The Use of Hard Rock TBMs in Turkey
Cutting Mechanism, Selection, Applications ,Problems

Hungarian Tunnelling Society
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Chairman of Turkish Tunnelling Society

Tunnel Boring Machines Using Disc Cutters

Single Gripper-TBM:

Double Gripper-TBM:

Single Shield TBM

Double Shield-TBM:

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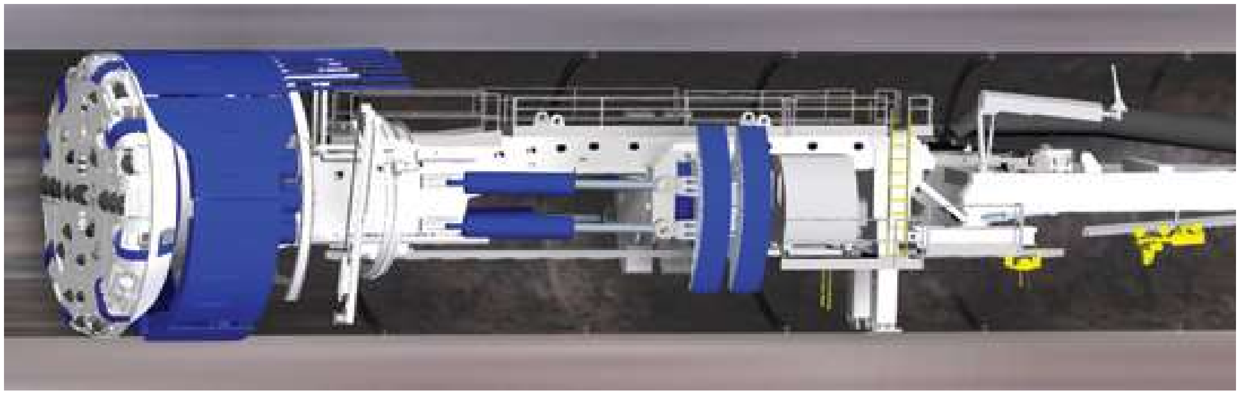
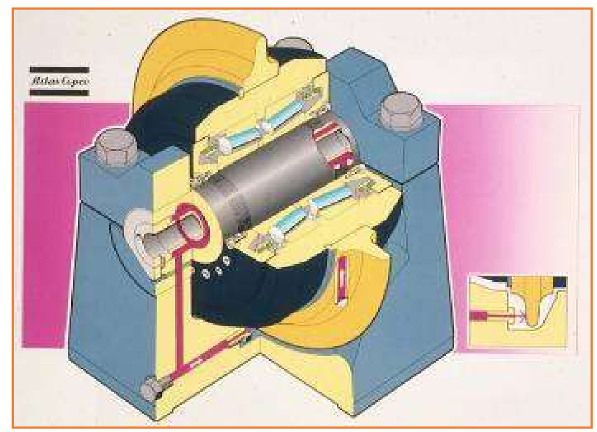
Gripper or Open Type TBMs





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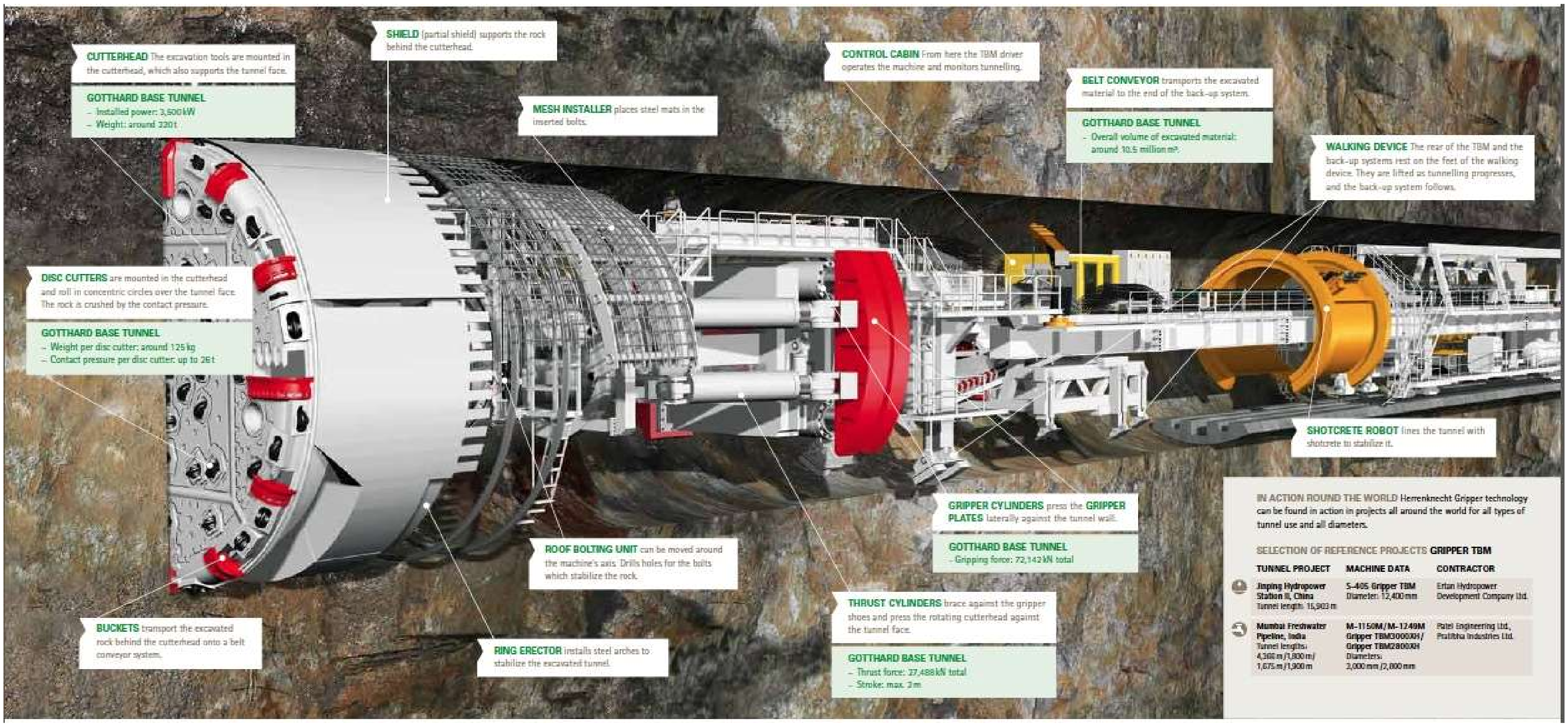
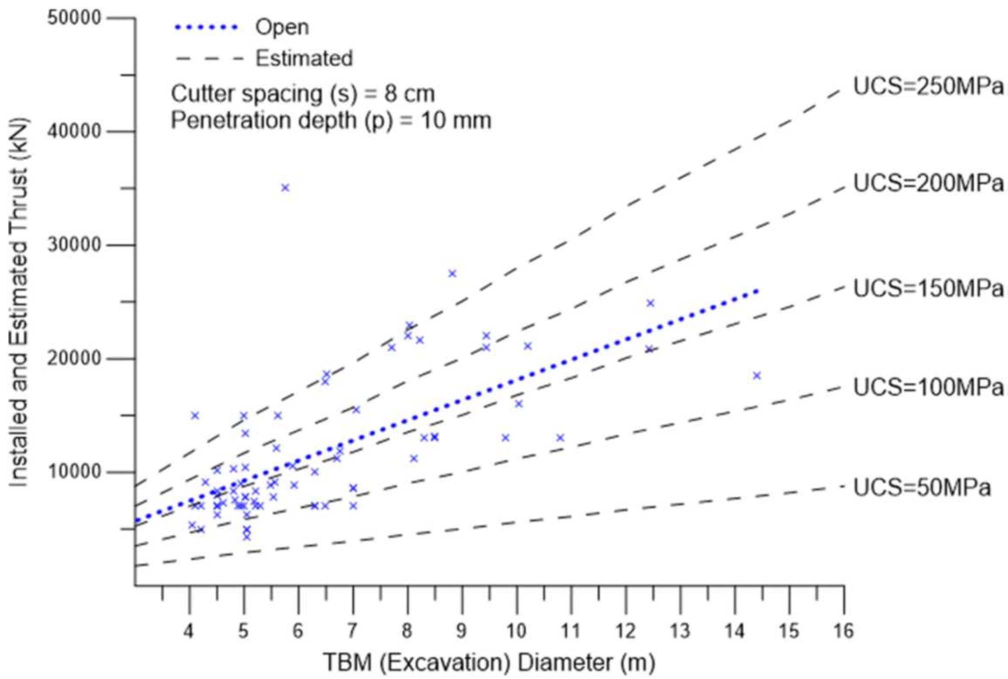
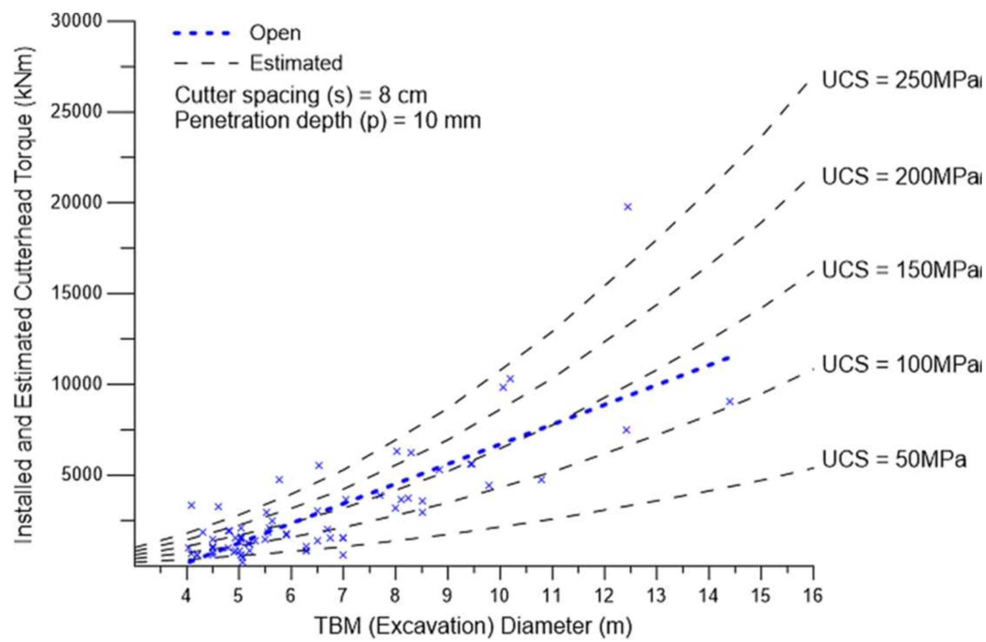
Gripper Type TBM (Herrenknecht) Used in Gotthard Tunnel



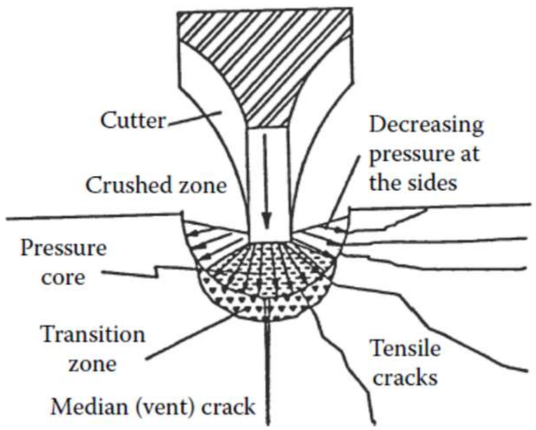
Estimation of Thrust and Torque of Gripper type TBM's

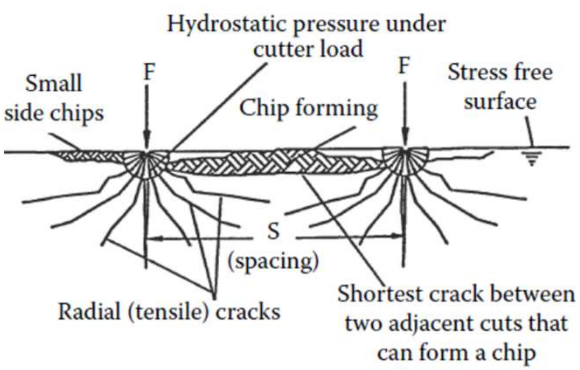


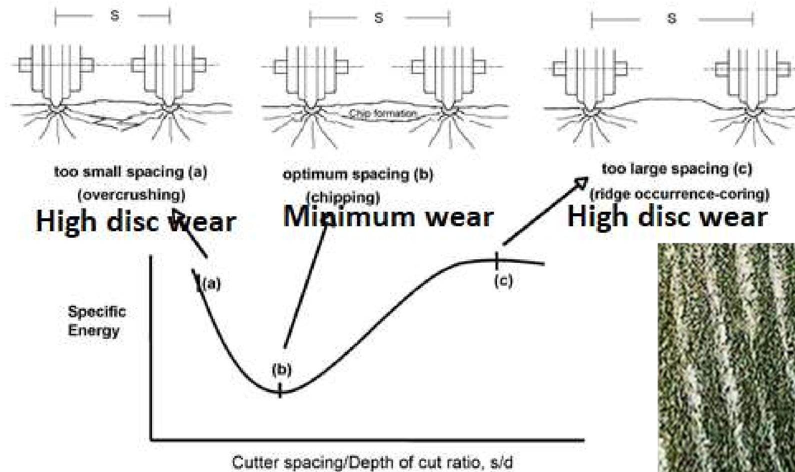


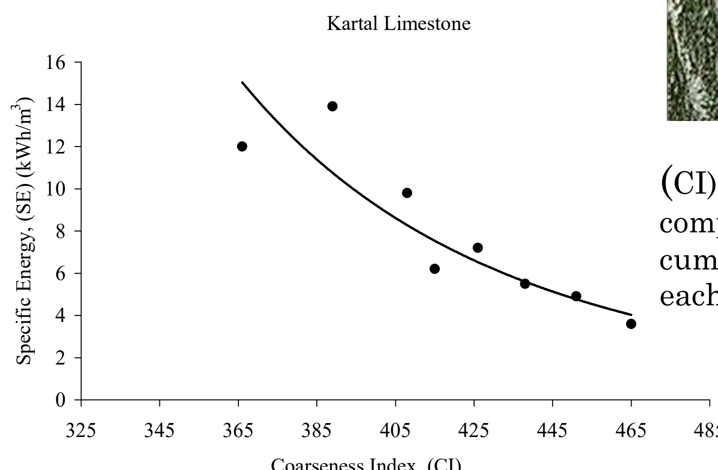
Bilgin, N., Copur, H., Balci, C. (2014) Mechanical*Excavation in Mining and CiviI Industries,* CRC Press, Taylor and Francis Group, London

