Underground Space Use: Analysis of the Past and Lessons for the Future – Erdem & Solak (eds)

The performance of a full face tunnel boring machine (TBM) in Tarabya (Istanbul)

N. Bilgin, C. Feridunoglu & D. Tumac
Istanbul Technical University, Mining Engineering Department, Istanbul, Turkey

M. Cınar, Y. Palakci, O. Gunduz & L. Ozyol
Tinsa Co., Istanbul, Turkey

ABSTRACT: The performance of a full face tunnel boring machine (Herrenknecht TBM) was evaluated within the research program of this study. TBM having a diameter of 2.9 m and cutting power of 560 kW was used to excavate the tunnel of 13270 m in length, which was situated between Sariyer and Baltalimanı. The main rock formations are Paleozoic aged sedimentary rocks, limestone, sandstone-siltstone, andesite dykes and sediment fillings. The project was commissioned to Tinsa – Öztaş – Hazinedaroğlu – Simelko consortium. The performance of TBM was recorded continuously for detailed shift analysis. A limestone block having dimensions of 0.4 × 0.5 × 0.4 m, representing majority of the rock formations was collected from one of the shafts. This rock block was subjected to full scale instrumented laboratory cutting tests using a disc cutter taken from the TBM. The relationship between thrust force and depth of cut was compared to the one obtained in the field. It is concluded that accumulated data and instrumented full scale rock cutting tests may serve as a valuable tool to predict the performance of full face tunnel boring machines in any type of rock formation.

1 INTRODUCTION

It is estimated that in the coming years the underground construction in Europe and in the other parts of the world will increase tremendously, typical examples are tunnels, microtunnels, storage caverns (oil, gas, waste etc.). Mechanical rock excavation offers many advantages over conventional drill and blast techniques. These include improved safety, minimal ground disturbances, elimination of blast vibration, reduced ventilation requirements etc. In addition, mechanical boring is capable of providing much higher rates of advance at lower cost than drill and blast excavation. A degree of uncertainty is always present on selecting equipment, predicting machine performance, estimating job duration, costs etc. However accumulated and published data from tunneling projects serve to improve predicting the machine performance and scheduling of job duration, this paper is prepared under this objective.

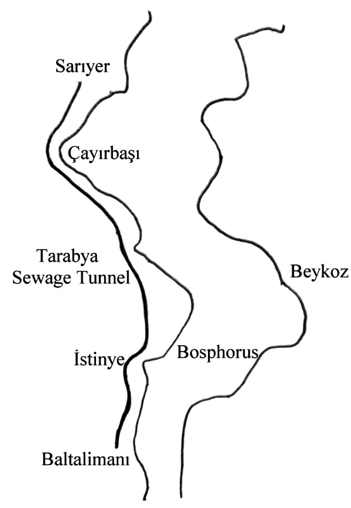

Figure 1. The general layout of the Tarabya Tunnel.

2 DESCRIPTION OF THE TUNNEL PROJECT AND TUNNEL GEOLOGY

Tarabya tunnel is a part of sewerage project, which is planned to clean the sea pollution in Istinye – Tarabya and Büyükdere bays around Istanbul Bosphorus. The tunnel having a length of 13,270 m and final diameter of 2 m is situated between Sarıyer and Baltalimanı as seen in Figure 1. 19 shafts are connected to the main tunnel with 15 tunnels being oval in shape with a size of 1200/1800 mm. Cross section of the main tunnel is given in Figure 2. The tunnel mainly passes through limestone and shale rock formations of Silurian-Devonian age and sandstone, siltstone rock formations of Carboniferous age. Some magmatic intrusions and sediment fillings are encountered in tunnel route.

Summary of the rock properties obtained from tender document is given in Table 1. The figures in Table 1 represent a tunnel length of 8847 m. The second part of the tunnel was also commissioned to the same contractors. However the second part of the tunnel was driven mainly in sediment fillings in majorities.

Some limestone samples were taken from the tunnel face in 18.09.2000 and 11.10.2000 for testing in the laboratories. It is noted that the compressive strength of the rock samples taken from the face could be different than given in general documents. The compressive strength values of the samples were 80 ± 7 MPa and 119 ± 16 MPa.

