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 an 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.

2 DESCRIPTION OF THE TUNNEL PROJECT

Küçüksu tunnel is apart of sewage project which is situated between Küçüksu and Hekimbaşı 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 m³/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 m³ 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 invert. In situ casted concrete
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/cm² 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/cm² and RQD 80–90%.

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

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).

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ICR = k \cdot \frac{P}{SE_{opt}}
\]  

(1)
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...
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 kg/cm² 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/m³. 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).

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
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 greater 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. This verifies findings of different research workers (Scheider 1988; Gehring 1977–1988; Vehigashi et al. 1987).

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.

Figure 11. Monthly advance rate of roadheader.
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

The authors are grateful to STFA Tunnel Construction CO authorities for permitting to access to the tunnel side for collecting data. The tremendous help of Prof. Dr. Levent Ozdemir from CSM EMI, USA is also acknowledgement for helping to construct and design the laboratory cutting rig.

### REFERENCES