Cutting Mechanism of Disc Cutters





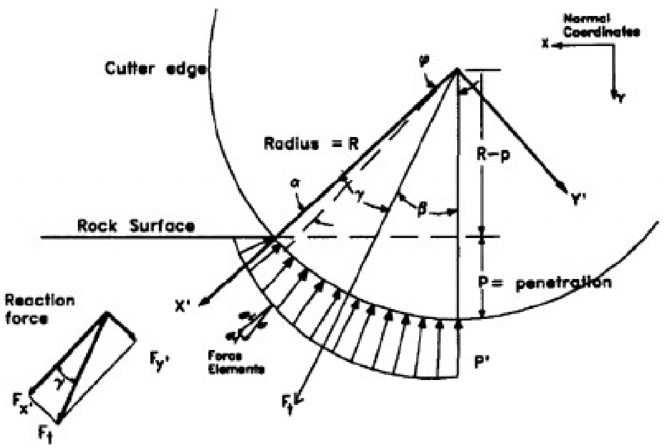




(CI) is a non – dimensional number used for comparison of muck size. It is the sum of the cumulative weight percentages retained in each sieve used.

Bilgin, N., Copur, H., Balci, C. (2014) Mechanical*Excavation in Mining and CiviI Industries,* CRC Press, Taylor and Francis Group, London

Mechanism of Disc Cutting After Rostami and Özdemir



$$\varphi = \cos^{-1}\left(\frac{R-p}{R}\right)$$

$$P_0 = C \cdot \sqrt[3]{\frac{s}{\varphi\sqrt{R \cdot T}} \cdot \sigma_c^2 \cdot \sigma_T}$$ φ is radian in this equation

$$F_t = \frac{P_0 \cdot \varphi \cdot R \cdot T}{1+\phi}$$ φ is radian in this equation

$$FN = F_t \cdot \cos(\varphi/2)$$ φ is degree in this equation

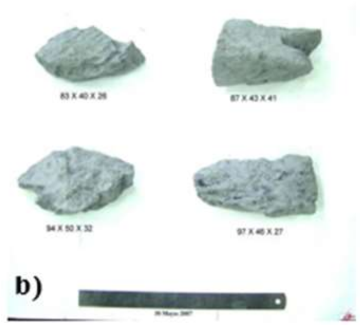
$$FR = F_t \cdot \sin(\phi/2)$$ φ is degree in this equation

where F_t is the total resultant force (kgf); R is the radius of cutter (cm); T is the width of disk (cm); φ is the constant for pressure distribution function (typically 0.2); ϕ is the angle of contact between the rock and disk cutter; p is the penetration per revolution (cm); P_0 is the pressure of crushed zone estimated from the rock strength and the cutting geometry as $P_0 = f(\sigma_c, \sigma_t, S, T, R, p)$, (kg/cm²); σ_c is the uniaxial compressive strength of the rock (kg/cm²); σ_t is the tensile strength of the rock (kg/cm²); $c = 2.12$; and s is the spacing between the cuts (cm).

Rostami, J., Ozdemir, L., 1993. A new model for performance prediction of hardrock TBMs. *Proceedings of Rapid Excavation and Tunnelling Conference*, USA, pp.794–809

The size of muck is related to geology and is a function of cutting efficiency

a) Chip formation in massive limestone



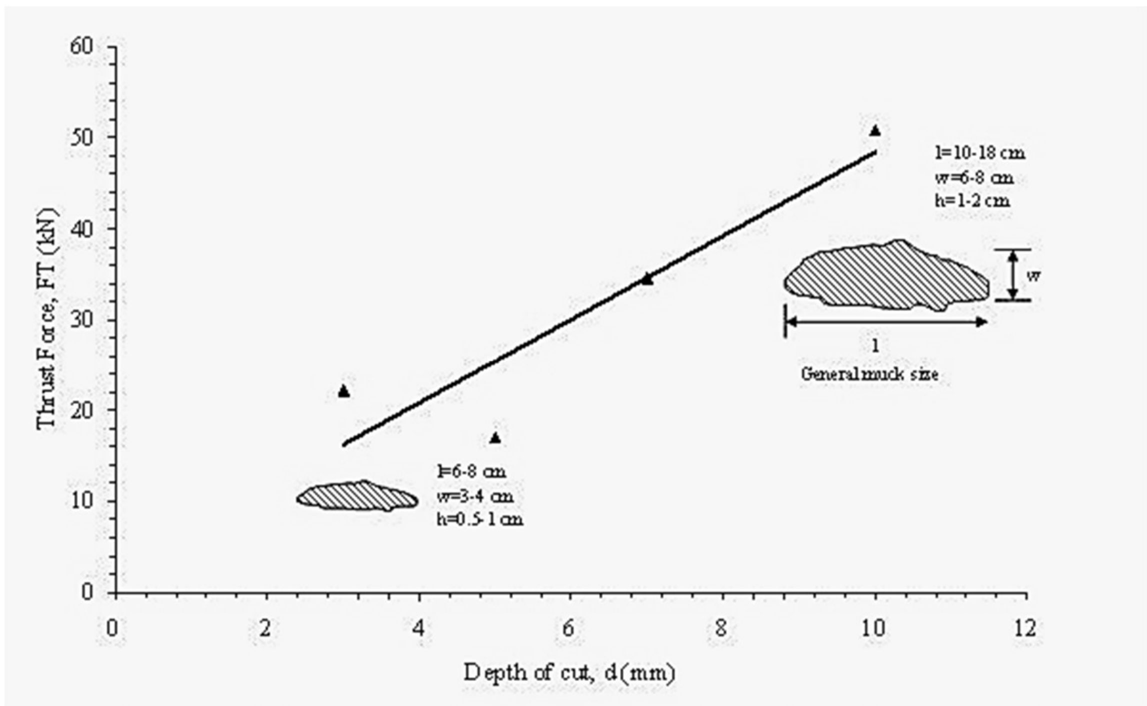
b) Chip formation in fractured zone

c) Big pebbles in Alluvion

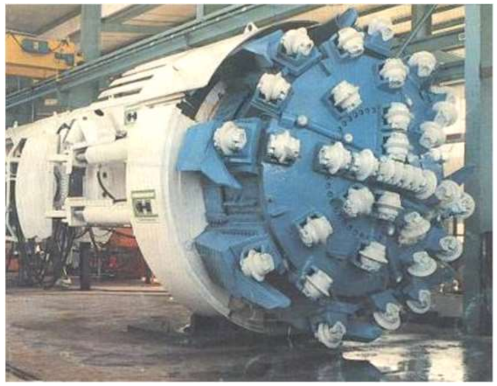
d) Muck in mudstone.

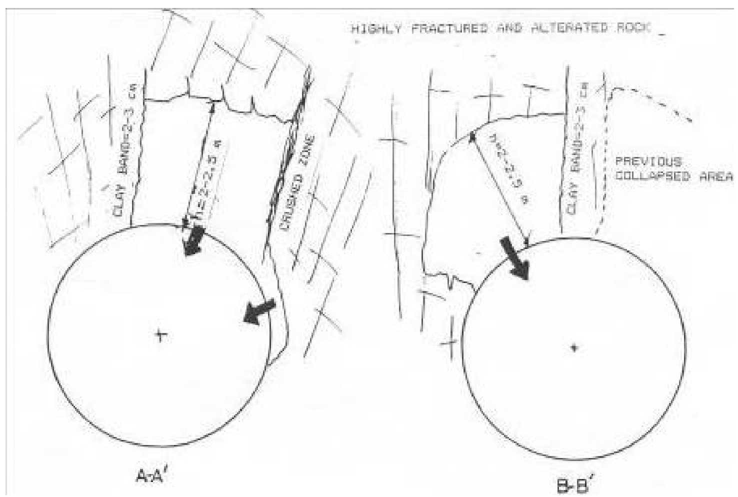
Bilgin, N., Çopur, H., Balcı, C. 2nd International Conference on Tunnel Boring Machines in Difficult Grounds (TBM DiGs Istanbul) Istanbul, 16–18 November 2016

There is a relation between muck size, thrust force and cutting efficiency



The First TBM used in Istanbul1984 Baltalimanı Sewerage Tunnel in very fractured rock. Lessons Learned : Never use griper TBM in highly fractured rock formation

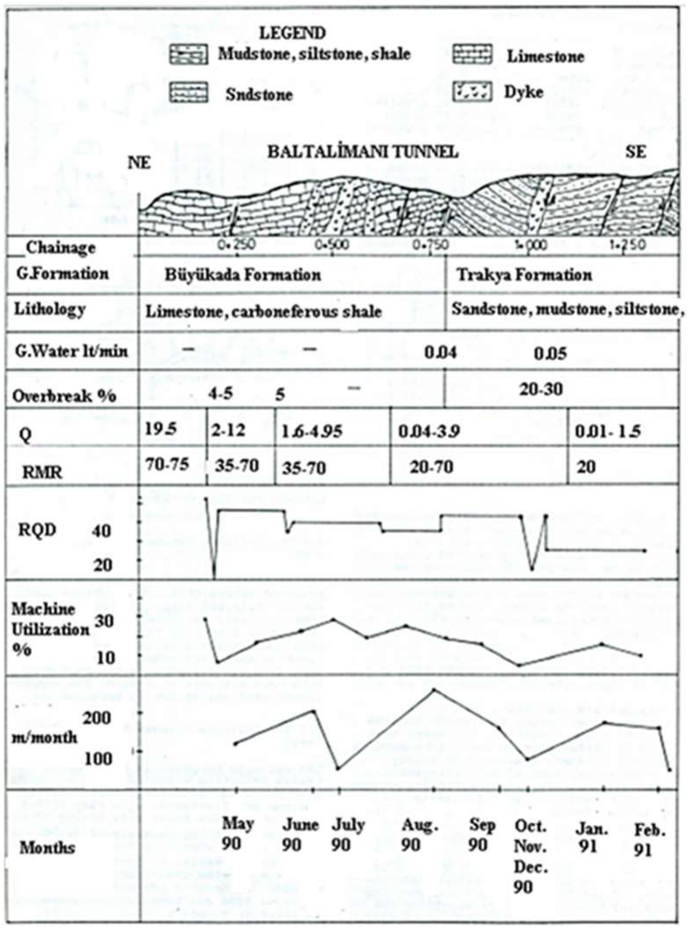




The collapses occured upon the tunnel

Bilgin, N., Copur, H., Balci, C. (2016). TBM Excavation in Difficult Ground Conditions, Case Studies from Turkey. Earns and Sohn. ISBN 978-3-433-031150-6.

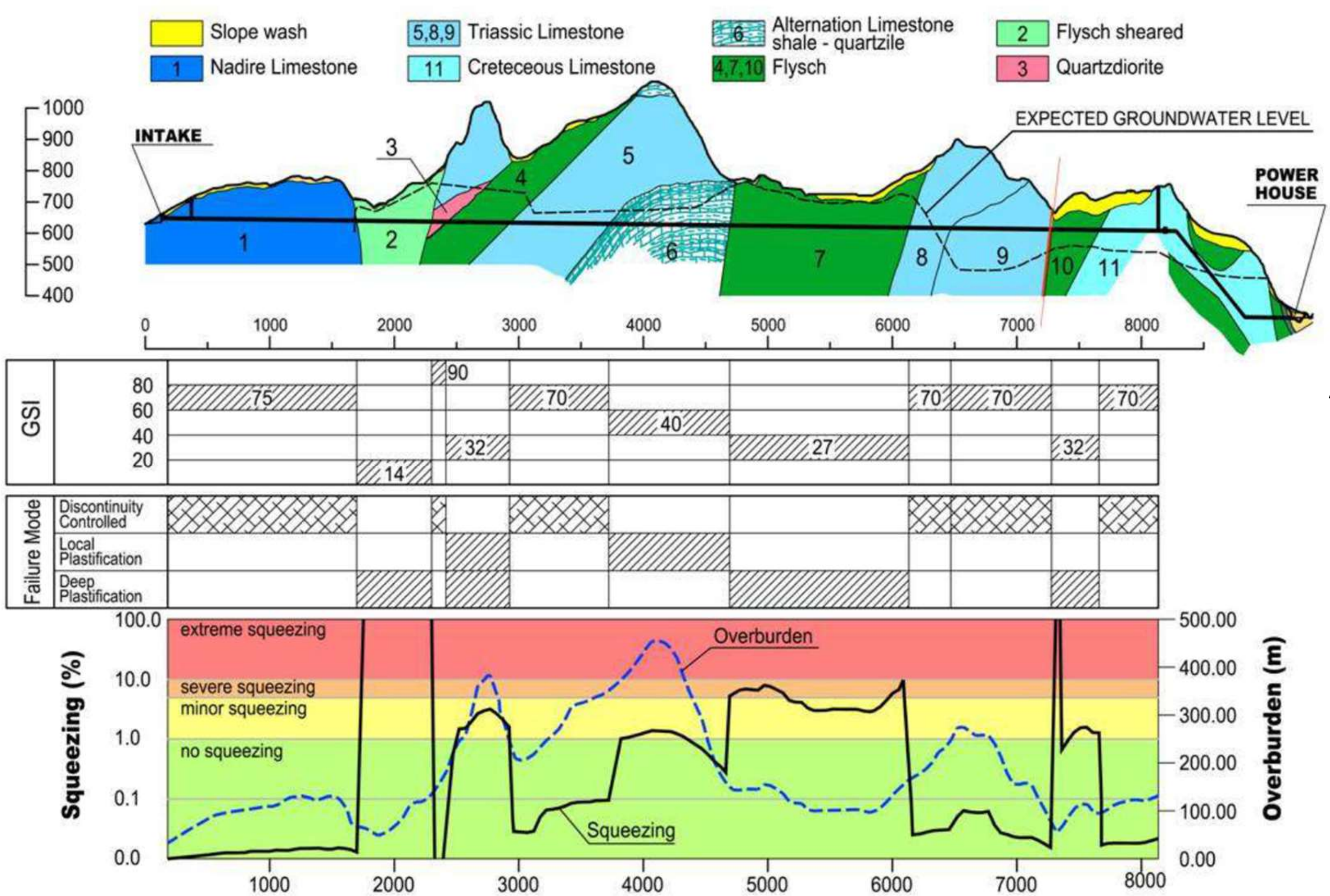
The Performance of Gripper Type TBM in Baltalimanı Tunnel, İstanbul