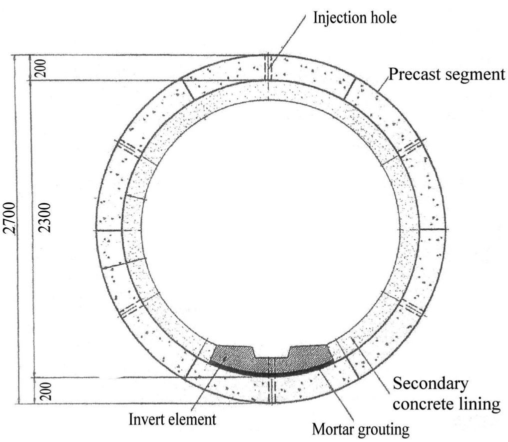

Figure 2. Cross section of the main tunnel.

Table 1. Summary of the rock properties encountered in tunnel route.

Rock formation % of the total	Compressive Strength (MPa)	Tensile strength (MPa)	Elastic modulus (MPa) $\times 10^3$
Limestone 65%	44–81	4–5	9–15
Shale 17%	55–59	2.4	9–10
Sandstone-Siltstone 12%	59	–	–
Dykes 1%	32–40	3	6–7
Sediment Filling 5%	–	–	–

3 DESCRIPTION OF TBM AND WORK STUDY ON MACHINE ASSEMBLAGE

General characteristics of Herrenknecht TBM used in tunnel drivage are given in Table 2.

TBM came to the field in 31 May 2000 and machine assemblage time took 30 days. Table 3 summaries machine assemblage time for different jobs. A typical view of TBM is given in Figure 3.

Table 2. General characteristics of TBM used in Tarabya Tunnel.

TBM excavation diameter	2915 mm
TBM shield diameter	2870 mm
Disc number	20
Disc diameter	305 mm (edge width 10 mm)
Max. rotational speed	16 rpm
Max. torque applied	725 kNm
Number of thrust cylinders	6
Max. thrust force	3750 kN (250 bar)
Max power	620 kW

Table 3. Machine assemblage time for different jobs.

Preparation of the shaft bottom	6%
Descending the cutting head and shield	7%
Pushing cutting head and shield to face	7%
Preparation of the rails for back-up system	3%
Descending the back-up system	3%
Preparation of the steel arch supporting the first rig	3%
Assemblage of back-up and hydraulic system	25%
Preparation of the conveyor band	3%
Assemblage of the laser measuring system	7%
Assemblage of the cooling system	7%
Test running of TBM	11%
Electrical breakdown	15%
Cooling system breakdown	3%

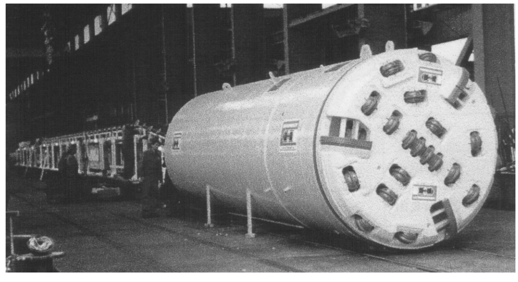

Figure 3. Typical view of TBM.

4 RECORDING THE PERFORMANCE OF TBM

The tunnel excavation started in July 2000 and finished in November 2004. The performance of TBM was recorded continuously for detailed shift analysis. Table 4 is a summary of overall performance for 7700 m of tunnel drivage.

The performance of the TBM between chainage 981 and 7700 m are summarized in Figures 4–7. As seen from these figures the average machine utilization time is 35%, breakdowns are between 24 to 27% of shift time. However it is interesting to note that the share of disc changing within the breakdown time is between 36 to 41%, which is a quite high compared to other applications. The machine utilization time was found to change between 15% to 55% in general.

Machine utilization time is one of the most important factors in determining the machine advance rate. As seen from Figure 8, an increase in machine utilization time from 15% to 55%, increases the machine advance rate from 0.2 m/h to 0.8 m/h. Machine utilization time is defined as the ratio of the net cutting time of the machine to the total working time; i.e., shift time.

Table 4. Overall TBM performance for 7700 m of tunnel drivage.

The best shift advance	18 m
The mean shift advance	4.5 m
The worst shift advance	0.75 m
The best daily advance	24.75 m
The mean daily advance	11.50 m
The worst daily advance	0.75 m
The best monthly advance	531 m
The mean monthly advance	376.7 m
The worst shift advance	144.75 m

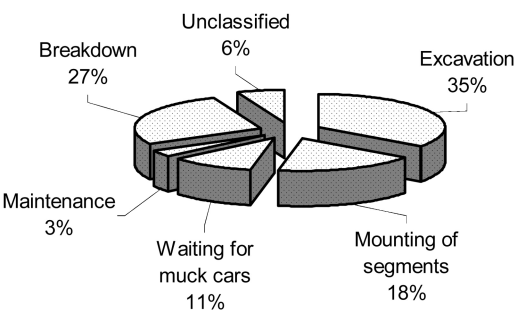

Figure 4. Machine performance between chainage 981–2260.

