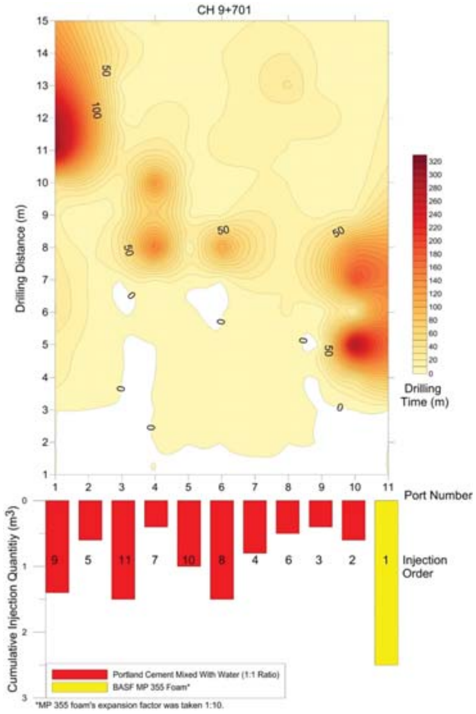
Probe Drılling In Kargı TUNNEL



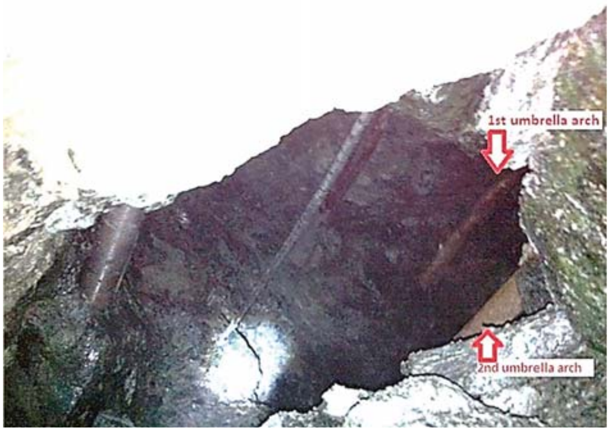
DRILLING FOR Umbrella Arch

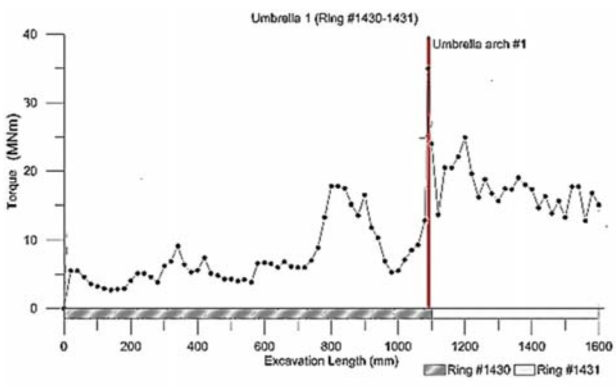


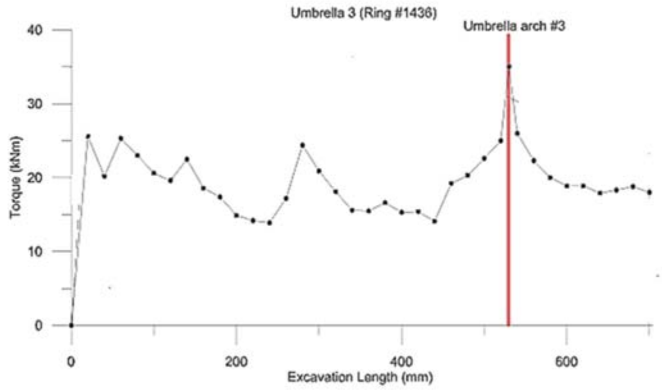
INTERPRETATION OF DRILLING DATA



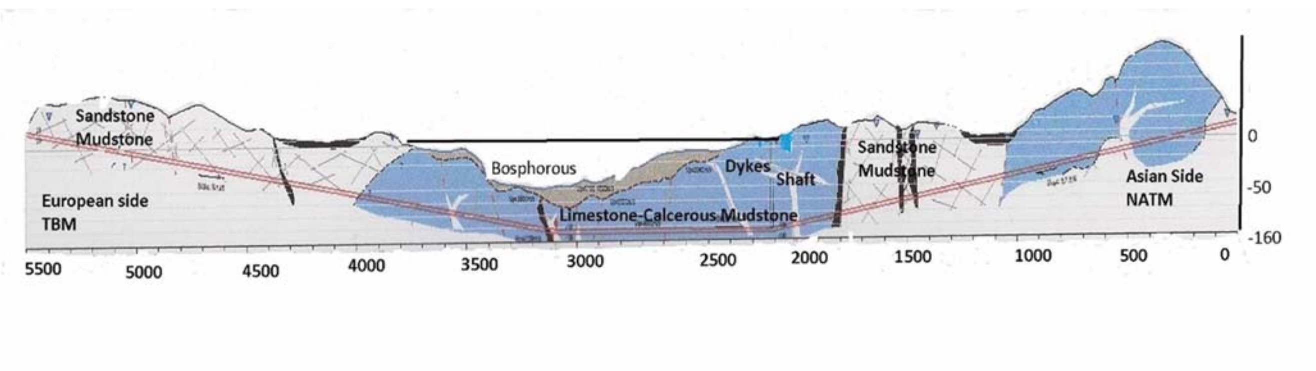
Kargi HEPP Project UMBRELLA ARCH







MELEN WATER TUNNEL UNDER THE INLUENCE ZONE OF NORTH ANATOLIAN FAULT AND POBLEM OF DYKES



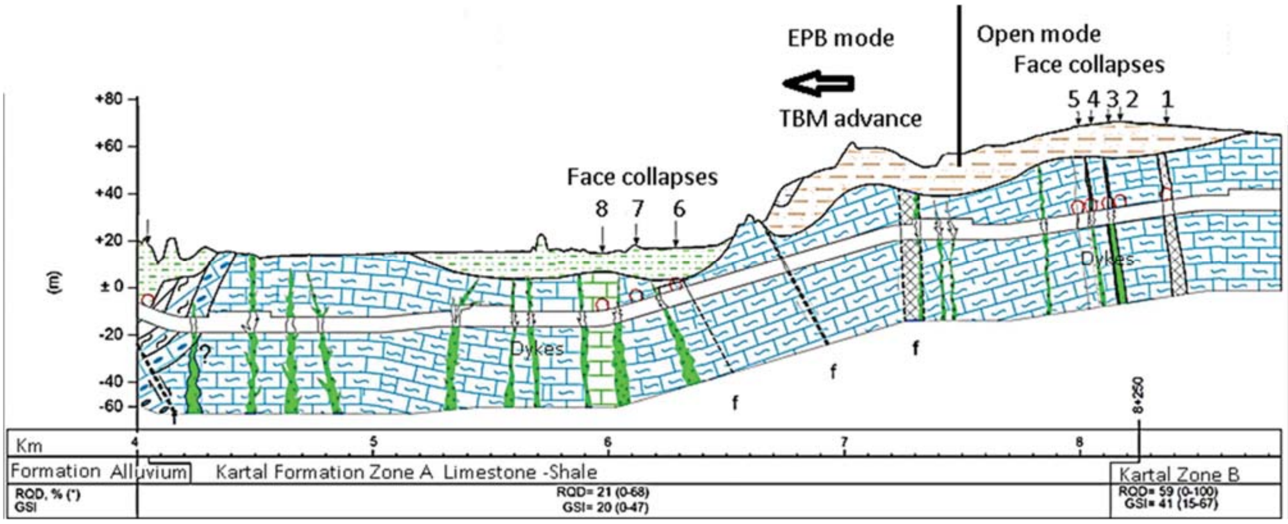
PROBLEMS OF DYKES AND PROB DRILLING

EFFECTS OF DYKES, BLOCKY GROUND AND REMEDIAL WORKS

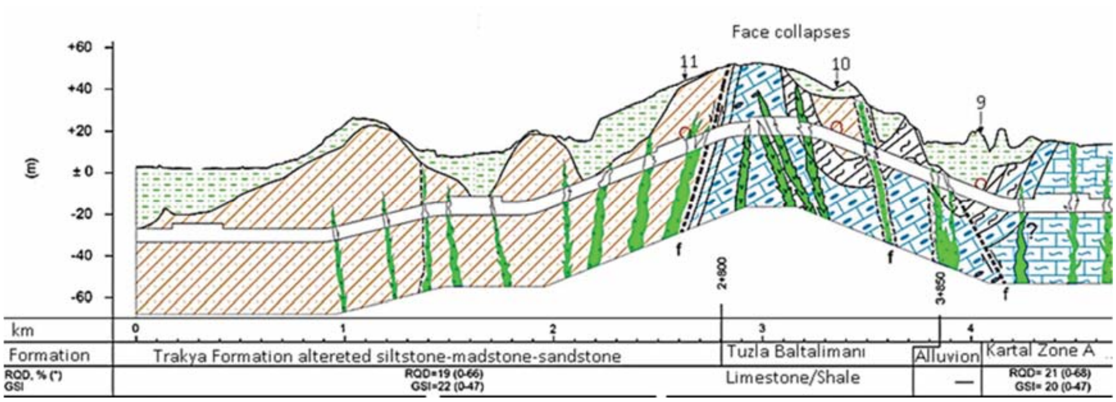
Dykes cutting the Paleozoic sedimentary rocks in the Istanbul region is known well by practicing tunnel engineers. These andesitic rocks, which are generally considered to be of Cretaceous age, make fractures in the country rock and cause several problems during TBM excavation such as blocking the cutterhead and excessive disc cutter consumption. Typical examples are the Goztepe-Kadikoy Metro tunnels, and tThe foloowing Figure shows typical big blocks coming from the interface of a dyke and the main rock formation causing the blockage of the cutterhead in different areas.