Parameter	Buyukada Form.	Trakya Form.
Machine utilization %	28.5	7.2
Machine downtime %	71.50	92.6
Net cutting rate m/h	1.22	1.7
Progress rate m/h	0.35	0.13
Average shift advance m/shift	3.15	1.24
Best shift advance m/shift	11.50	9.57
Lowest shift advance m/shift	0.60	0.2
Average daily advance m/day	7.18	3.12
Best daily advance m/day	20	16.5
Lowest daily advance cm/day	0.22	0.5
Average weekly advance m/week	43	21
Best weekly advance m/week	46	66
Lowest weekly advance m/week	9.95	1.9
Average monthly advance m/month	197	84
Best monthly advance m/month	261.4	177.65
Lowest monthly advance m/month	56.2	17.33

Bilgin, N., Çopur, H., Balcı, C. 2nd International Conference on Tunnel Boring Machines in Difficult Grounds (TBM DiGs Istanbul) Istanbul, 16–18 November 2016

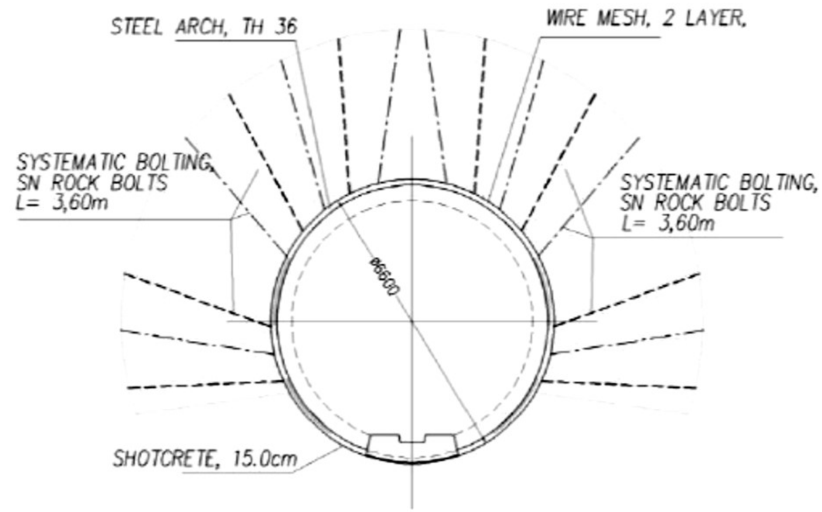
The Geology of Ermenek Power Tunnel, a Good Example for Single Shield TBM



After Koçbay, Marence and Linorther 2004, Hydropower Tunnel Ermenek/Turkey, Pressure Tunnel, design and construction

The Geotechnical Properties of Rock Formations in Ermenek Tunnel and Typical Support System in Weak Rock

Rock	Limestone	Ophiolit (claystone, sandstone, serpentine)	Limestone-sandstone	Claystone-sandstone-limestone	Limestone with clay-claystone
Length (m)	2275	911	1195	2293	1354
Unit weight (kN/m^3)	26.50	26.00	26.50	26.00	26.00
Uniaxial compressive strength (MPa)	120	10	70	40	80
Cohesion (kPa)	350	100	300	120	300
Friction angle (^{0})	40	15	32	15	35
Porosity (%)	2	1.21	1.1	0.80	1.1
Q (Barton, 1974)	18	0.01	16	5	8
Rock class for Q	Good	Very poor	Good	Fair	Fair



After Koçbay, Marence and Linorther 2004, Hydropower Tunnel Ermenek/Turkey, Pressure Tunnel, design and construction

Tunnel Support in Ermenek Tunnel with Gripper Type TBM

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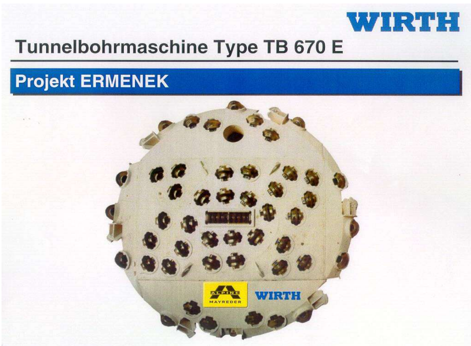
Ermenek Power Tunnel



TBM	WIRTH (Now Creg)
D	6.7 m
Discs No	52
Disc Diam.	432 mm
Power	1800 kW
Rotation	0-8.1 rpm
Torque	2020 kNm
Thrust	9600 kN

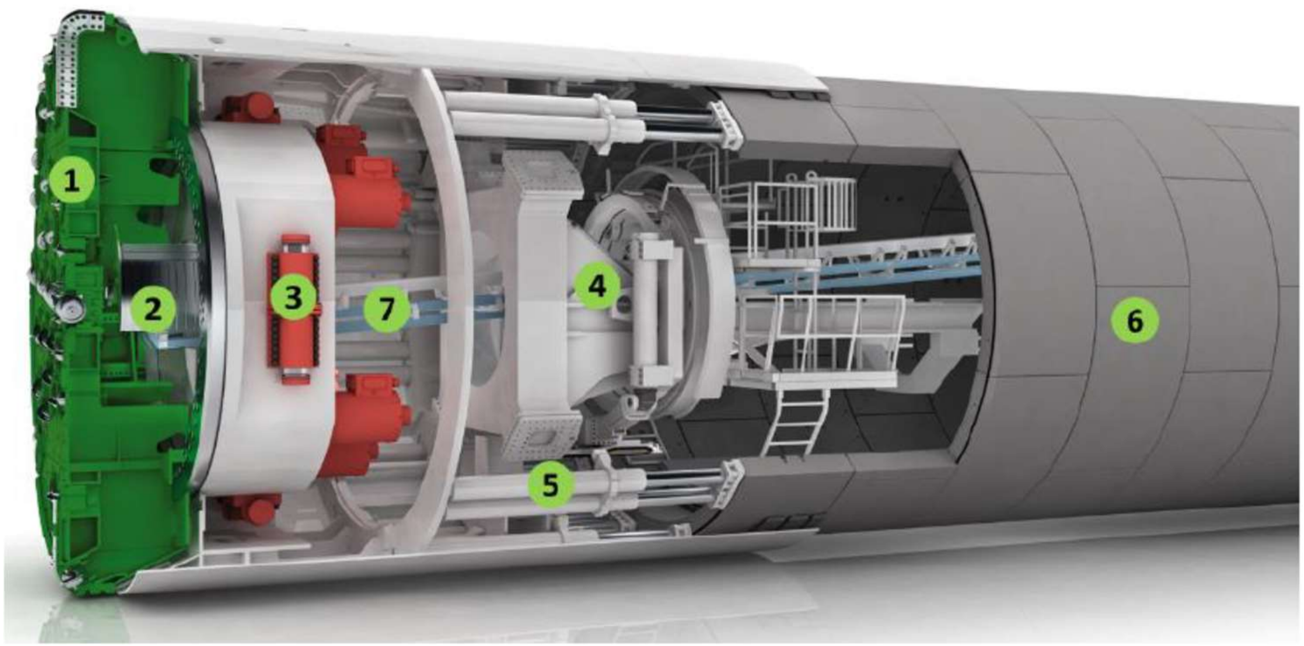
After Koçbay, Marence and Linorther 2004, Hydropower Tunnel Ermenek/Turkey, Pressure Tunnel, design and construction

Table 3. TBM progress results in Ermenek Dam pressure tunnel

	Months	Total progress per month (m)	Worked day in month	Progress per day (m)	Lithology
1	August 2003	208.00	15	13.87	Limestone
2	September 2003	438.00	22	19.91	Limestone
3	October 2003	150.00	27	5.56	Limestone and Ophiolit
4	November 2003	88.00	21	4.19	Ophiolit and Limestone - sandstone
5	December 2003	497.00	20	24.85	Limestone - sandstone
6	January 2004	275.00	12	22.92	Limestone - sandstone
7	February 2004	681.00	21	32.43	Limestone - sandstone and claystone - sandstone - limestone
8	March 2004	392.00	26	15.08	Claystone - sandstone - limestone
9	April 2004	1004.00	26	38.62	Sandstone - Limestone
10	May 2004	738.00	24	30.75	Sandstone - Limestone
11	June 2004	647.00	24	26.96	Limestone with clay- Claystone
12	July 2004	230.00	24	9.58	Claystone - sandstone - limestone
13	August 2004	306.00	25	12.24	Claystone - sandstone - limestone
14	September 2004	247.00	16	15.44	Claystone - sandstone - limestone
15	October 2004	-	-	-	-
16	November 2004	167.00	17	9.82	Claystone - sandstone - limestone and limestone
17	December 2004	222.00	26	8.54	Limestone ve Ophiolit
18	January 2005	178.00	19	9.37	Ophiolit
19	February 2005	695.00	26	26.73	Ophiolit and Limestone
20	March 2005	865.00	19	45.53	Limestone

Single Shield TBM s

Single shields are built to advance in solid or fractured rock. Like other shield machines, they use thrust cylinders (5) to advance and an erector (4) to build segmental lining (6). The rock chips which have been cut by the cutterhead (1) are lifted up by buckets in the cutterhead and drop onto the muck ring (2). From here, they fall onto a belt conveyor (7) which removes them from the TBM. The maindrive is held within the steel structure by using a hydraulic torque box (3). This allows precise control of the cutting process.



Brabant., J, Duhme, R, 2017. Hard Rock TBM Tunneling – Technical Developments and Recent Experience, The World Congress on Advanced in Structural Engineering and Mechanics (ASEM17), Seoul, Korea

Single Shield TBM in Fractured Rock, in Kozyatağı Kadıköy Metro Tunnel

- In the contact zone between Trakya Formation and Dyke, and in very fracture face collapses may occur, In these cases the openings in front of TBMshould be reduced. Typical examples, Kadıköy –Kartal , Metro tunnel, Marmaray Project, Beykoz sewearage tunnel, Kargı hess tunnel, Köseköy Tunnel

TBM Diameter	6.57 m
Number of discs	26 single + 6 twins (12) = 38
Max. Disc Capacity	267 kN
“ Main bearing” capacity	20,000 kN static
Cutting Head Power	1,260 kW (4x315)
Rotational speed	1.6-5.5 rpm
Cutting Head Torque	5,200 kNm at 1.6 rpm
	1,515 kNm at 5.5 rpm
Thrut capacity	42575 kN at 350 bar

Big Blocks Coming from TBM Face Kozyatağı-Kadıköy Metro Tunnels

Joint surface

45 cm

Lebgth of the piece 50 cm

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Putting Grizly Bars to Stop Tunnel Face Collapses

Initial cutting head

TBM-360 cutting head with grizzlt bars

Problems Encountered Kozyatağı-Kadıköy Metro Tunnels at the The Beginning of the Tunnel Excavation

Tunnel Excavation started in 20 August 2007

Face collapses ocuured due to the geological discontinuities. Mean daily advance was 2.49m untill 7 February 2008 .

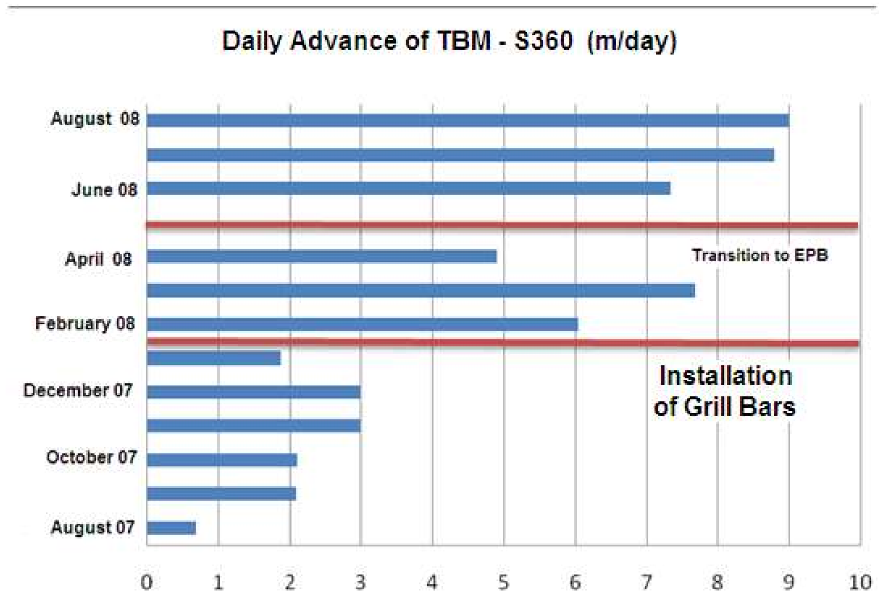
Grizzly bars were added to the openings to stop face collapses. Around the same date such precautions were taken in Marmaray and Beykoz tunnels

From 7th September till 15the April mean daily advance increased to 8.48m.