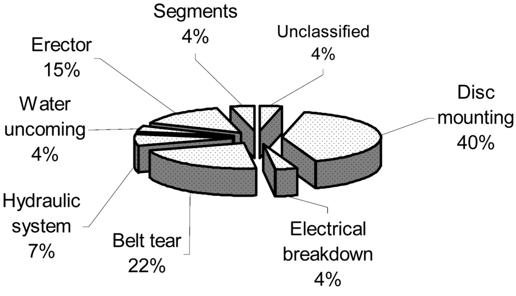

Figure 5. Classification of breakdowns between chainage 981–2260.

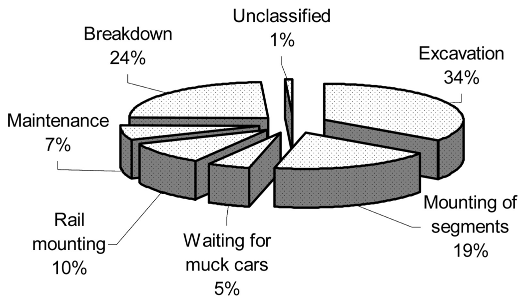

Figure 6. Machine performance between chainage 2500–7700.

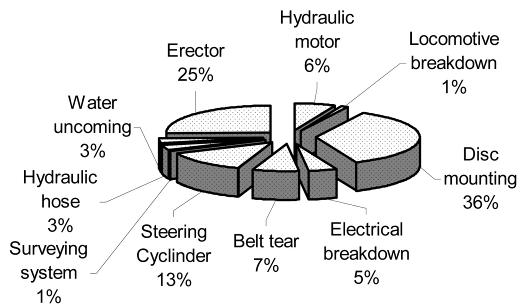

Figure 7. Classification of breakdowns between chainage 2500–7700.

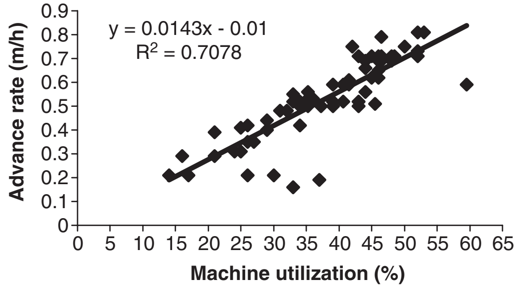

Figure 8. The relationship between machine advance rate and machine utilization time between chainage 981–2260.

5 FULL SCALE ROCK CUTTING TESTS IN THE LABORATORY AND ESTIMATION OF THE MACHINE CUTTING RATE

The main objective of the laboratory rock cutting tests was to see how the in situ measured machine performance values were close to the predicted values from laboratory rock cutting tests, which will contribute to rock cutting mechanics for further industrial applications. For 4 mm depth of cut the measured net cutting rate was 9 m^3/h. Figure 9 represents the relationship between disc thrust force and depth of cut measured in the field for 1 rev/min when excavating limestone formation.

Full-scale rock cutting tests were carried out in the laboratory using the cutting rig as outlined in Figure 10. The rig was designed and manufactured within NATO-TU excavation project. A high quality aircraft aluminum block equipped with strain gauges is used as a dynamometer to record thrust forces up to 50 t. A data acquisition card included eight independent channels. Data recording rate is adjustable up to 50000 Hz.

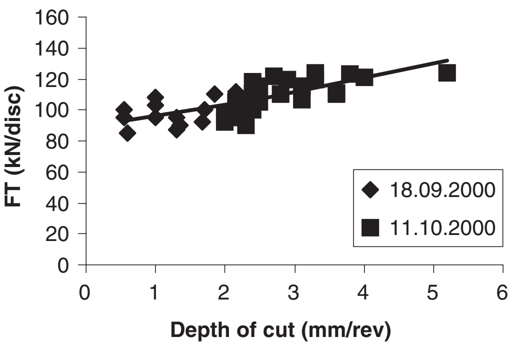

Figure 9. The relationship between disc thrust force and depth of cut measured in the field.

