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

The performance of a roadheader in high strength rock formations in Küçüksu tunnel

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ABSTRACT: The main objective of this study was to investigate the performance of a roadheader used for the excavation of Küçüksu Sewage Tunnel having a length of 1037.52 m. The tunnel is located in Anatolian part of Istanbul and constructed by STFA for Istanbul Water and Sewerage Administration (ISKI).

Detailed statistical analysis showed that net advance rate of the roadheader is directly influenced by rock compressive strength, rock mass quality designation and water income.

In the second stage of the research study, a big rock block taken from the tunnel face was subjected to full-scale rock cutting tests in the laboratory using a linear cutting machine. Cutter force and specific energy values were recorded for different depths of cut and cutter spacings and likely net cutting rate of the roadheader excavating rock formation was predicted using specific energy and cutter head power.

In situ cutting rate and laboratory predicted values were compared in order to test the validity of the full scale rock cutting tests.

1 INTRODUCTION

The application of roadheaders in hard formations, has increased in recent years, considerably in both civil and mining engineering fields. The prediction of instantaneous (net) cutting rate and machine utilization time, determining daily advance rates, play on important role in time scheduling of the tunneling projects and in determining the economy of tunnel excavation. This paper is a summary of a research study in this respect.

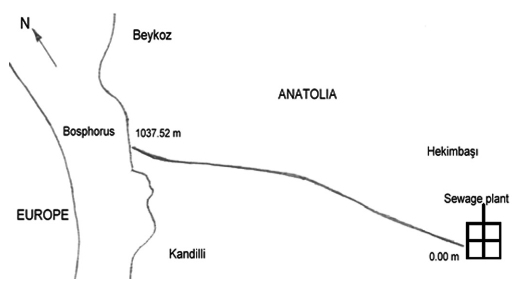

Figure 1. The route of Küçüksu tunnel.

2 DESCRIPTION OF THE TUNNEL PROJECT

Küçüksu tunnel is apart of sewage project which is situated between Küçüksu and Hekimbaşi in the Anatolian part of Istanbul. The route of the tunnel is shown in Figure 1. The project commissioned to STFA consists of a sewage plant having a capacity of 7 m^3/sn, three shafts and two tunnels having final diameters of 2.2 m and length of 95.8 and 1037.2 m. The tunnels were excavated using SM1 model shielded Herrenknecht roadheader which is shown in Figure 2, the machine had a cutting power of 90 kW and total power of 224 kW. The cutting head is axial type having 36 conical cutters of 75° tip radius. The excavation of tunnels started in 27th August 2002 and finished in 9th August 2003. The crew consisted of 5 civil engineers, three surveyors and 12 workers per shift. The excavated material was transported using Clayton locomotive of 21 hp and cars of 2.5 m^3 in volume. 2 × 7.5 kW ventilator and ventube of 500 mm in diameter realized the ventilation of tunnel.

Cross-section of the tunnel is shown in Figure 3. Precast segments prepared in tunnel side are used as initial tunnel support; each segment has a length of 0.75 m and thickness of 0.10 m. Each rig consists of 4 precast segments and an invent. In situ casted concrete

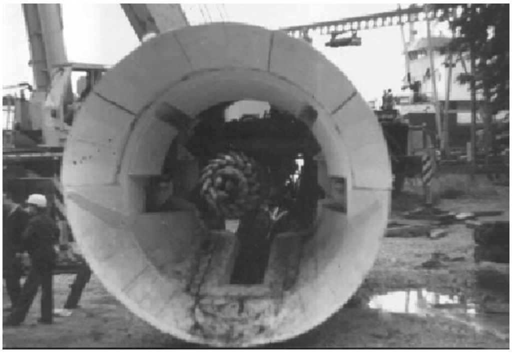

Figure 2. SM1 model Herrenknecht roadheader.

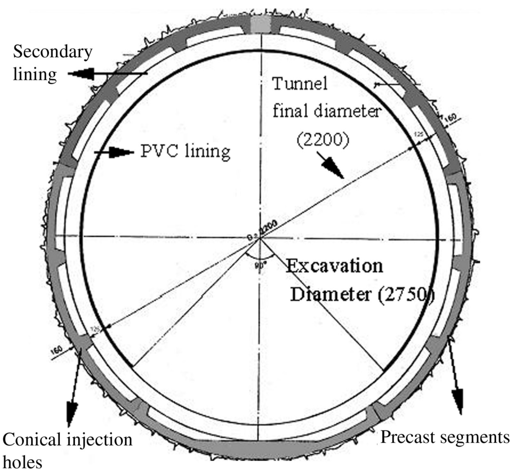

Figure 3. Cross section of the tunnel.

lining was used as secondary tunnel support and PVC lining to protect concrete from harmful effect of the sewage water.