Bilgin, N., Copur, H., Balci, C. (2016). TBM Excavation in Difficult Ground Conditions, Case Studies from Turkey. Earns and Sohn. ISBN 978-3-433-031150-6.

The Effect of Putting grizzly on Bars and Changing to Closed Mode (EPB) from Open Mode

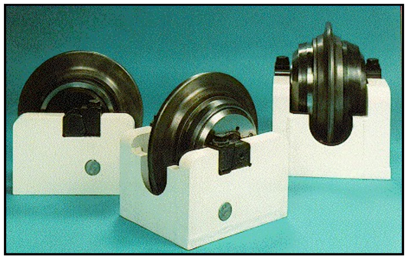
Putting grizzly bars on cutterhead

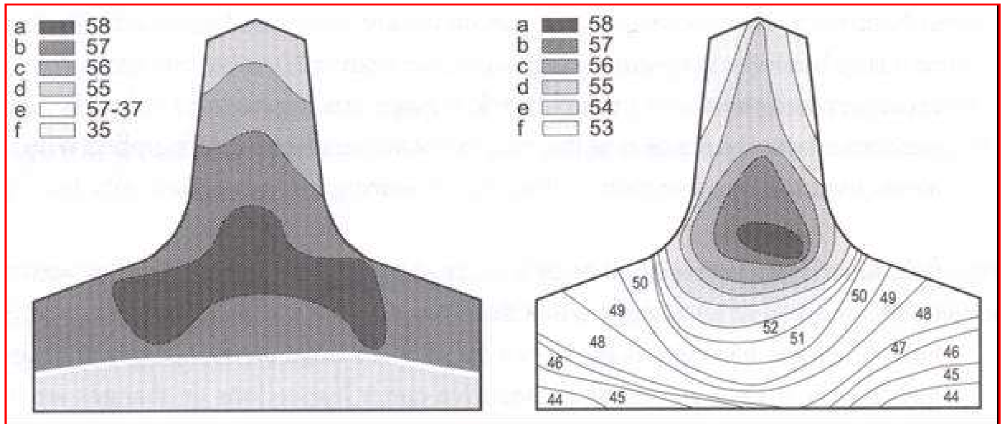


Aug 07	Sep 07	Oct 07	Nov 07	Dec 07	Jan 08	Feb 08	Mar 08	Apr 08	May 08	Jun 08	Jul 08	Aug 08
0,7 m/gün	2,1	2,1	3	3	1,9	6,1	7,7	4,9	0	7,4	8,8	9

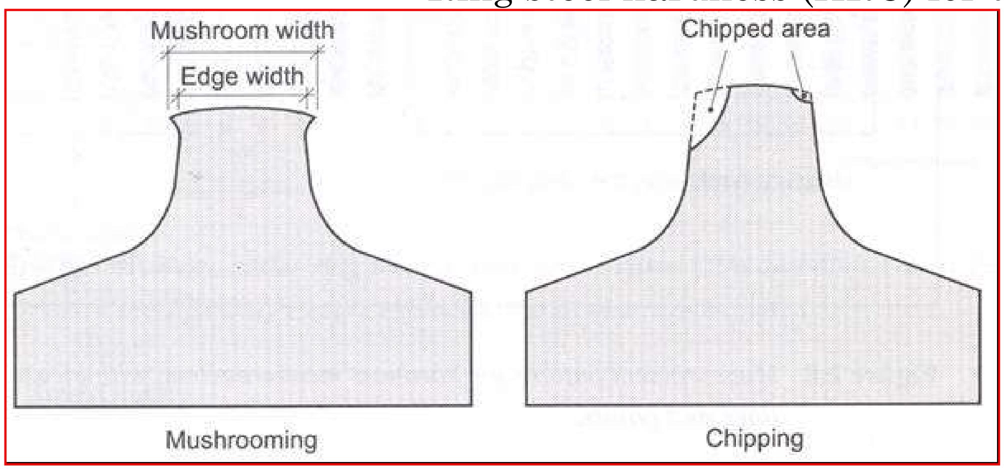
Bilgin, N., Copur, H., Balci, C. (2016). TBM Excavation in Difficult Ground Conditions, Case Studies from Turkey, Earns and Sohn. ISBN 978-3-433-031150-6.

Disc Cutters and Tool Material





Ring steel hardness (HRC) for two types of rings



Destructive wear types of cutter rings

After A. Bruland, NTNU

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 in ring 1480 and thrust increased gradually up to ring 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 9 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.

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

Bilgin, N., Copur, H., Balci, C. (2016). TBM Excavation in Difficult Ground Conditions, Case Studies from Turkey. Earns and Sohn. ISBN 978-3-433-031150-6.

The Effect of Big Blocks on Disc Blockage

Failure of discs between 1480-1491 rings due a fault zone

The variation of thrust and torque withi rings 1480-1491

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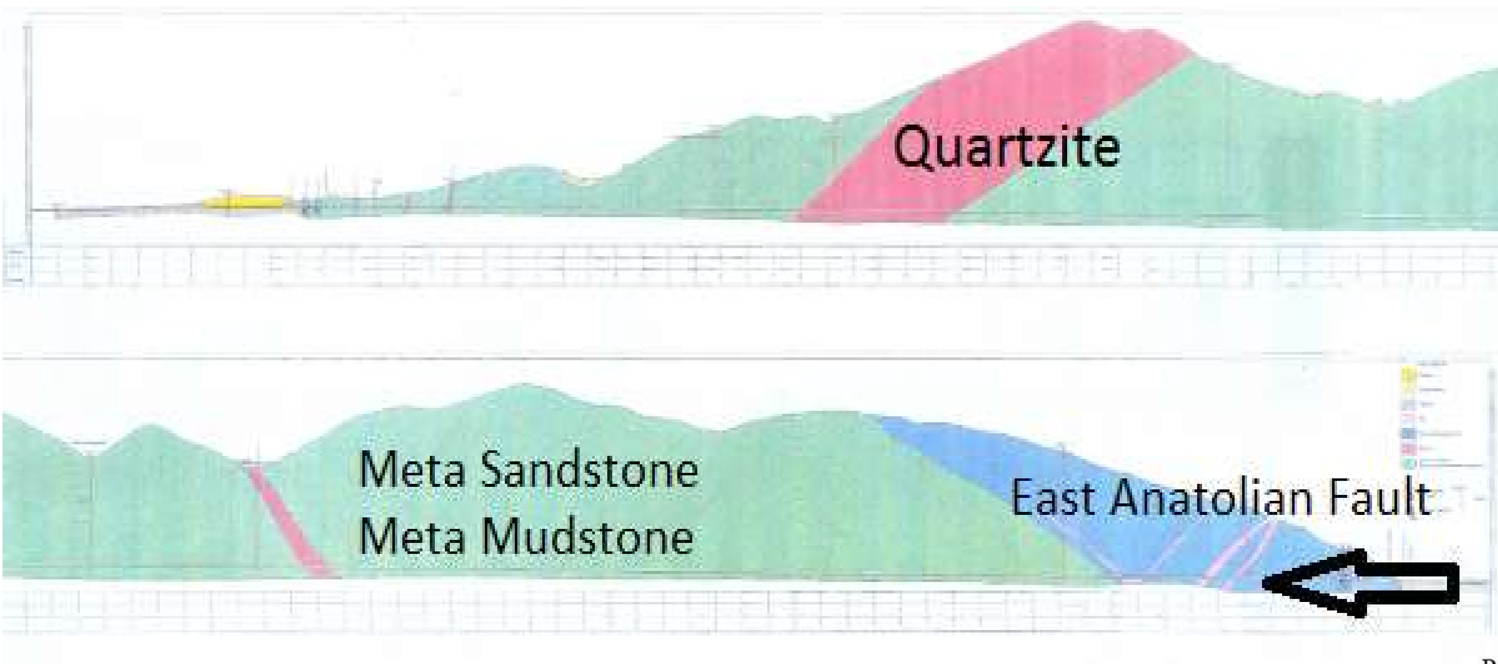
Single Shield TBM in the Hardest Rock in Turkey, Nurdağı Tunnel

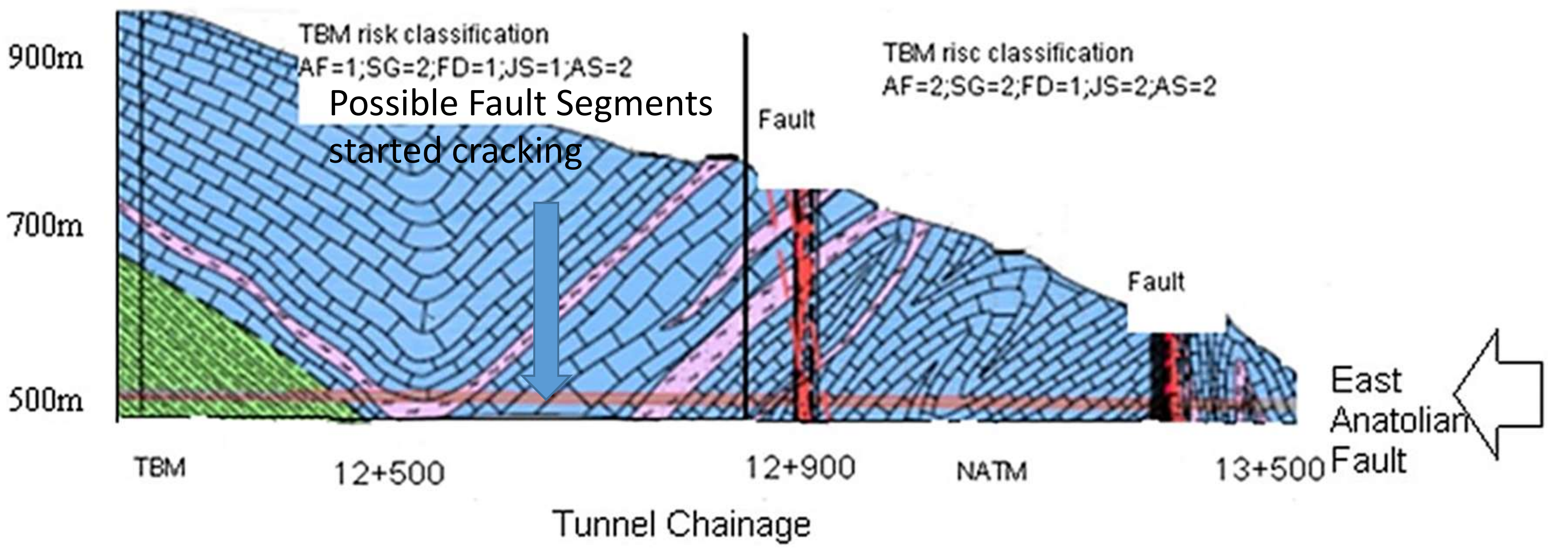
The tunnel is for railway transportation, and the project involves two tubes, each with a length of 9750 m. The excavation is planned to start from chainage 13+450 km and to terminate at chainage 3+700 km. The chainage from 13+450 to 12+400 km involves Karadag limestone of Mesozoic age, which is affected 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

The Geology of 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



Single Shield TBM in Nurdağı Tunnel



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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.	

Portal in Nurdağı tunnel

Single Shield TBM used in Nurdağı Tunnel, Robbins TBM SS268-398

Technical Specification of High Performance Single Shield Robbins Hard Rock TBM SS268-398

TBM diameter	8 m
Number of buckets	8
Over cut	40 mm on radius
Number of disc cutters	53x19"
Maximum disc load	3111 kN
Average cutter spacing	77.6 mm
Cutterhead torque	9,635 kNm at 0-3.3 rpm
Exceptional torque	14,453 kNm at 0.33 rpm
Recommended max. thrust	16,500 kN
Cutterhed total power	10X330 kW

This Machine is currently excavating the hardest and the most abrasive rock ever cut in Turkey

Geotechnical Characteristics of the Rocks, in Nurdağı Tunnel

Compressive strength of the rock to be encountered in the tunnel route

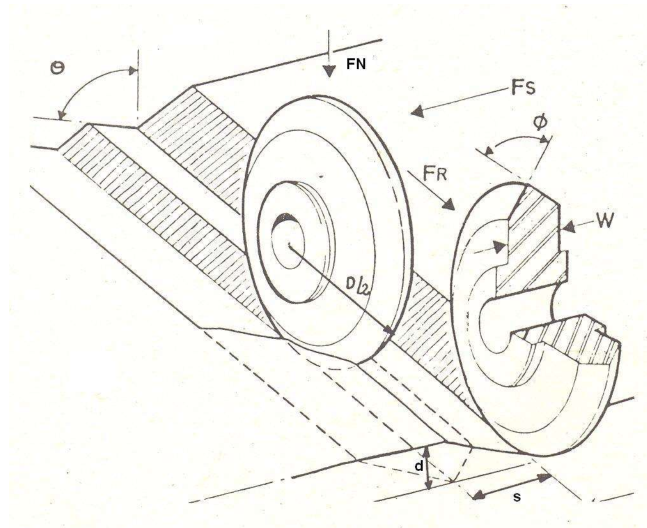
Rock	UCS Maximum MPa	UCS Minimum MPa	UCS Mean MPa +/- s.d
Meta - Sandstone	301.3	167.0	213 +/-55.4
Meta - Mudstone	327.4	80.4	136.1 +/- 61.7
Mudst-Sandst	136.4	70.6	107.1+/- 25
Mean			151.2+/-67.2
Limestone	104.5	74.7	79.5+/-15.5

