TBM cutting performance in Istanbul

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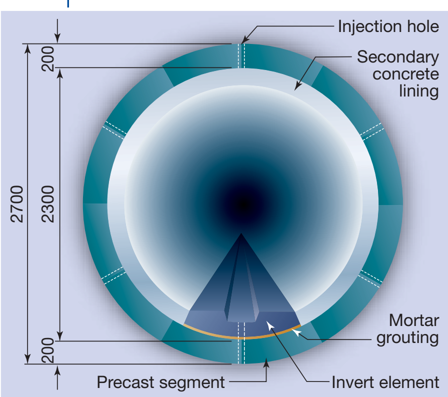
Below: Fig 1 - Map of the Tarabya Tunnel

Table 1:

Rock formation % of the total		Compressive Strength (MPa)	Tensile Strength (MPa)	Elastic modulus (Mpa) 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%	-	-	-

The Tarabya tunnel forms a major part of a sewerage project currently under construction in Istanbul, Turkey, designed to clean up the unacceptable pollution present in the Istinye – Tarabya and Büyükdere bay areas of the city's Bosphorus River.

The tunnel is 13,270m long with an i.d. of 2m and is situated between Sariyer in the north and Baltalimani in south (figure 1). The construction contract was awarded to a consortium made up of contractors Tinsa/Öztas /Hazinedaroglu/Simelko, which used a 2.9m diameter, 560kW Herrenknecht TBM to bore the tunnel. The performance of the TBM, which began boring in July 2000 and finished in November 2004, was recorded for detailed shift analysis.



Above: Fig 2 - Cross section of the tunnel

Some limestone samples were taken from the tunnel face in September and November 2000 for testing in the laboratory. These were thought to be representative of the geology along the majority of the alignment and were subjected to full-scale laboratory cutting tests using one of the TBMs disc cutters. The relationship between thrust force and depth of cut recorded in the lab was compared to those obtained in the field to assist future research into machine utilization. The compressive strengths of the samples were found to be 80±7MPa and 119±16MPa respectively.

The geology and TBM

The tunnel passes through limestone and shale rock formations of the Silurian-Devonian age, and sandstone, siltstone rock formations from the Carboniferous period. Some magmatic intrusions and sediment fillings are also found along the alignment.

A summary of the rock properties obtained from the tender documents is given in Table 1. These figures correspond to the initial 8,847m of the tunnel. The rest was driven mainly through sediment fillings.

The 2.9m diameter Herrenknecht TBM (Table 2) was delivered on 31 May 2000 and as stated earlier, began boring in July 2000 with completion in November 2004.

The performance of the TBM between chainage 981m and 7700m are summarised in Figures 3-6 (on p18). As seen from these figures the average machine utilization time was 35%, with downtime taking up between 24-27% of shift time. However it is interesting to note that disc changing within the downtime takes up some 36-41%, which is a quite high by comparison. Machine utilization was found to generally vary between 15-55%.

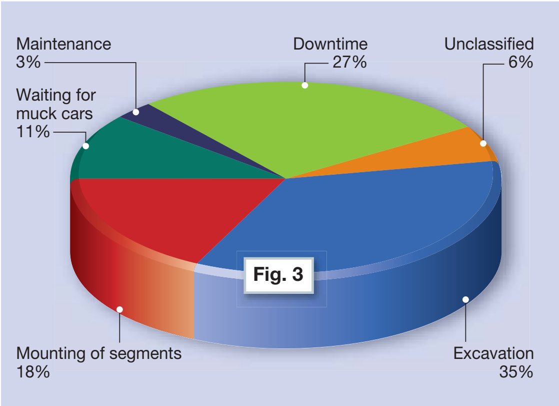
Machine utilization is one of the most important factors in determining advance rates. As seen from figure 7 (p18), an increase in machine utilization time from 15-55%, increases the machine advance rate from 0.2m/h to 0.8m/h. Utilization is defined as the ratio of the machine's net cutting time to the total working time; ie, shift time.