Big blocks coming from the face in Goztepe-Kadikoy Metro Tunnel.

Problems of Dykes in Göztepe- Kadıköy Metro Tunnels



Problems of Dykes in Göztepe- Kadıköy Metro Tunnels



TBM Blockages in Göztepe- Kadıköy Metro Tunnels

Area	Line No	Ring No	Tunnel m	Stoppage	Cause of the problem
1	1	73	8+366	27days	Fault zone
2	2	260–279	8+170	14 days	Contact zone between dyke and Kartal Formation
Opening ratio was reduced by adding grizzly bars on the TBM cutterhead					
3	1	232	8+120	7.5 days	Contact zone between dyke and Kartal Formation
4	1	282	8+046	2 days	Contact zone between dyke and Kartal Formation
5	1	321	7+993	6 days	Contact zone between dyke and Kartal Formation
Screw conveyor was mounted within the cutting chamber and EPB mode was used thereafter					
6	2	1349	6+286	2.5 days	Fault zone
7	2	1461	6+118	3 days	Contact zone between dyke and Kartal Formation
8	1	1483	5+973	1 day	Dyke contact zone
9	1	2272	4+046	2.5 days	Fault zone
10	1	2731	3+356	3 days	Transition zone between Trakya and Baltalimani Formation.
11	1	3021	2+628	24.5 days	Shear zone next to the tunnel connection

EFFECTS OF DYKES, BLOCKY GROUND AND REMEDIAL WORKSFigure

The remedial work was to put some grizzly bars within the openings of the cutterhead. Figure 1 shows the cutterhead of TBM used in Goztepe–Kadikoy Metro tunnel and Figure 2 shows the cutterhead after modification with grizzly bars. The effect of remedial work is clearly seen in Figure 3 showing that the mean advance rate was **3 m/day and this value increased up to 7 m/day after the modification of the cutterhead**. However, it is interesting to note that the daily advance rate in-creased to 10 m (day) after installing screw conveyor within the TBM chamber and passing to Earth Pressure Balance (EPB) mode. **Mean time in different tunnels in Istanbul same remedial works were carried out for Beykoz and Marmaray Tunnels** . Figure 3 shows TBM performance before and after TBM modification

Figure 1-2. Cutterhead before and after modification in Goztepe-Kadikoy Metro Tunnel.

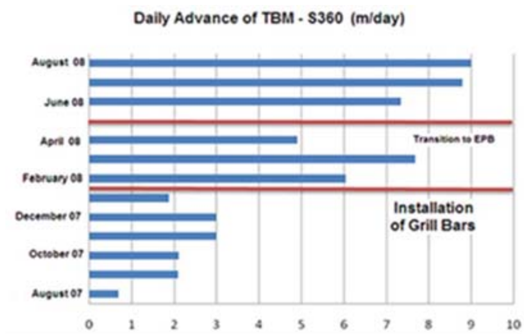


Figure 3. TBM performance before and after TBM modification.

The wear of twin disc cutter due of stalling disc cutter in blocky ground.

In November 2008, during the excavation of Goztepe-Kadikoy Metro tunnel with a **6.6 m EPB TBM in blocky sandstone** it was reported that thrust **force started increasing from 10000 kN gradually up 19860 kN**, however, **this was reverse for torque decreasing from 2.7 MNm down to 1.6 within the same rings.** This phenomenon is illustrated in the following Figures. This is typical behavior of chisel cutters or rippers where the cutting force (equivalent to torque) is less than normal force (or thrust) in most cases. The operation was stopped to check the cutterhead. It was noticed that 6 center double discs and 4 single discs were flattened as seen in Figure below and one disc were destroyed completely. The careful observation of checking the change in thrust and torque values of TBM prevented demolishing the cutterhead.