3 TUNNEL GEOLOGY AND SOME ROCK PROPERTIES

Rock samples were collected systematically and geological observations were made during tunnel excavations.

The main rock formation is limestone (72%) having compressive strength values changing from 600 to 1452 kg/cm^2 and RQD values from 40% to 90%. 16% of the rock formations are andesite and diabase dykes with compressive strength from 741 to 1638 kg/cm^2 and RQD 80–90%.

Petrographic descriptions of the samples collected from different tunnel chainages are given in Table 1.

Table 1. Petrographic description of the rock formations.

Tunnel chainage	Petrographic description
251.25	Porphyritic andesite (fine and medium size hornblende and plagioclase matrix)
288.00	Limestone with %95 calcite content
288.75	Limestone with %95 calcite content
306.00	Carbonated sandstone
306.75	Carbonated sandstone
375.00	Siltstone with foliation, abundant with quartz and calcite
447.00	Medium size limestone with fossils
462.00	Limestone with large size calcite crystals
465.75	Limestone abundant with amphiboles and large plagioclase crystals
486.75	Limestone with fossils
506.25	Limestone with organic detritals
547.50	Altered andesite with albite, calcite and epidote crystals
560.25	Limestone with fossils
613.50	Large sized carbonated siltstone
630.00	Cretaceous aged andesite, hornblende ferro-crystals, altered plagioclase, fine graine amphiboles
645.00	Limestone with 90% calcite of 1 mm in size
660.00	Carbonated diabase, 50% of calcite crystals and feldspars
684.75	Carbonated siltstone, 35% calcite, 7–8% muscovite, fine grain quartz, crystals with 0,1 mm in size

A geological cross section of the tunnel with RQD and water income values in different rock strata is given in Figure 4.

4 PERFORMANCE PREDICTION OF THE ROADHEADER IN KÜÇÜKSU TUNNEL

In recent years the application of roadheaders in hard rock formations has increased considerably. However the prediction of the net cutting rate and machine utilization time determining daily advance rates still stays a key factor in determining the economy of tunnel excavation. Although in the past many roadheader performance prediction models were published (McFeat-Smith, Fowell 1977–79; Bilgin et al. 1990–1996–1997; Thuro, Plinninger 1998–1999; Çopur 1997–1998), one of the most realistic method to predict the cutting rate of any excavation machine in massive rock formations was reported to use cutting power, optimum specific energy and energy transfer ratio as given in Equation 1 (Rostami, Ozdemir 1994).

$$ICR = k\frac{P}{SE_{opt}} \qquad (1)$$

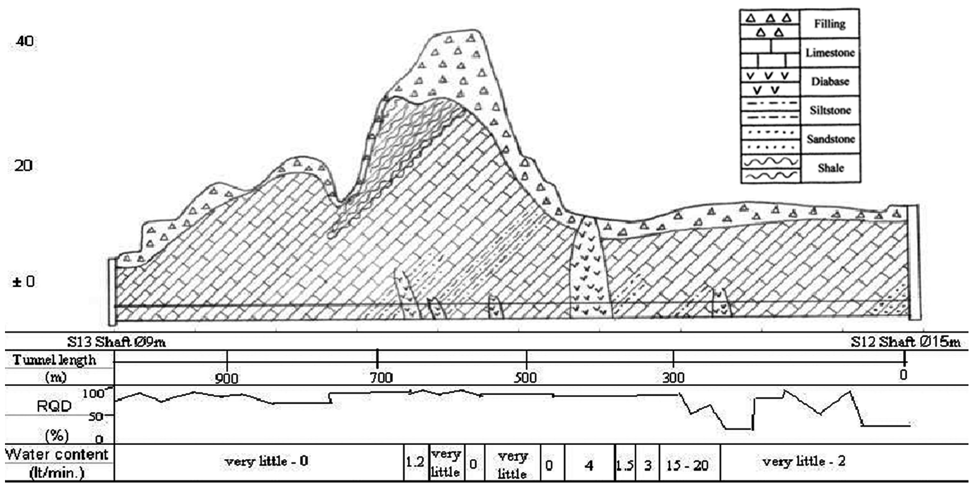

Figure 4. A geological cross section of the tunnel.