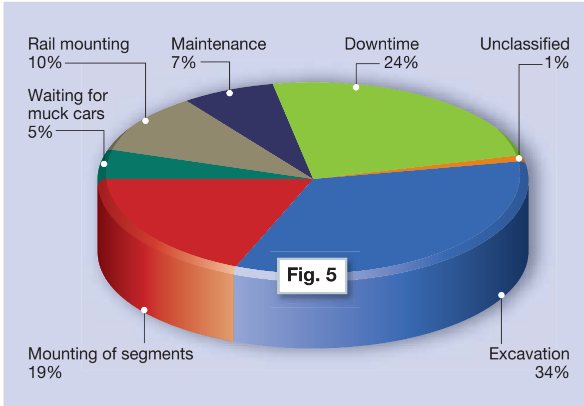
Rock cutting test

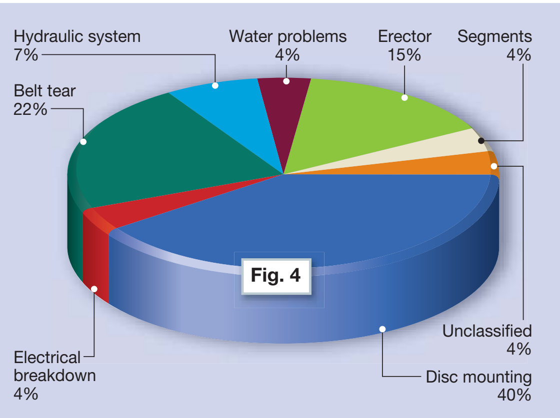
The main objective of the laboratory rock cutting tests was to see how close the in-situ measured machine performance values were to the predicted values from the laboratory rock cutting tests.

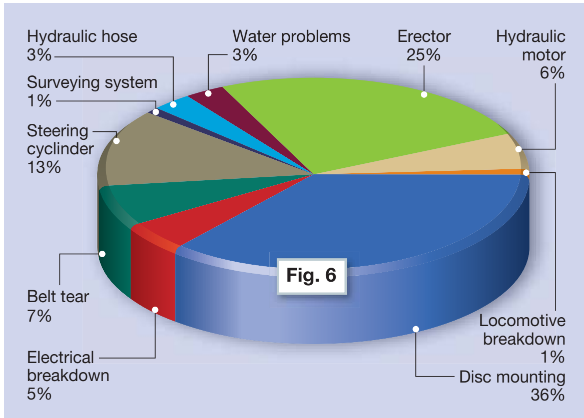
For a 4mm depth of cut, the measured net cutting rate was $9m^3/h$. Figure 8 (p18) represents the relationship between disc thrust force and depth of cut measured in the field for 1 rev/min when excavating through the limestone formation.

Full-scale rock cutting tests were carried out in the laboratory using a special cutting rig. A high quality aircraft aluminum block equipped with strain gauges was used as a dynamometer to record thrust forces up to 50t. A data acquisition card included eight independent channels and the data recording rate was adjustable up to 50,000Hz.



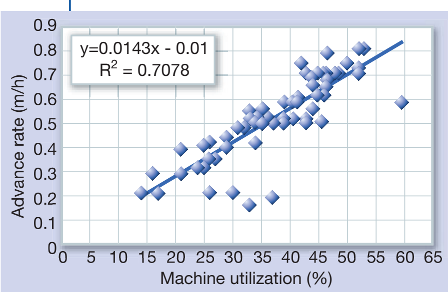






Top and bottom left (Chainage 981-2260): Fig 3 - Machine performance. Fig 4 - Classification of downtime.
Top and bottom right (Chainage 2500-7700): Fig 5 - Machine performance. Fig 6 - Classification of downtime

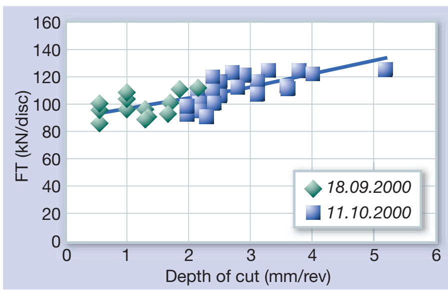
The hydraulic cylinders can move the sample box in which the rock sample is cast (with concrete), to eliminate pre-failure of the specimen. The cutter is fixed with a tool holder directly to the dynamometer. The specific energy obtained, by dividing the mean rolling force to yield (volume of rock removed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



Above: Fig 7 - Relationship between TBM advance rate and utilisation (chainage 981-2260)

The philosophy behind the laboratory rock cutting tests lies in the fact 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, where the specific energy is the energy needed to excavate a unit volume of rock (kwh/m^3), and s/d is the cutter spacing/cutting depth ratio (figure 9 Ozdemir, 1992[4]). The first and second cuts are found to be inefficient, with the optimum chip formed in the third pass, given a minimum specific energy value which is preferred for an efficient excavation. Groove deeping should always be avoided for successful operations. Bearing in mind that the distance between disc cutters in a TBM cutter head is constant, the optimum s/d ratio will directly dictate optimum cutting depth. The relationship between depth of cut, disc thrust force, and disc rolling force, may be obtained directly from full scale rock cutting tests carried out on large rock blocks that represent the rock formations likely to be found along the tunnel alignment. 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 using the following equations (Bilgin, 1999[1]).