Tensile strength of the rocks to be encountered in the tunnel route

Rock	σt Maximum MPa	σt Minimum MPa	σt Mean MPa
Meta Sandstone	27.2	11.63	17.8+/-2
Meta - Mudstone	19.2	17.6	18.8+/1.1
Mean			18.1+/-1.5

The mean values of Cerchar Abrasivity values of meta-sandstone, meta-mudstone of the samples changes between 3-4.5

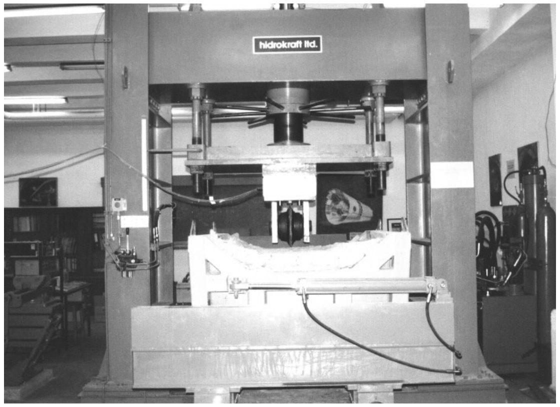
Specifications of TBM in Nurdağı Tunnel Were Decided after Full Labaoratory Cutting Experiments



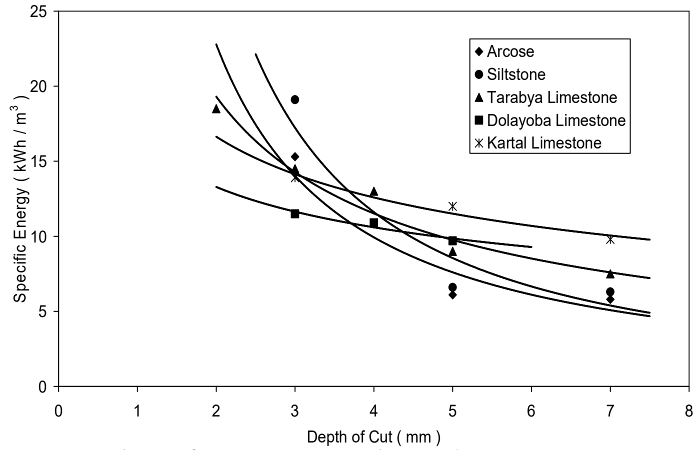
Specific Energy Obtained in the Laboratory for Relieved and Unrelieved Cutting Experiments

$$NPR = k \cdot P / SE$$

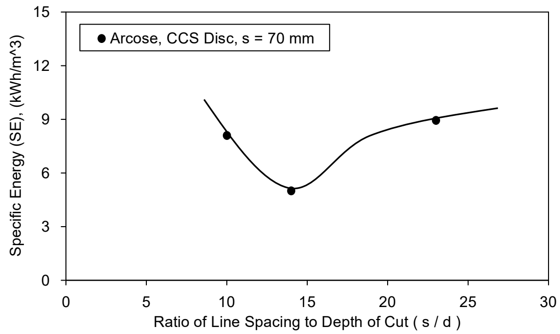
$$SE = 2 \cdot \pi \cdot N \cdot T / NPR$$



Full scale laboratory cutting rig



Typical specific energy curve obtained in unrelieved cutting mode



•Typical specific energy curve obtained in relieved cutting mode

N. Bilgin, C. Balci, H. Copur, D. Tumac & E. AvundukRock mechanics aspects related to cutting efficiency of mechanical excavators, 25 years of experience in Istanbul, Eurock, stockholm, 2012
,

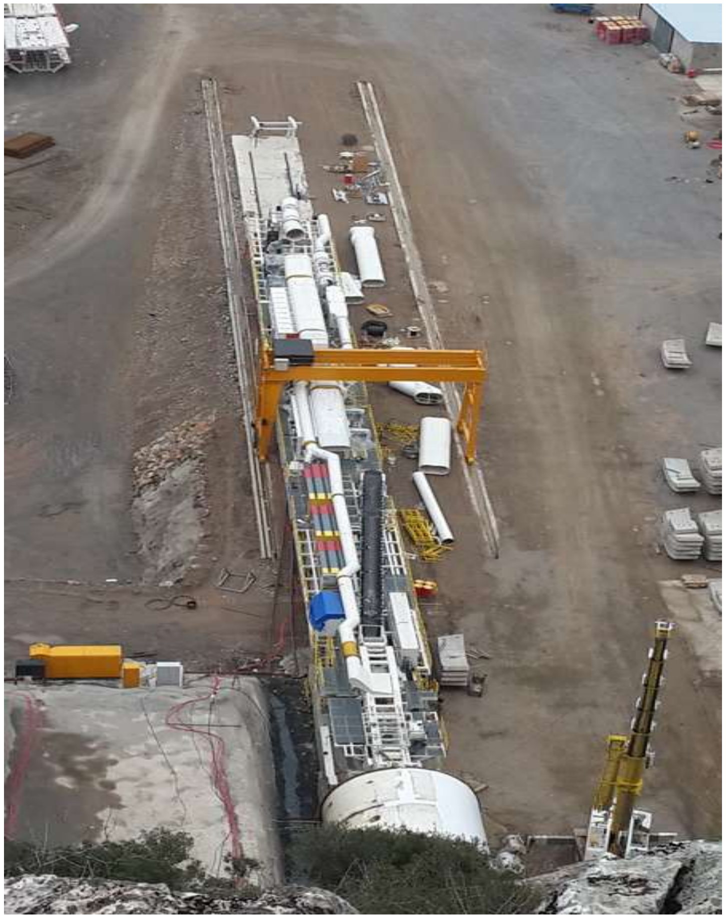
Prof.Dr.Nuh Bilgin, İTÜ

Recommended TBM Parameters after Laboratory Full Scale Cutting Tests and TBM Mannufacturer Values

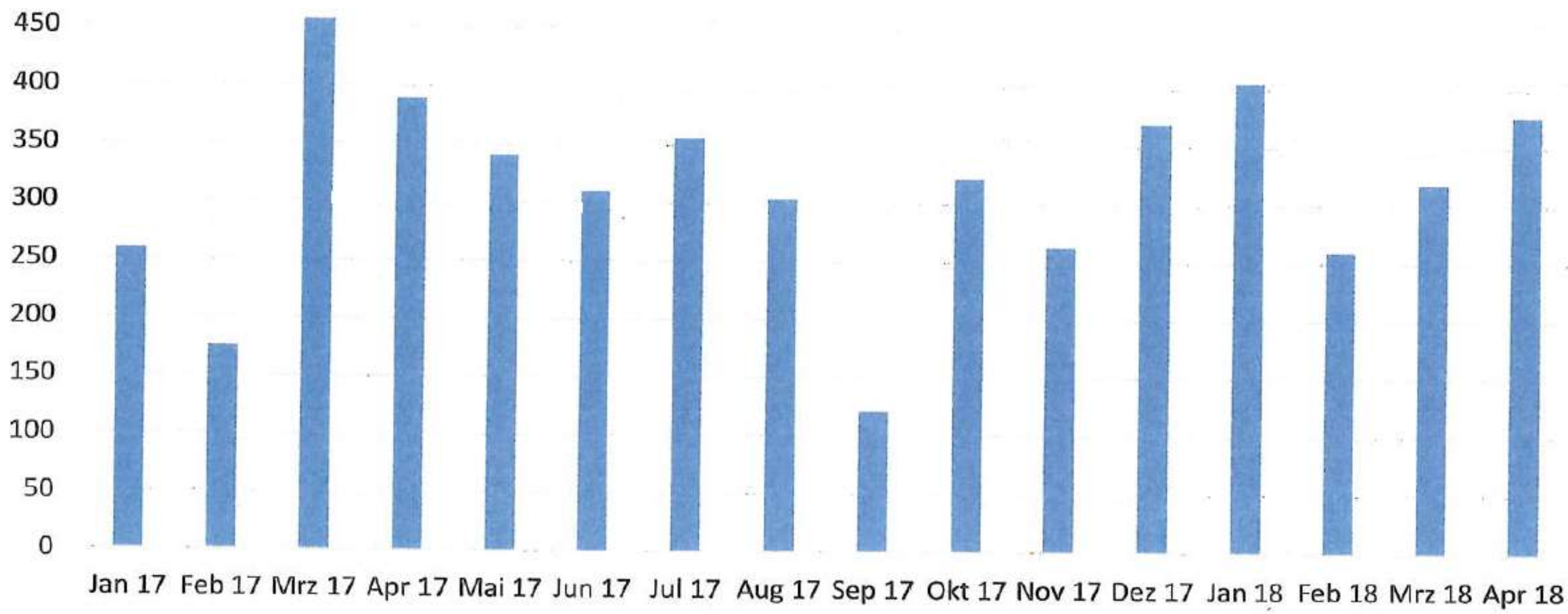
Parameter	Empfohlener Wert *Recommended Value*	Ausgeführter Wert/ *TBM Manufacturer Value*
Schneidrollen: Anzahl und Durchmesser/ *Disc number and diameter*	53; 19"	53; 19"
Maximale Belastung pro Schneidrolle/ *Maximum load per disc*	311 kN	311 kN
Schneidrollenabstand/ *Disc spacing*	80 mm	77.6 mm
Gesamtleistung/ *Total power*	3250 kW	10 x 330 kW
Drehmoment Bohrkopf/ *Cutterhead torque*	4500 kNm	4588 kNm bei 6.9 U/min/ *4588 kNm at 6.9 rpm*
Maximales Drehmoment/ *Exceptional torque*	N/A	14 453 kNm bei 0–3.3 U/min/ *14 453 kNm at 0–3.3 rpm*
Empfohlene Schubkraft mit Bezug auf die Schneidrollenlagerung/ *Recommended thrust based on disc bearing capacity*	16 483 kN	16 503 kN
Maximale Schubkraft/ *Maximum thrust*	N/A	88 543 kN

Jordan,D.,Bilgin,N., 2018. Turkey's hardest rock,the Bahçe-Nurdağ high spead tunnel, tunnel, 4, pp 22-28

TBM Was Assembled in the Tunnel Side



Monthly Advance Rates of Single Shield TBM in Bahçe-Nurdağ High Speed Tunnel



Jordan,D.,Bilgin,N., 2018. Turkey's hardest rock,the Bahçe-Nurdağ high spead tunnel, tunnel, 4, pp 22-28

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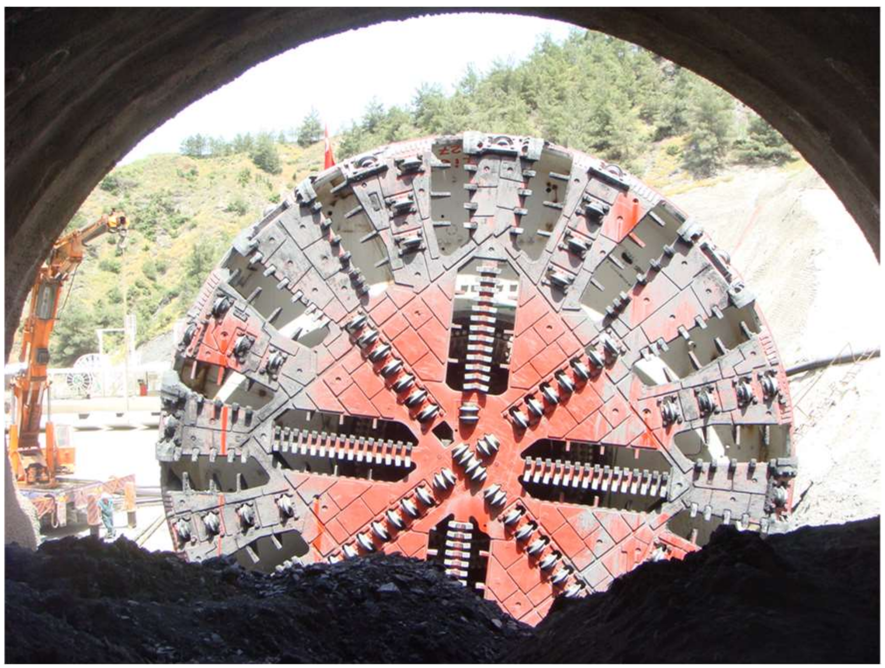
Single Shield TBM in Koseköy-Bilecik High Speed Tunnel

The excavation of T26 Tunnel started with conventional tunnelling 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.**

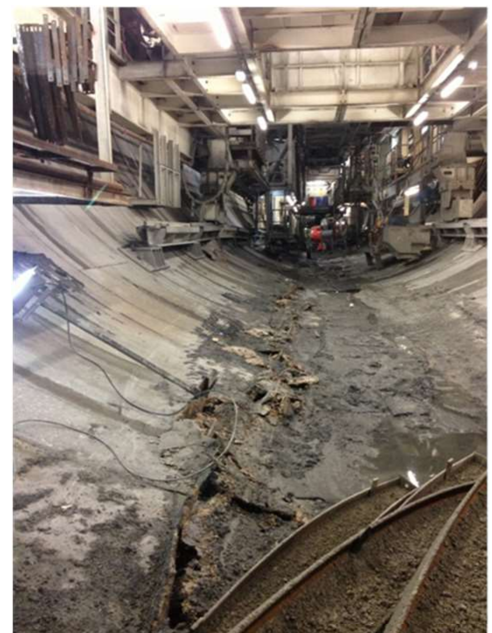
Due to difficulties encountered during NATM, it was decided to continue the tunnel excavation with 13.7 m diameter single shield TBM

Problems in Graphitic Shists with a Single Shield TBM in 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



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Collapsing and Disaster in Köseköy High 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.