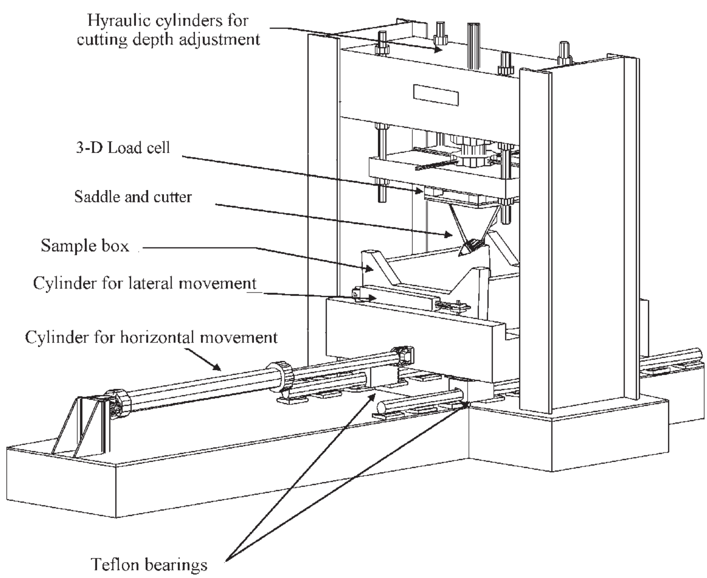

Figure 5. Schematic view of ITU LCM.

where, ICR is instantaneous cutting rate in m^3/h, k is energy transfer ratio from cutting head to the rock formation, P is cutting power of cutting head in kW and SE_{opt} is optimum specific energy in kWh/m^3.

It is strongly emphasized that the SE_{opt} should be obtained from full-scale linear cutting tests in optimum conditions using real life cutters. Rostami and Ozdemir pointed out that k changes between 0.40 for roadheaders to 0.90 for TBM's (Rostami, Ozdemir 1994).

A limestone block having a size of 30, 40, 50 cm was collected from one of the shafts in order to carry out full scale cutting tests in ITU laboratories

4.1 *Rock cutting test*

The linear cutting machine used in this study was built as an outcome of NATO supported project (Eskikaya 2000). The schematic view of the cutting rig is given in Figure 5. It includes a stiff reaction

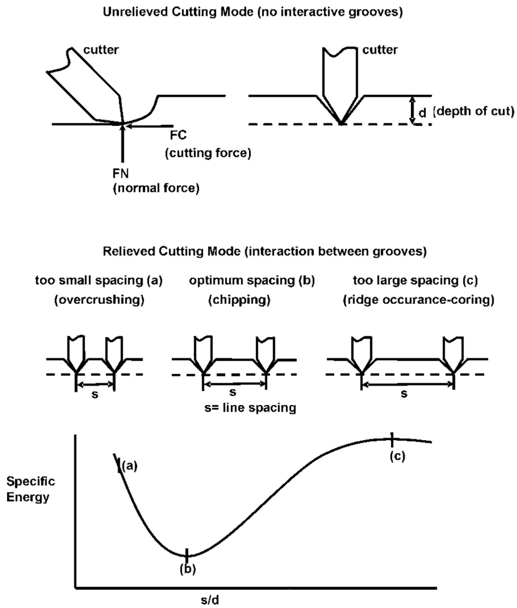

Figure 6. Unrelieved and relieved cutting modes and the effect of cutter spacing and depth of cut on specific energy.

frame on which the cutter and the force dynamometer of 50 t capacity are mounted.

A data acquisition system is used to record the cutter forces in three perpendicular directions. Data recording rate is adjustable up to 50,000 Hz. 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 initial cutting tests are carried out in unrelieved mode to determine the variation of specific energy with depth of cut. This helps to find the optimum depth of cut value at which the relieved cutting tests will be carried out to determine the optimum specific energy and cutter spacing. Optimum specific energy will serve to predict the cutting rate of the machine intended to be used in the rock formation tested. Unrelieved cutting modes and the effect of cutter spacing and depth of cut are shown in Figure 6.

A limestone sample collected from tunnel face and having compressive strength value of $1100 \pm 112\,kg/cm^2$ was subjected to rock cutting tests in the laboratory. The results are given in Figures 7, 8, 9. As seen in Figure 9 the optimum specific energy for $d = 9$ mm depth of cut is $7\,kWh/m^3$. As explained above the net cutting rate (ICR) of the roadheader used in Küçüksu tunnel may be calculated using equation (1). Bearing in mind that, energy transfer ratio k is reported to be 0.40 by Rostami and Özdemir (1997).