(1) $$T = \sum_{i=1}^{i=n} r_i \, .FR$$



Above: Fig 8 - Relationship between disc thrust force and depth of cut measured in the field

Table 2: Field and measured thrust force values

Depth of cut (mm) % of the total	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

(2) $$P = 2\pi NT$$

In these Equations FR is the rolling force, n is the total number of disc cutters in the cutter head of the TBM, ri is the distance from the cutter to the centre of the machine, T is torque, N is the 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.

(3) $$ICR = k\,x\,\frac{\mathrm{P(kw)}}{\mathrm{SE\ (kWh/M^3)}}$$

In Equation 3, ICR is the instantaneous cutting rate in m^3/h, k is the energy transfer ratio changing between 0.7 and 0.8, P is the power consumed during the cutting process, and SE is the optimum specific energy obtained in full scale laboratory cutting tests as explained in Figure 9.

The relationship between depth of cut and cutter forces obtained in the laboratory for a limestone having a compressive strength of 100±8MPa is given in Figure 10.

The disc cutter from the TBM used in the rock cutting tests had a diameter of 305mm and an edge width of 10mm. The actual cutter forces and measured values of thrust forces are given in Table 2. As seen, the field values were very close to the lab results, meaning that the thrust force values obtained in the lab could predict the actual field 'depth of cut' values for 1 rev/mm, and subsequently the TBM net cutting rate.

In situ FT values for one disc are calculated by dividing the total thrust force from the TBM thrust cylinders by the total disc number. However, actual thrust values applied to the rock surface are usually less than those calculated due to system efficiency and losses such as friction losses from contact between the shield and the rock. This was found to be around 20% during excavation. It has been reported, in other research, that net average cutter thrust force can easily be 40% less than the average gross force calculated from hydraulic cylinder pressures (Nelson, 1993[3]).

The optimum specific energy for the limestone rock excavated along the Tarabya tunnel was calculated to be 5.7kwh/^{3} for an s/d ratio of 14. Cutter spacing of the face cutters in the TBM was 86mm, given an optimum depth of cut of 6mm. Rolling force FR for one disc for 6mm depth of cut was calculated to be 9.82kN from figure 12. The torque and the cutting power for optimum depth of cut are calculated using equation 1 and 2 as 142.4kNm and 239kw consecutively. In optimum cutting conditions, instantaneous cutting rates of the TBM may be calculated using equation 3 as given below.

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

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

The optimum thrust force for one disc cutter from figure 10 is found to be 10.8t. The optimum thrust force that a TBM operator should apply taking into account the 20% friction losses therefore equals:

1.2 x 20 disc x 10.8 = 259t

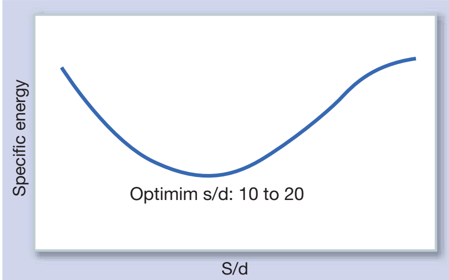
In the field, during the excavation of Tarabya tunnel the instantaneous cutting rate of 33.5m/h was obtained during some shifts.

Conclusion

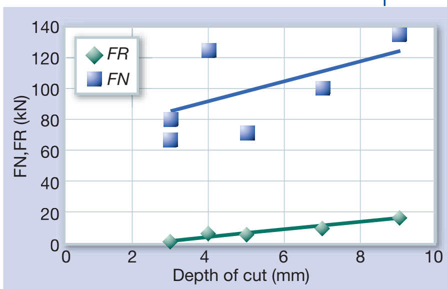
Excavation through sedimentary rocks, limestone, sandstone – siltstone and andesite dykes, started in July 2000 and finished in November 2004. A mean monthly advance rate of 377m was obtained with a machine utilization of 35%.

It has been shown that full scale lab cutting tests can be as a useful guide for TBM efficiency. Optimum cutting conditions were obtained using a total machine thrust force of 259t given an optimum disc penetration of 6mm/revolution. T&T

The full-scale cutting rig



Above: Fig 9 - Relationship between specific energy and optimum cutter spacing/depth of cut



Above: Fig 10 - Relationship of depth of cut and cutter forces in the laboratory

ACKNOWLEDGMENTS

The authors are grateful to Tinsa/Öztas/ Hazinedaroglu/Simelko consortium for allowing access to field data and Prof Dr Levent Ozdemir from CSM, US, for helping to construct laboratory facilities.

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