The Effect of Half Closing the 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

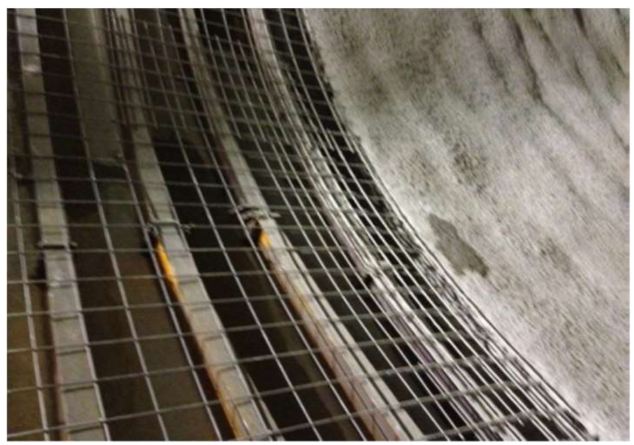
Example
Ring 147
N=2.8/60 revolution per second
T=14600 kNxm
Excavation area 3.14x13.7x13.7/4= 147.4m2
TBM penetration=107 mm/min
NPR= 0.107x60x147.4 = 907m3/h
SE=2xπx2.8x14600/(60x907)
SE= 4.7 kW(m3)

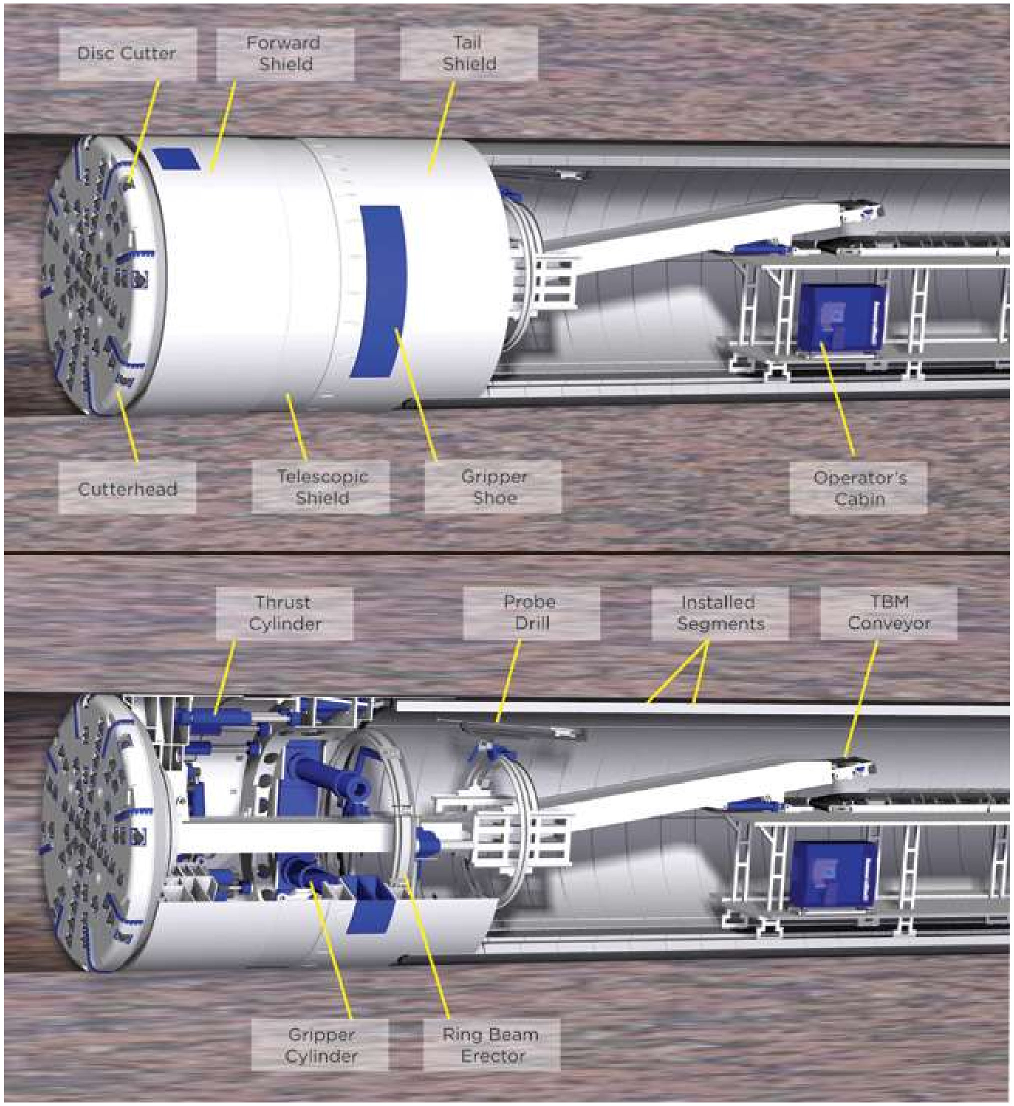
In the area where the openings were opened
Date 19.09.2011, Ring 146-150, SE = is 3.57 kWh/m^3.
Bentonite application in the area where the openings were half closed.
Date 3-11 2011, Ring 155-165, SE = 12.6 kWh/m^3.
The openings are half closed, bentonite is not applied
Date 17.11.2011, Ring 190-199,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

The Collapse of Köseköy High 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.

The Collapse of Segments and Tunnel in Köseköy Tunnel





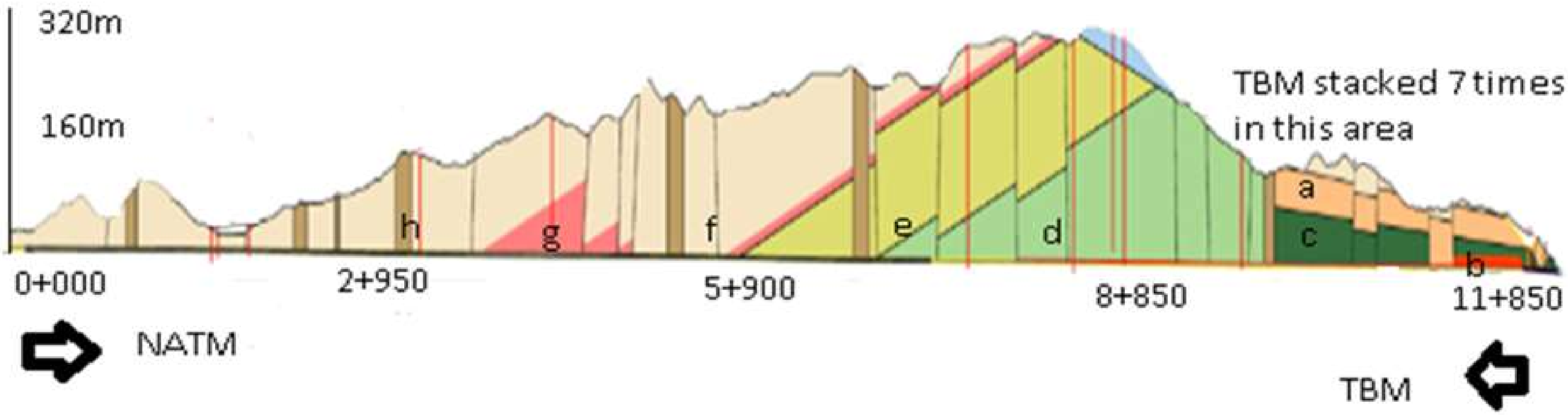
Double Shield TBM

High advance rate since TBM may advance while installing the segments
Typical example:
KARGI HEPP Project
Between1-20 September 2013 an advance rate of 470m (23.5 m/day) was reached

Double Shield TBM, Kargi Hepp Tunnel

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.**

The Geology of Kargı Project



a=sandstone gravels, silty sand and clay
b=ultramatic rocks
c=ophiolotic rocks, serpentine
d=metapellites, micashist, grapitic shist
f=andesitic basalt
g=aglomerate
h=dykes

Double Shield TBM Assembled in the Field, Kargı Power Tunnel

Tunnelling Performance in Kargı

Performance	TBM	D&B
Best month (m/month)	723	282
Best day (m/day)	40	12
Average week (m/week)	38	8
Average month (m/month)	271	174
Time to mobilize (month)	16	4
Boring length (km)	7.8	4
Months to complete	28	23

Overall comparisons of TBM performance before and after modification in Kargi Tunnel.

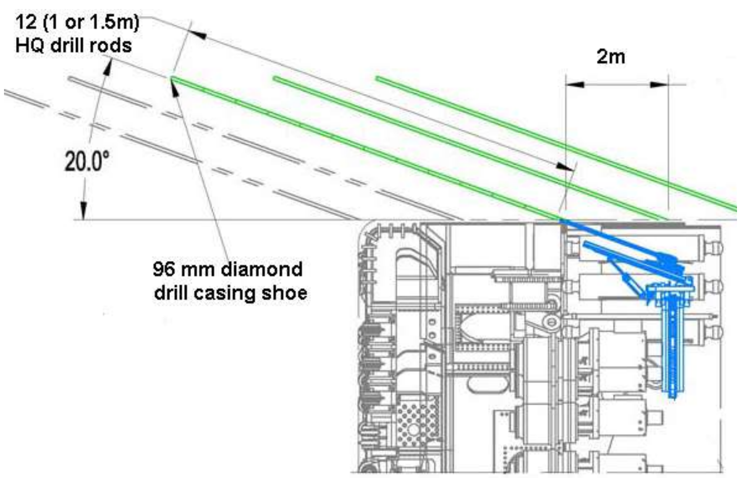
Performance	Before modification	After modification
Minimum (m / month)	35.7	14.3
Best (m / month)	329.4	723.2
Average (m / month)	154.4	407.7

Home, L. 2015. Hard rock TBM tunneling in challenging ground: Developments and lessons learnt from the field. In: Tunnel Boring Machines in Difficult Grounds, Singapore.

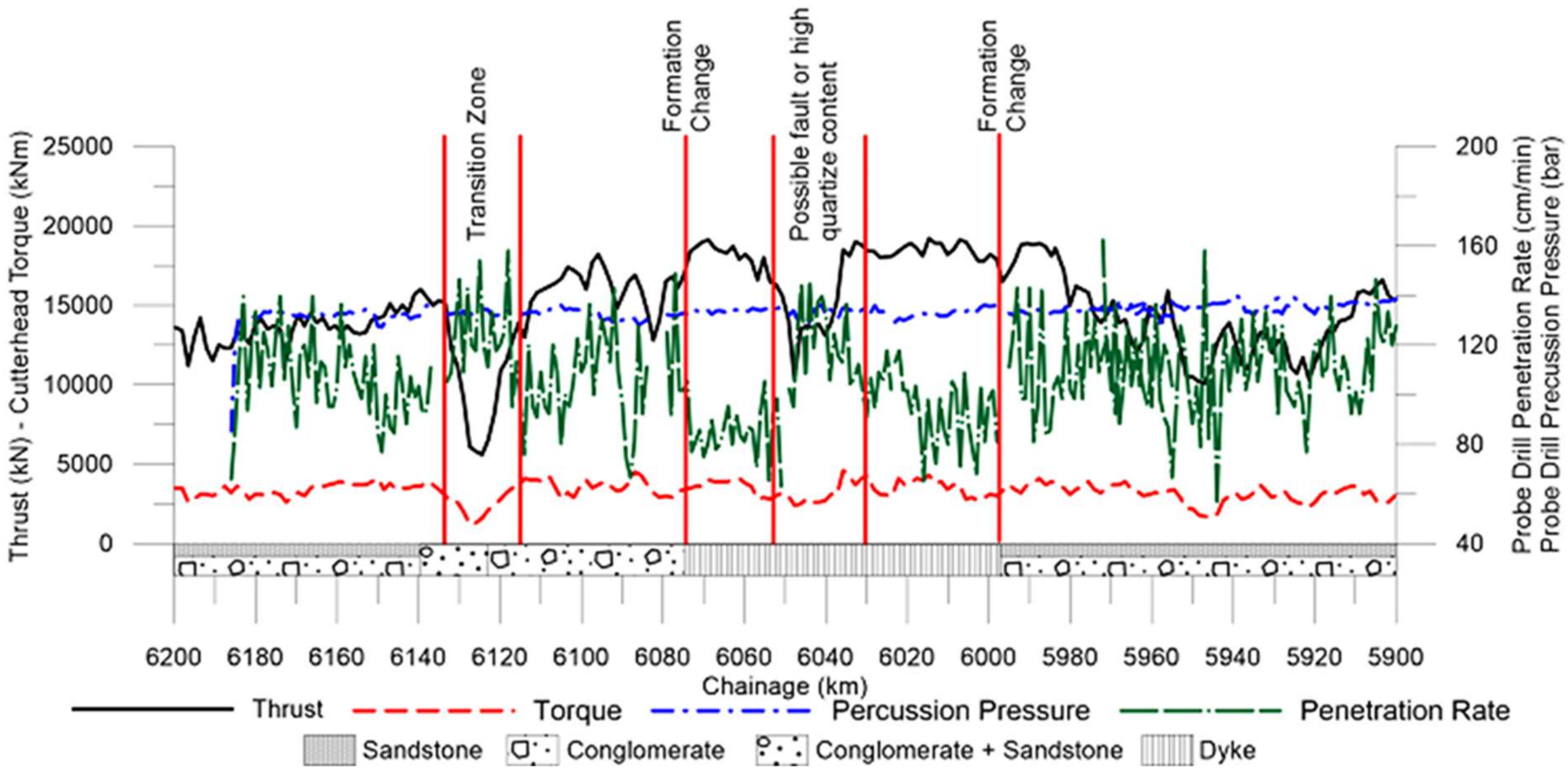
Barton, N., Bilgin, N. (2016). Fast or slow progress with TBM in ideal or faulted conditions. Proceedings of Eurock 2016, Turkey. Rock mechanics and rock engineering from past to present. Ulusay at.al. Taylor and Francis, pp.1157-1162.