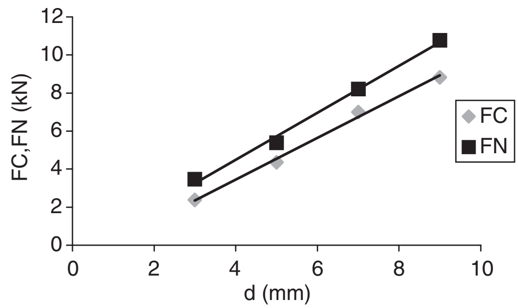

Figure 7. The variation of mean cutter forces with depth of cut.

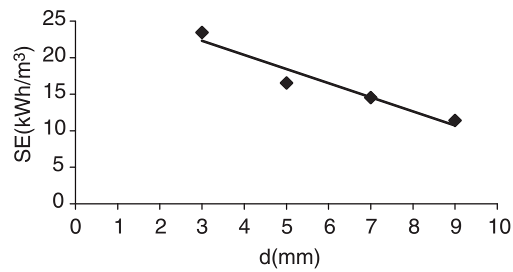

Figure 8. The variation of specific energy with depth of cut.

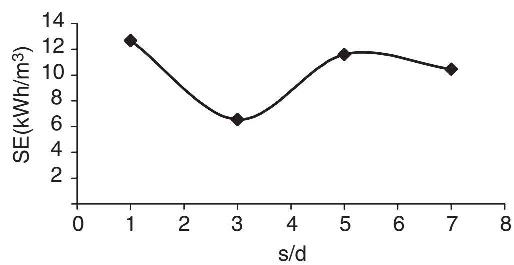

Figure 9. The variation of specific energy with s/d.

$$ICR = k\frac{P}{SE}$$

$$ICR = 0.4\frac{90kW}{7kWh/m^3}$$

$$ICR = 5.1m^3/h$$

5 RECORDING THE PERFORMANCE OF ROADHEADER AND COMPARISON OF PREDICTED AND ACTUAL VALUES

The performance of roadheader was recorded continuously during tunnel excavation. The summary of the roadheader performance is given Table 2 and Figure 10. Monthly advance rates of the roadheader are shown in

Table 2. Summary of the roadheader performance.

The best daily advance (m/day)	9
The mean daily advance (m/day)	3.3
The best advance per shift (m/shift)	4.5
The mean advance per shift (m/shift)	2.1
The best weakly advance (m/week)	36.8
The mean weakly advance (m/week)	23.3
The best month advance (m/month)	106
The mean monthly advance (m/month)	81.7

Table 3. Mean compressive strength of the rock formation encountered during tunnel excavation.

Rock	Compressive strength (kg/cm^2 ± sd)
Limestone	1118 ± 240
Sandstone	557 ± 57
Siltstone	833 ± 71
Andesite	1200 ± 449
Diabase	770 ± 82

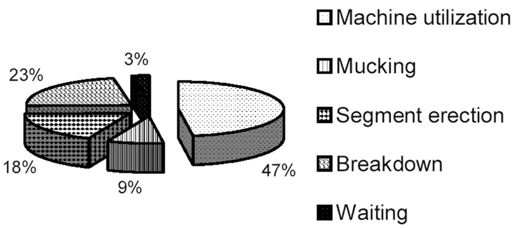

Figure 10. Overall performance of roadheader.

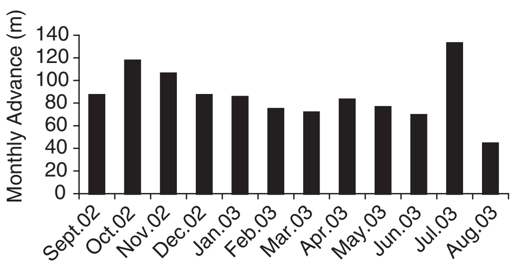

Figure 11. Monthly advance rate of roadheader.

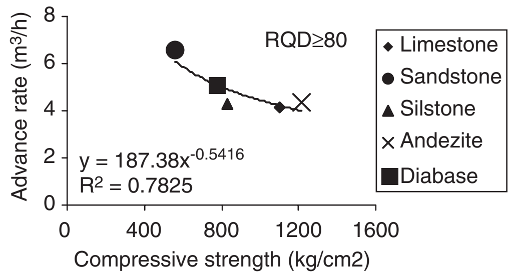

Figure 12. The variation of net cutting rate in different rock formations.