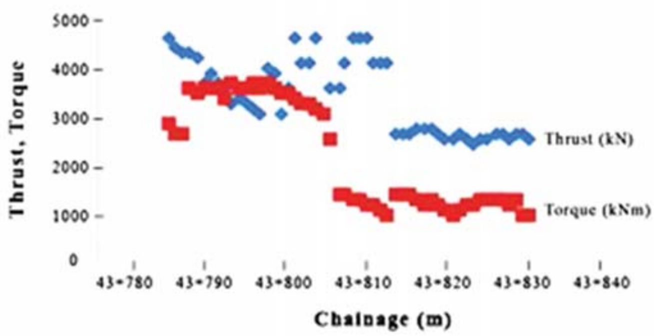
The increase of thrust force due to stalling of disc cutters in blocky ground.

The decrease of torque due of stalling of disc cutters in blocky ground.

The wear of twin disc cutter due of stalling disc cutter in blocky ground.

CLOGGING OF THE CUTTERHEAD

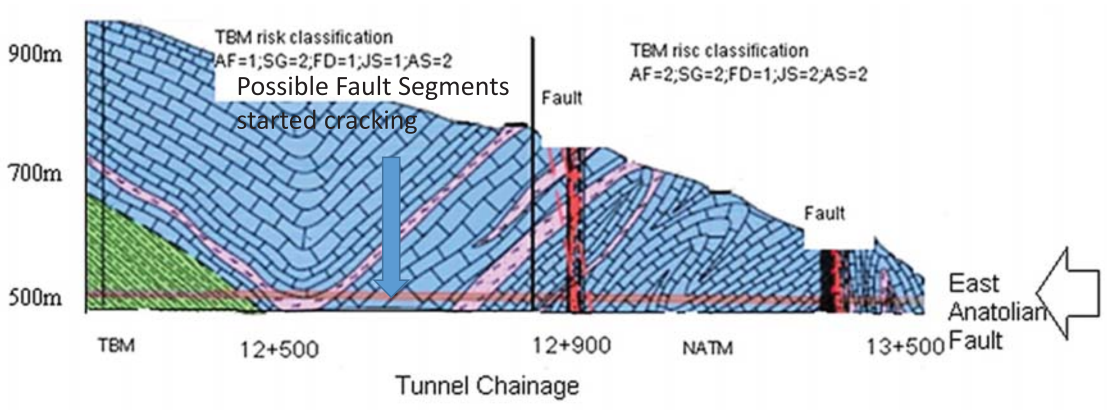
Clogging of the cutterhead in clayey rock for-mations is one of the major problems which de-creases the daily advance rates as encountered in Suruc Water Tunnel. The main rock formation in this tunnel is marl and clayey limestone. XRD anal-ysis showed that clay minerals such as kaolinite caused clogging of the TBM cutterhead. Anti-clogging agents are needed in most case to stop the clogging effect. The Figure given below is a typical example showing the effect of clogging on thrust and normal forces of TBM



Effect of clogging the cutterhead in Suruc Tunnel

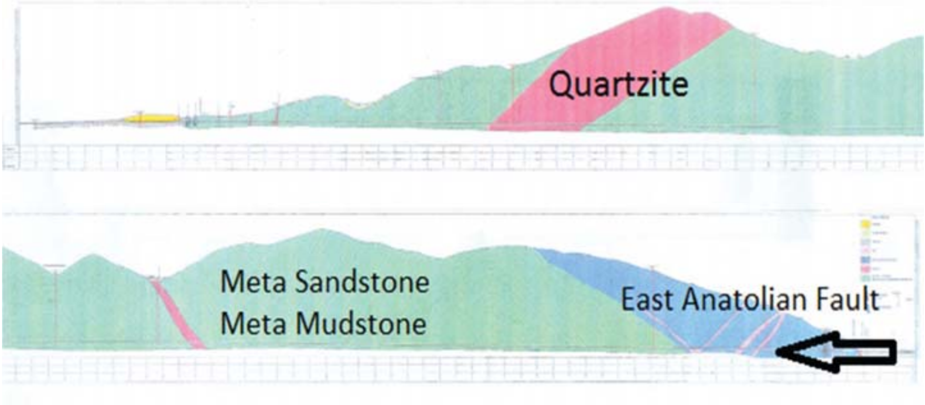
The tunnel is for railway transportation, and the project involves two tubes, each with a length of 9750 m. The excavation is planned to start from chainage 13+450 km and to terminate at chainage 3+700 km. The chainage from 13+450 to 12+400 km involves Karadag limestone of Mesozoic age, which is affected by the East Anatolian Fault (EAF), fracturing the rock formation to a great extent. High water ingress is expected in this area. Karadag limestone discharges the water at the toe of the mountain at the Nurdagi site. Several springs are available along the EAF. Due to technical difficulties and time necessary to procure the TBM, the first 1050 m in limestone is being currently opened using NATM. The geological cross-section of this area, which is planned to be opened by drill and blast method, is seen in the following Figure