Probe Drilling in Kargı Power Tunnel

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 Drıllıng In Kargı Tunnel



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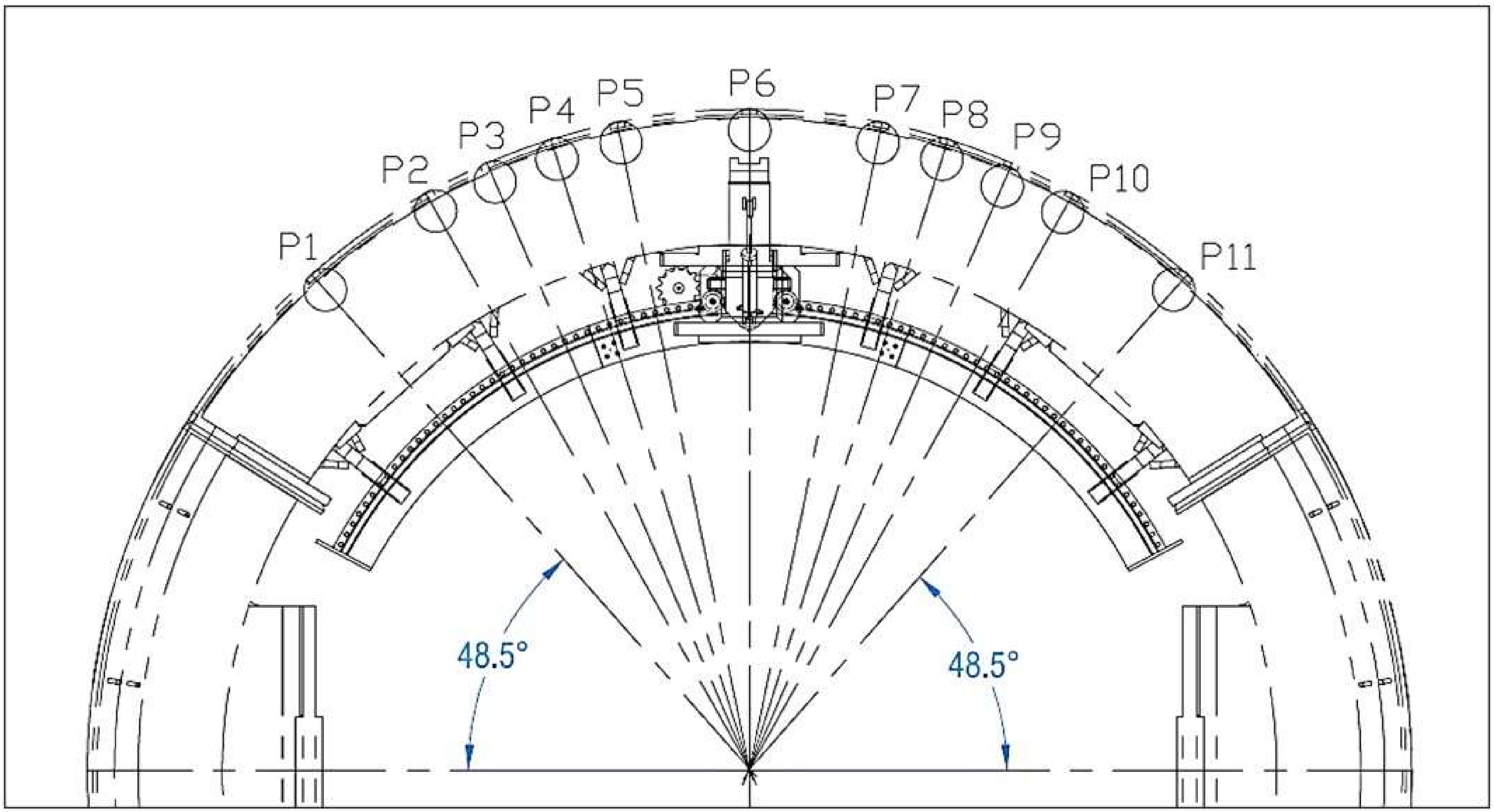
Drilling for Umbrella Arch in Kargı Tunnel



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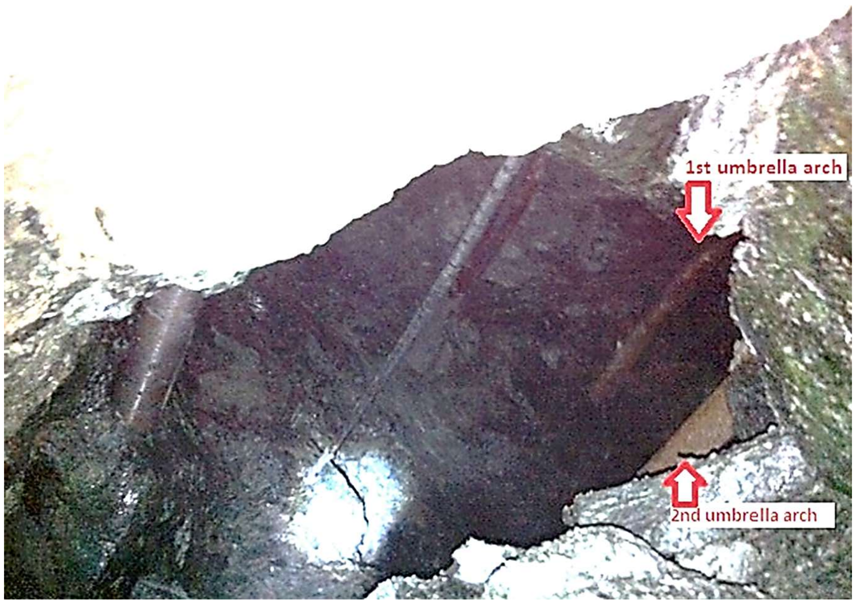
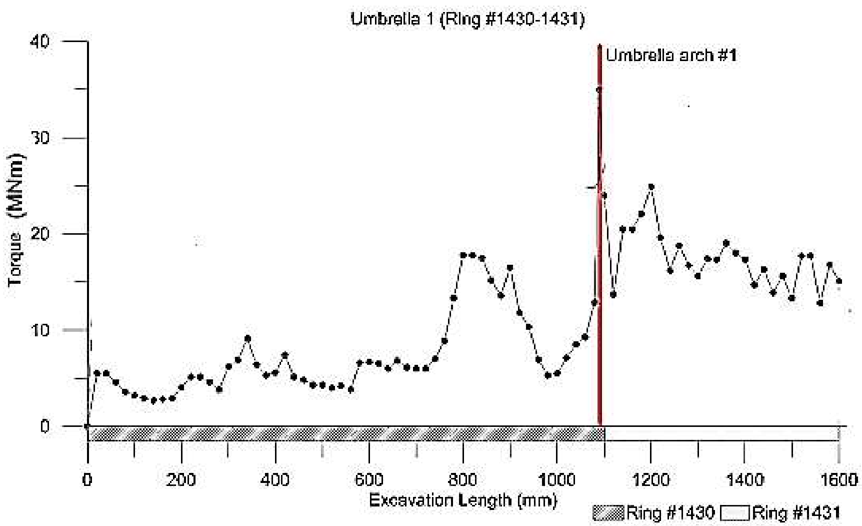
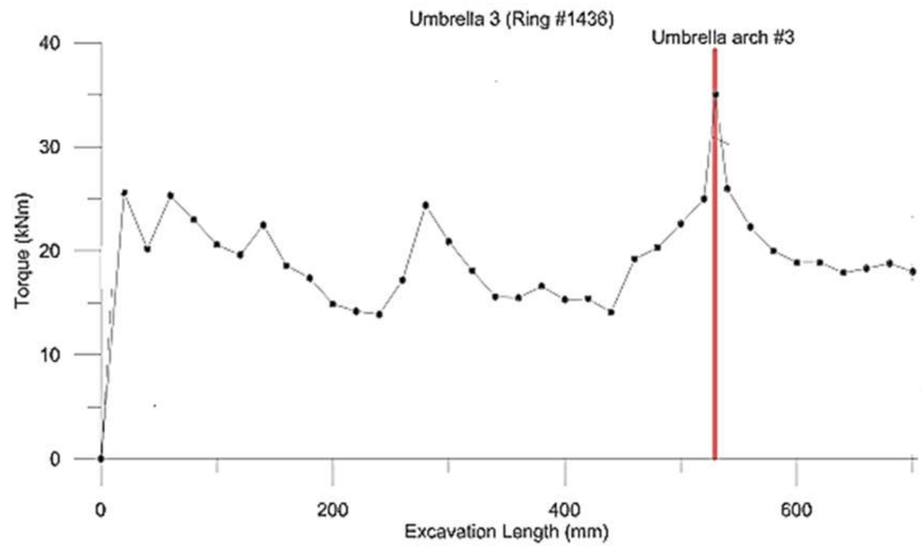
The Application of Umbrella Arch in Kargi Power Tunnel



The Criteria for Umbrella Arch in Kargı Tunnel





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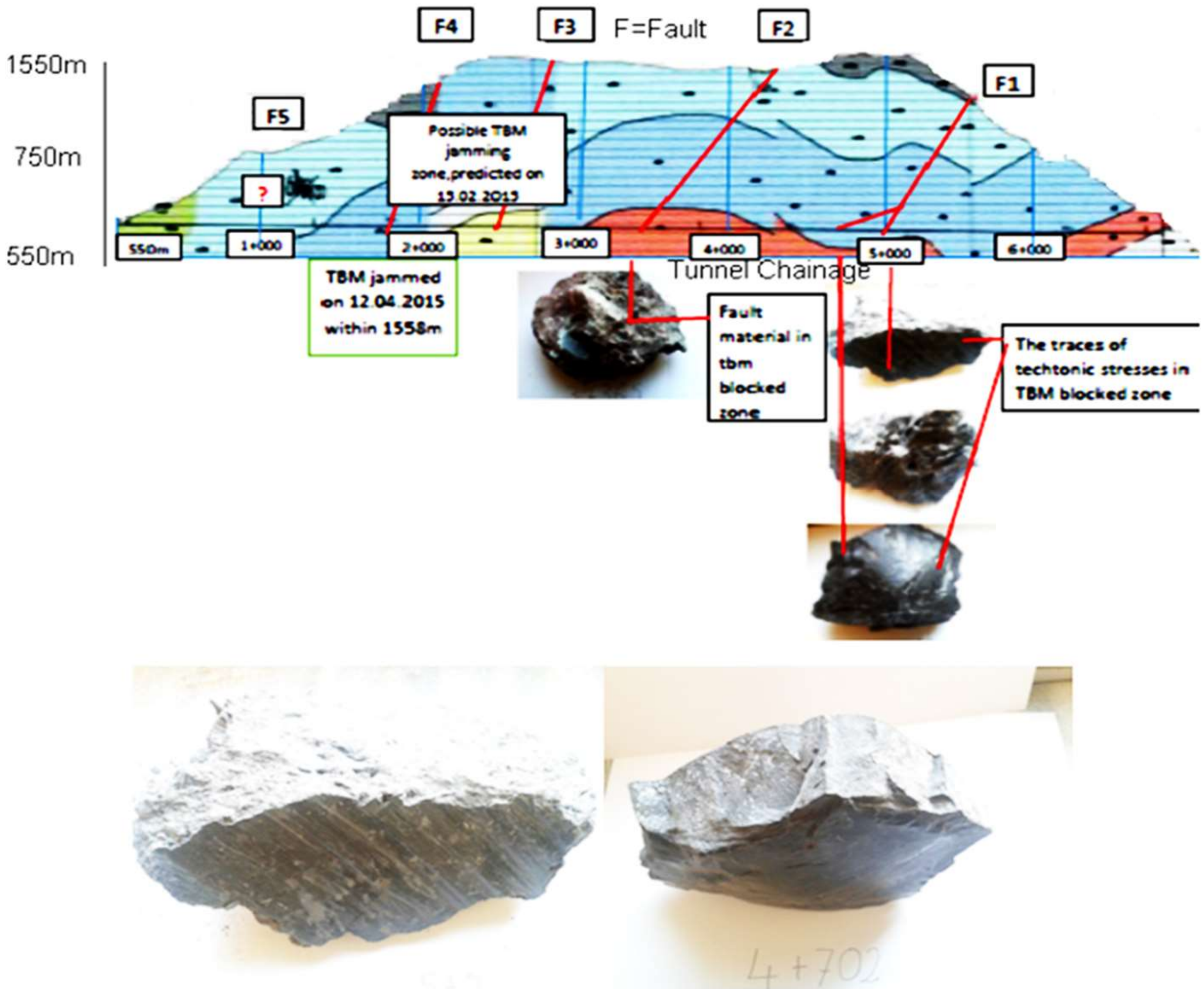
Double Shield TBM in Doğançay Tunnel and Squeezing Problem due to Tectonic Stresses

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. The followingFigure shows the general layout of the tunnel route with the main faults (F1, F2 etc.)