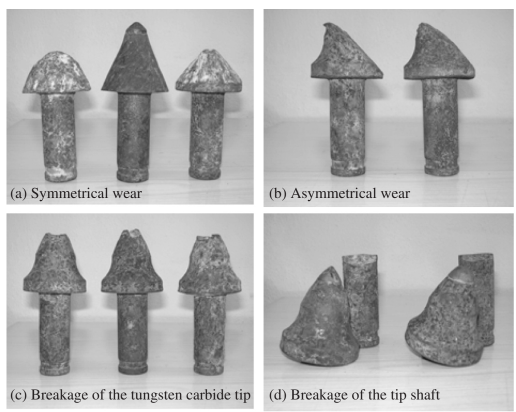

Figure 13. Classification of cutter wear in Küçüksu tunnel.

Figure 11. However, to be more precise, rock samples were collected continuously from tunnel face for testing in the laboratory. Limestone, sandstone, siltstone, andesite and diabase zones were encountered in tunnel route as noticed in Figure 4. The mean compressive strength values of different rock formations are given in Table 3. The relationship between compressive strength and advanced rate for RQD values grater than 80% is given in Figure 12. This verifies findings of different research workers (Scheider 1988; Gehring 1977–1988; Vehigashi et al. 1987).

It is strongly emphasized that the predicted cutting rate of roadheader as calculated in section 4 is very close to the actual value for limestone as seen in Figure 12.

However during the field studies, it is observed that geological discontinuities specially RQD values less than 50% and water income effect tremendously the advance rates as observed recently in Nuh cement factory tunnel (Bilgin 2004). Excavation of Küçüksu tunnel is an experience in high strength rocks with RQD values greater than 80% leading a tremendous problem in cutter consumption. Four types of cutter wear were experienced in tunnel excavation, symmetrical wear 36%, asymmetrical wear 17%, breakage of tungsten carbide tips 7% and breakage of the cutter shaft 40%. The classification of the cutter wear is illustrated in Figure 13 and 14.

Breakage of the tungsten carbide tips are mainly due to the close contact of tips to the shield of roadheader. Peak normal forces up to 3000 kg were observed during laboratory rock cutting tests. The main raison of breakage of the cutter shaft may due to high forces encountered during the roadheader excavation. As seen from Table 4, the mean cutter consumption is

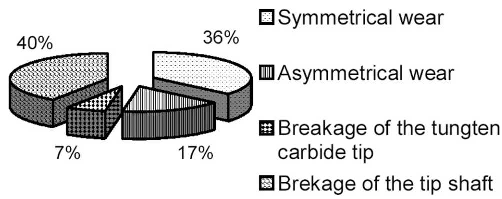

Figure 14. Classification of cutter wear in Küçüksu tunnel.

Table 4. The summary of cutter consumption.

Month	Formation	Cutter consumption (cutter/m^3)
September 02	Sandstone-Limestone	0.143
October 02	Limestone	0.264
November 02	Limestone-Diabase	0.305
December 02	Limestone-Siltstone	0.077
January 03	Limestone-Diabase	0.452
February 03	Limestone-Diabase	0.421
March 03	Limestone-Diabase	0.669
April 03	Limestone-Diabase	0.649
May 03	Limestone	0.390
June 03	Limestone	0.334
July 03	Limestone	0.180
August 03	Limestone	0.079
Total		0.330

0.33 cutter/m^3, varying from 0.077 cutter/m^3 in siltstone to 0.669 cutter/m^3 in limestone-diabase.

6 CONCLUSION

It is fact that the roadheaders are not recommended in high strength rock formations. However, the excavation of Küçüksu tunnel with a shielded roadheader of 90 kW of cutter power, showed that an instantaneous cutting rate of 5 m^3/h is possible to obtain in high strength rock formation having compressive strength values of more than 1000 kg/cm^2 with RQD values higher than 80%. The overall performance of the roadheader showed that machine utilization time of the roadheader was 47%. It is also important to note that the tool consumption is important disadvantage in excavating high strength rocks with peak values up to 0.7 cutter/m^3. Another important point emerging from this research study is that insitu cutting rate of roadheaders may be predicted from full scale cutting tests realized in the laboratory, using energy transfer ratio 0.40 from cutting head to rock formation.

7 ACKNOWLEDGMENT

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