NURDAĞI TUNNEL



Nurdağı Tunnel

The length of the two tubes railway tunnel is 9750 m and diameter is 8 m
It was decided to open the first 1000 m of the tunnel by NATM since the tunnel was under the influence of East Anatolian Fault



Risk Classification System for Using TBM

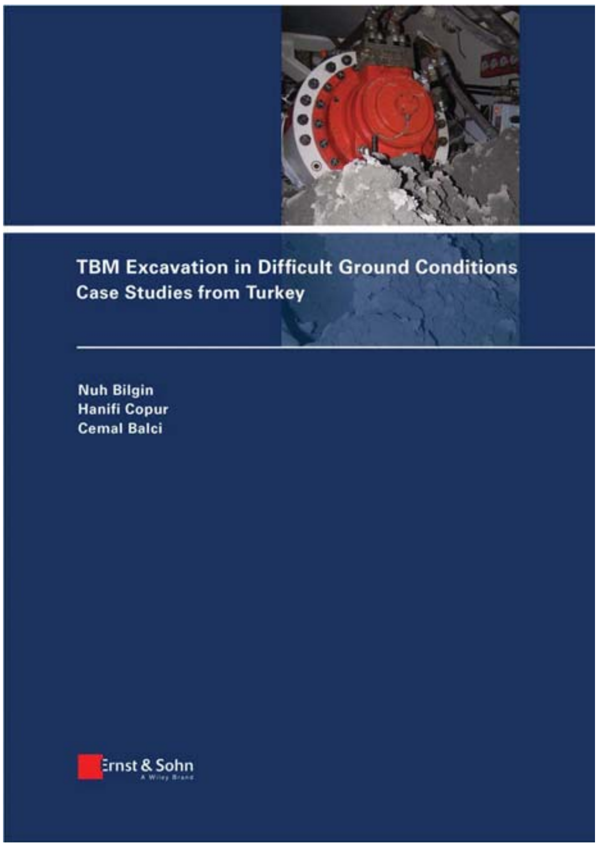
The tunnels excavated close to the NAF and EAF led to the development of a risk classification method defined in the following Table. According to this table, the use of a TBM in the Nurdagi tunnel at 13+500 to 12+800 km is very risky, 12+800 to 12+500 km is risky and it is favorable up to 4+850 km

Factors effecting the risk of using TBMs	Classification
1. Distance of the tunnel to NAF and EAF, the possibility of tectonic stresses. AF	1. Within 0.5–2 km of NAF and EAF 2. Very close to NAF and EAF
2. The possibility of large amounts of water ingress into the tunnel. Detailed geological reports and careful observation of drilling logs are necessary. SG	1. Less than 100 lt/sec 2. More than 100 lt/sec
3. The possibility of seeing geological discontinuities in front of tunnel face. The criterion is that in NATM it is easy to see and control geological discontinuities in the tunnel face. FD	1. Easy 2. Difficult
4. Geological discontinuities, RMR, Q, JS	1. Q, RMR 2. Q, RMR
5. The presence of anticlinal and synclinal AS	1. One per 1 km 2. More than one per 1 km
If the total mark is 8–10, it is very risky to use TBM; if the total mark is 5–8, it is risky; if the total mark is 2–5, the risk of using TBM is in medium level; if the total mark is 0–2, using TBM is not risky.	

Typical effect of Nort Anatolian Fault in the rock formation

Portal in Nurdağı tunnel

Nurdağı Tünelinde kullanılan tek kalkanlı Robbins TBM
SS268-398



You may find some more information in this book which was published in 2016

DRIVING A TBM IN A DIFFICULT GROUND IS NOT A JOKE IT NEEDS AN INTERNATIONAL GROUP OF EXPERTS FOR A SUCCESS, AS IN MELEN (From USA, Switzerland and Turkey) AND EUROSIA TUNNEL (From USA, Germany, UAS and Turkey)

THANK YOU LISTENING TO ME