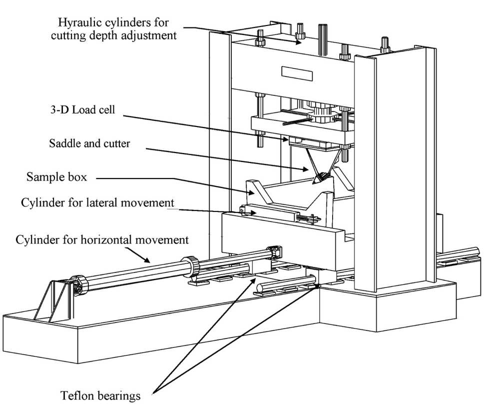

Figure 10. Schematic view of full scale cutting rig.

The hydraulic cylinders can move the sample box in which the rock sample is cast with concrete to eliminate pre-failure of the specimen. The cutter is fixed with a tool holder directly to the dynamometer. The specific energy obtained by dividing mean rolling force to yield (volume of rock removed per unit length) is a key factor in determining the efficiency of cutting process. It is advisable to work with operational parameters given minimum specific energy which is obtained for a given cutter spacing/depth of cut ratio.

The philosophy behind the laboratory rock cutting tests lies in the reality that as a basic rule of rock cutting mechanics, for a given cutting tool and rock formation, optimum specific energy is obtained for a defined s/d ratio. Specific energy is the energy to excavate a unit volume of rock (kWh/m^3) and s/d is cutter spacing/cutting depth ratio. This phenomenon is illustrated in Figure 11 (Ozdemir, 1992). The first and second cuts are inefficient, optimum chip is formed in the third pass given a minimum specific energy value which is preferred for an efficient excavation. Groove deeping should be always avoided for successful operations. Bearing in mind that the distance between disc cutters in a TBM cutting head is constant, the optimum s/d ratio will be directly dictate optimum cutting depth. The relationship between depth of cut, disc thrust force, disc rolling force, may be obtained directly from full scale rock cutting tests realized on big size rock blocks representing the rock formations which are likely to be found in tunnel line. Thrust force for a predetermined depth of cut will directly dictate total machine thrust which the machine operator must apply for an efficient cutting operation. Rolling force for a given disc cutting depth, may be directly used to calculate the power consumed during the cutting process. The torque and the power consumed in optimum cutting conditions may be calculated with the following Equations (Bilgin, 1999).

$$T = \sum_{i=1}^{i=n} r_i . FR \tag{1}$$

$$P = 2\pi NT \tag{2}$$

In these Equations FR is rolling force, n the total number of disc cutters in cutting head of the TBM, r_i is the distance from the cutter to the center of the machine, T is torque and N is revolution per minute of the cutting head and P is the power consumed during the cutting operation. Instantaneous cutting rate or net cutting rate may be calculated using the relation given in Equation 3.

$$ICR = k \times \frac{P(kW)}{SE\ (kWh/m^3)} \qquad (3)$$

In the Equation 3 (ICR) is instantaneous cutting rate in m^3/h, k is the energy transfer ratio changing between 0.7 and 0.8, (P) is power consumed during the cutting process and (SE) is optimum specific energy obtained in full scale laboratory cutting tests as explained in Figure 11.

The relationship between depth of cut and cutter forces obtained in the laboratory for a limestone having a compressive strength of 100 ± 8 MPa is given in Figure 12. A disc cutter taken from the TBM was used in rock cutting tests. Disc has a diameter of 305 mm and edge width of 10 mm. The actual cutter forces and measured values of thrust forces are given in Table 5. As seen from this table the field values are very close to laboratory results meaning that thrust force values obtained in the laboratory may lead to predict field depth of cut values for 1 rev./mm, hence net cutting rate of TBM.