Doğançay Tunnels and Sqeezing of Double Shield TBM due to TechtonicStresses



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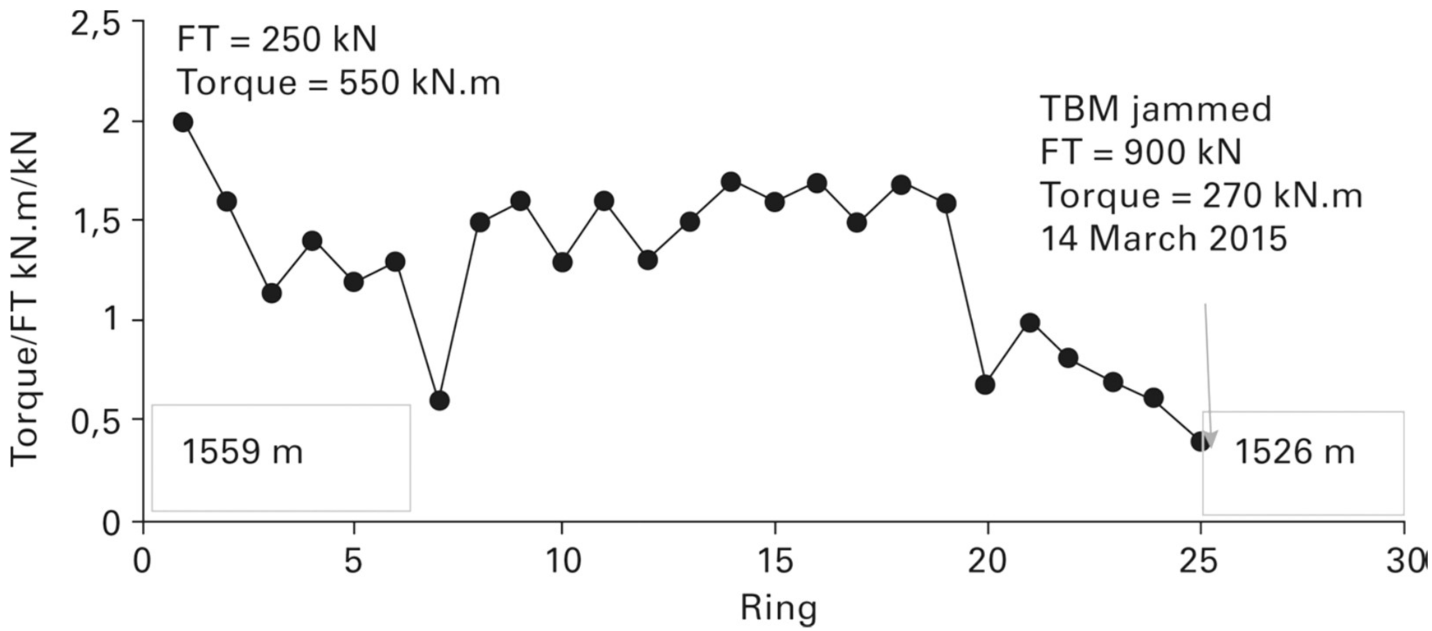
Indication of TBM Squeezing in Doğançay Power t-Tunnel

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 7^{th} ring, then later increased up to 1.5 and dropped again to 0.5, and the TBM was jammed within the 25th ring.



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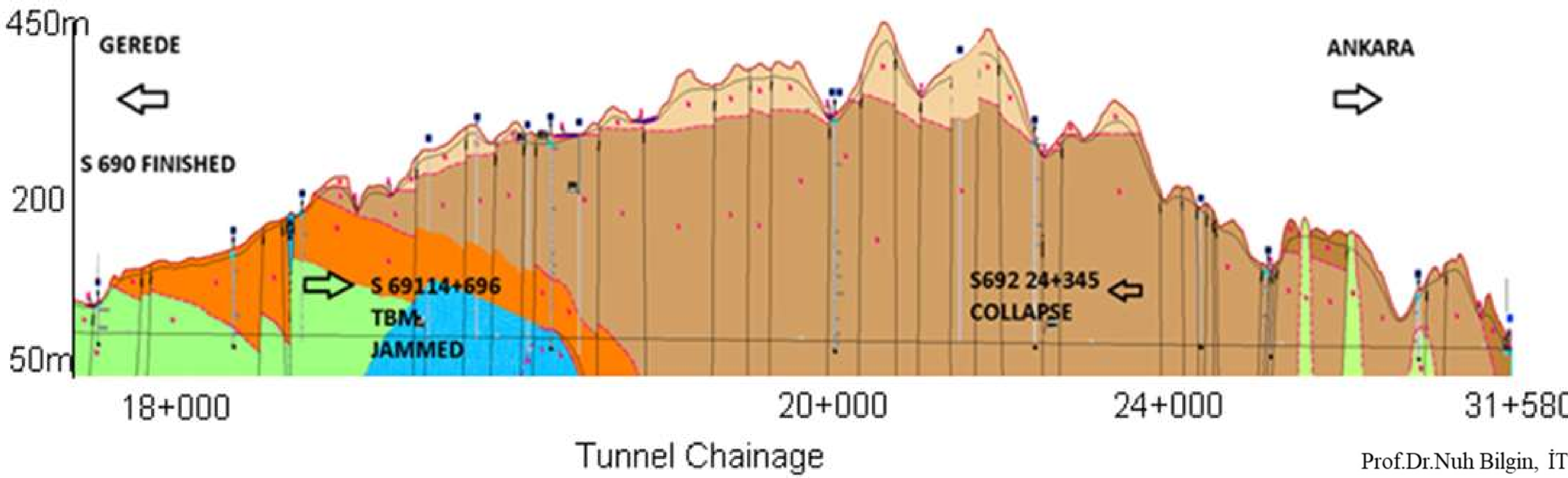
Double Shield TBM in Gerede Water Tunnel

The purpose of the project is to supply drinking water to Ankara, via a tunnel having a length of **31.6 km and a final diameter of 4.4 m. The geology of the Gerede tunnel consists mainly of volcanic units.** 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**. The TBM S 690 excavated a length of 9588 m and the first part was finished.** However, this has been one of the most problematic TBM tunneling operations in Turkey



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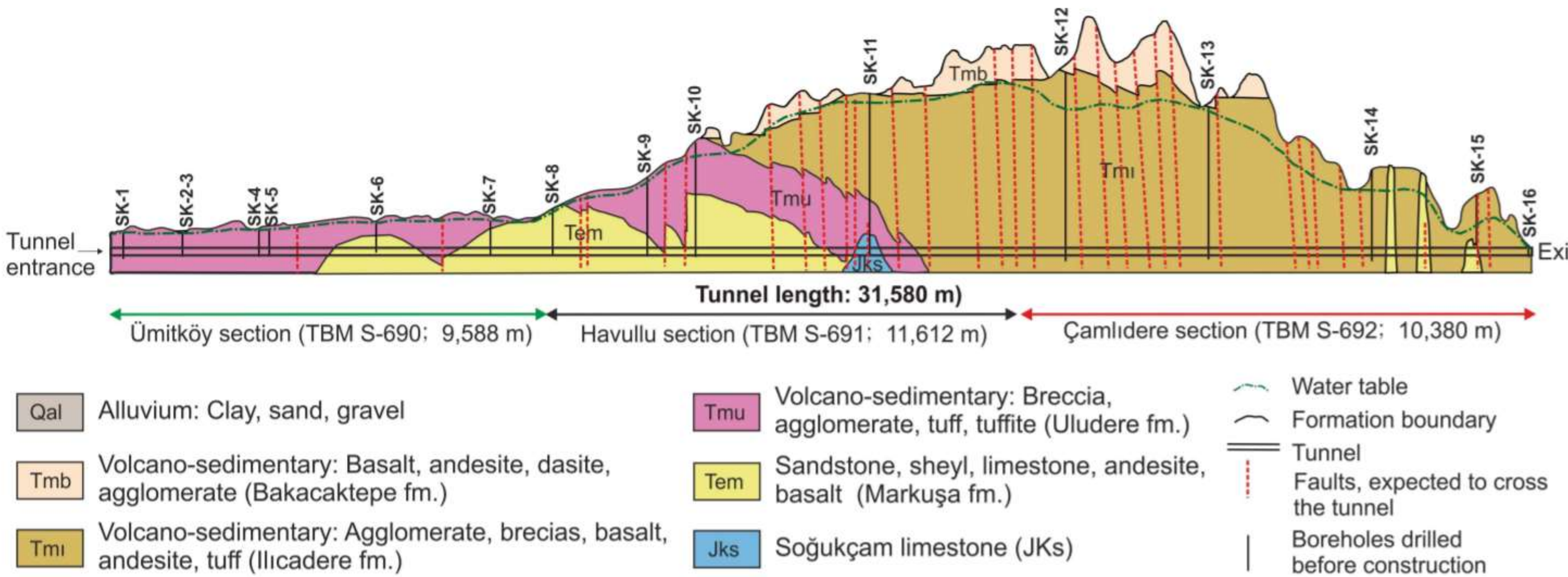
Cross Section of Gerede Tunnel



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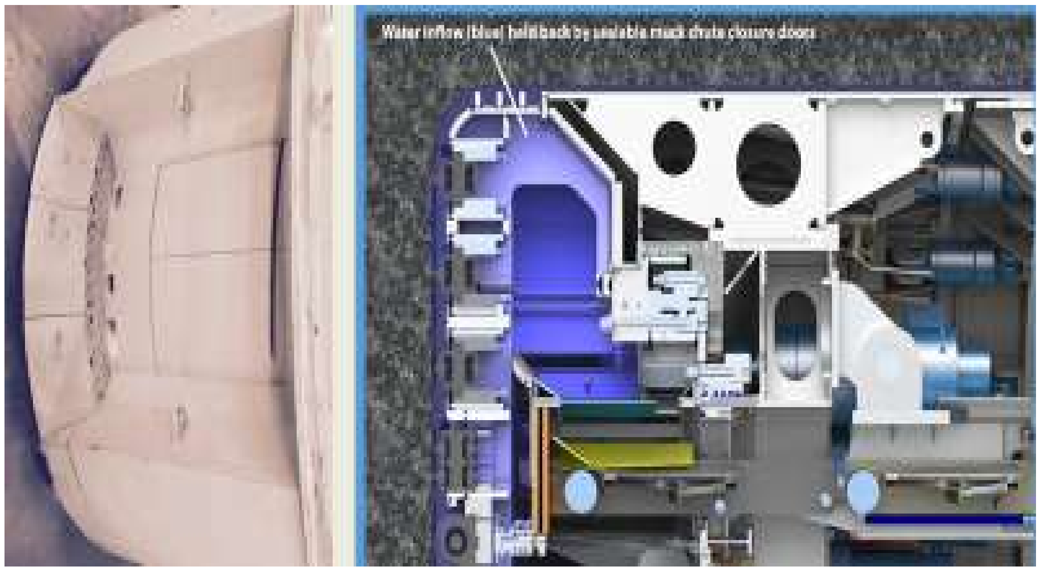
Double Scield TBM in Gerede Tunnel

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**

The Collapse of Third Drive the 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

Robbins TBM with Muck Chute Closure Doores



Home,L. Carving a Path through Extreme Conditions: an Integritade Ground Investigation System Optimized for Turkey's Difficult Geology, 2nd Int. Conf. on Tbm's in Difficult Grounds (TBM DiGs Istanbul) Istanbul, 16–18 November 2016

Lessons Learned in Difficult Ground Conditions

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>

Conclusive Remarks in Big Fault Zaunes

1.In big fault zones, within the influence area of the zone, stress measurements are necessary or watch the muck, you will see the traces of the stresses on the muck.

2. Big fault zones will result squeezing ground or blocky ground.

3. For squeezing ground follow the rules of lubricating the shield skin by bentonite injection.

4.Your TBM should have proper probe drilling equipment. Be careful of interpreting the results.

5. Care of excessive water ingress.

6.In blocky ground polyurethane (geofome) injection will be necessary.

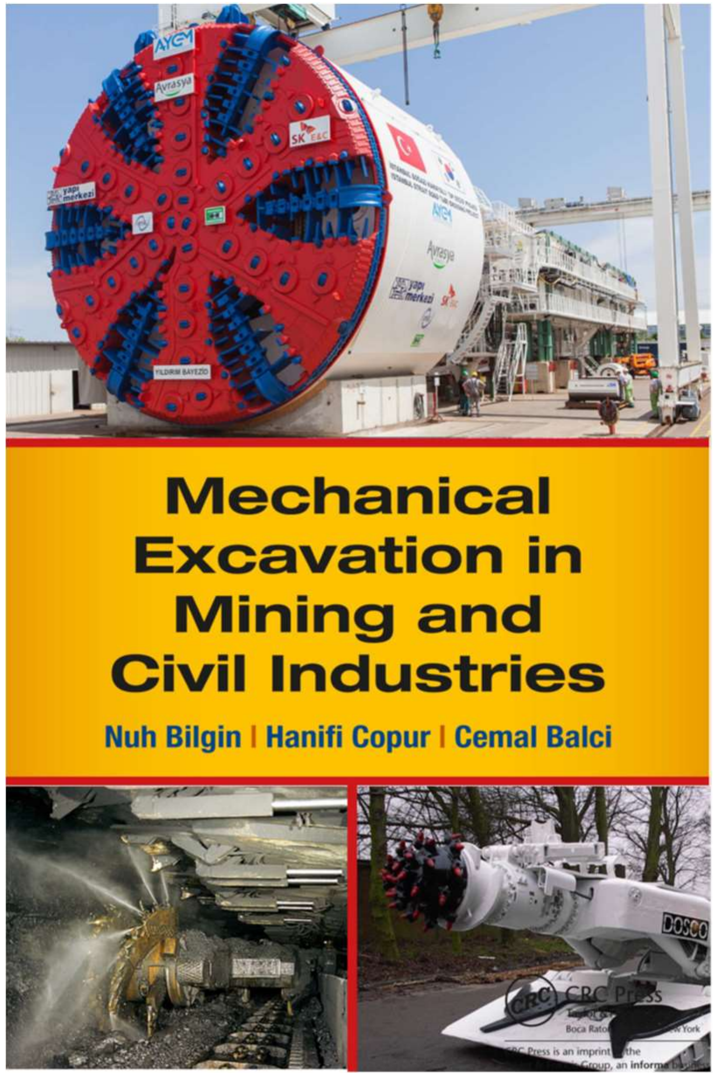
7. Watch careful Torque/thrust ratio of TBM. It will tell you if you are approaching squeezing zone or not.

8. Full scale laboratory tests will help you to select the proper TBM in very hard rock formations.

9.Properly designed TBM and experience crew are a necessity.

- Thank you very Much Listening to me.
- Please follow the boks given below for further detailed information.

- Prof Dr. Nuh Bilgin
- bilgin@itu.edu.tr



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TBM Excavation in Difficult Ground Conditions
Case Studies from Turkey

Nuh Bilgin
Hanifi Copur
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