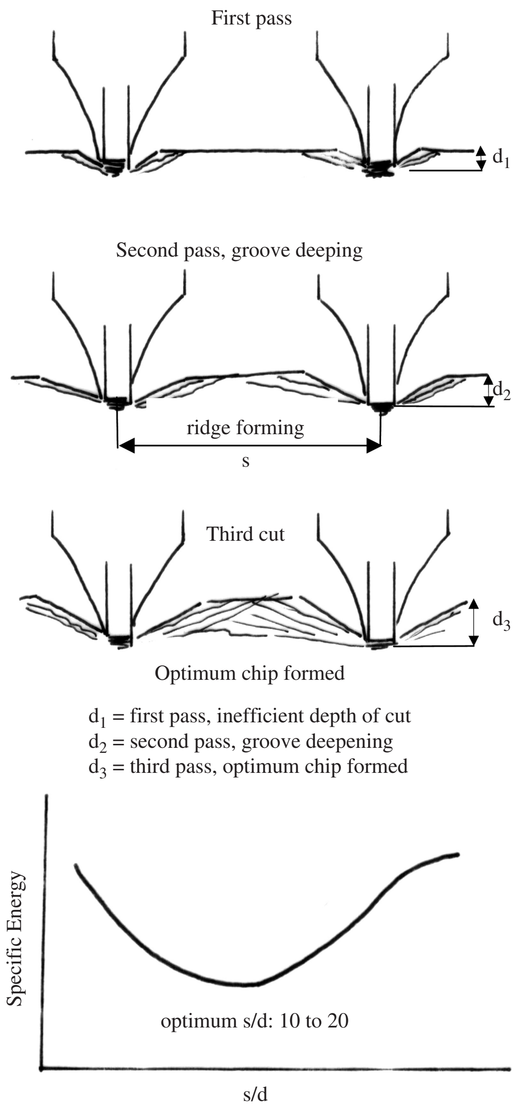

Figure 11. The relation between specific energy and optimum cutter spacing/depth of cut.

In situ FT values for one disc are calculated by dividing total thrust force applied by thrust cylinders of TBM divided by total disc numbers. However actual thrust values delivered to rock surface is usually less then calculated values due to system efficiency and losses such as back-up system towage during mining or friction losses from contact between the shield and the rock. This is experienced to be around 20% during the excavation of Tarabya tunnel. It is reported by different investigators that net average cutter thrust force can be easily 40% less than average gross force calculated from hydraulic cylinder pressures (Nelson, 1993).

The optimum specific energy for the limestone rock formation excavated in Tarabya tunnel is calculated to be 5.7 kwh/^{3} for s/d ratio of 14. Cutter spacing of the face cutters in TBM is 86 mm, given an optimum

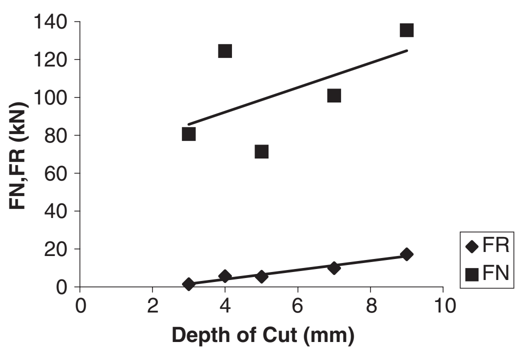

Figure 12. The relationship between depth of cut and cutter forces obtained in the laboratory.

Table 5. Field and measured thrust force values.

Depth of cut (mm)	Measured in situ FT (kN)	In situ FT with 20% less due to friction factors, (kN)	Measured laboratory values FT, (kN)
2	100	81	80
3	110	87	88
4	120	94	96
5	135	101	108

depth of cut of 6 mm. Rolling force FR for one disc for 6 mm depth of cut is calculated to be 9.82 kN from Figure 12. The torque and the cutting power for optimum depth of cut are calculated using equation 1 and 2 as 142.4 kNm and 239 kW consecutively. In optimum cutting condition instantaneous cutting rate of the TBM may be calculated using equation 3 as given below.

$$ICR = 0.8x\frac{239}{5.7}m^3 / h$$

$$ICR = 33.5\ m^3 / h$$

Optimum thrust force for one disc cutter from Figure 12 is found to be 10.8 t Optimum thrust force that TBM operator should apply taking into account the 20% friction losses;

1.2 x 20 disc x 10.8 = 259 t

In field, during the excavation of Tarabya tunnel the instantaneous cutting rate of 33.5 m/h was obtained during some shifts.

6 CONCLUSION

Tunnel excavation in Tarabya started in July 2000 and finished in November 2004. The main rock formation excavated were Paleozoic aged sedimentary rocks, limestone, sandstone – siltstone and andasite dykes. The mean monthly advance rate of 377 m was obtained with a machine utilization time of 35%. It is shown that laboratory full-scale cutting tests may serve as a useful guide for an efficient excavation. It is shown that optimum cutting conditions were obtained using a total machine thrust force of 259 t given an optimum disc penetration of 6 mm/revolution.

7 ACKNOWLEDGEMENT

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