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From research to practice "Development of Rapid Excavation Technologies"

S. Eskikaya, N. Bilgin, C. Balci & H. Tuncdemir
Istanbul Technical University, Mining Engineering Department, Istanbul, Turkey

ABSTRACT: This paper is a summary of a research sponsored by NATO Sfs programme, on "Development of Rapid Excavation Technologies" for the Turkish mining and Tunneling Industries.

Full-scale cutting tests were carried out on rock samples collected from different tunneling sides and machine performance was predicted for each case due to a model developed using specific energy values. Tunnel boring machines application in Tuzla-Dragos Tunnel gave a unique opportunity to compare predicted and actual machine performance data.

An empirical model for the prediction of roadheaders and jackhammers performances was also created using a database collected from several tunnel excavation activities. This model makes possible to predict net cutting rate of a machine using power of the machine, rock compressive strength and RQD (Rock Quality Designation) of the rock formation.

A detailed research programme was carried out using numerical modeling software (Franc 2D/L) and a small scale rock cutting rig to investigate the effect of rock stresses on machine performance. Previously described cutting performance models for roadheaders were reevaluated using the results of numerical modeling and data cutting test results under stressed conditions.

Underground environmental measurements were taken in Istanbul Metro Tunnels and Middle Anatolian Lignite Mine to compare dust and noise levels accountered in tunnel drivages both with roadheaders and impact hammers.

1 INTRODUCTION

Turkey has a large potential for tunneling projects in both civil and mining industries. Nearly a total of 140 km/year of various tunnels are being constructed, including mine developments, drifts, raises and shafts, hydroelectric projects, underground storage, highway, metro, sewer and irrigation tunnels (Bilgin et al, 2000). However the advance rates, in many cases, are too small which necessitates new excavation technologies for more efficient tunneling. The primary goal of the research program described in this paper was significantly advance the current level of excavation technology utilized in the Turkish Mining and Civil Underground Construction Sectors to speed up project completion schedules, to reduce costs and improve worker health and safety. This goal was planned to be accomplished by conducting research in new excavation techniques and introducing them into the industry by field implementation of the research findings (Bilgin et al, 2000)

2 LABORATORY FACILITIES

Laboratory facilities were created under the specific purpose of providing the tunneling and mining industries with solid solutions to practical problems. The laboratories contain a selection of equipment that allows physical testing of every type of commercially available rock cutting or drilling tools at full scale and also, rock mechanics equipment, ventilation-health and safety equipment.

2.1 *Full scale linear cutting machine*

The linear cutting machine used includes a stiff reaction frame on which cutter and dynamometer (load cell) are mounted. The triaxial pillar-type dynamometer with 50 tons of thrust capacity monitors orthogonal forces acting on the cutter. The rock sample is cast in concrete within a heavy steel box to provide the necessary confinement during testing. A schematic drawing of the linear cutting machine used is presented in Figure 1.

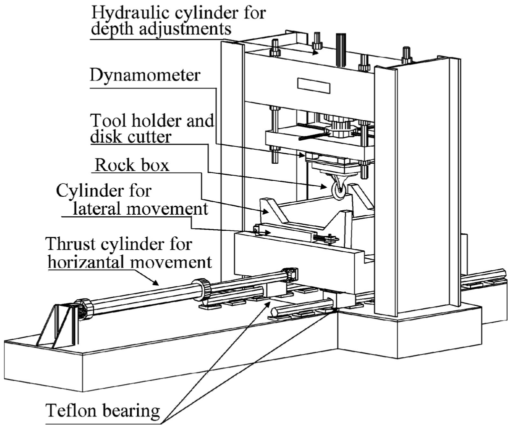

Figure 1. Schematic drawing of linear cutting machine.

A servo controlled hydraulic actuator forces the sample through the cutter at a preset depth of cut, width of spacing and constant velocity. The dynamometer measures the normal, drag, and sideways forces acting on the cutter during the cut. The rock box is moved sideways after each cut by a preset spacing to duplicate the action of the multiple cutters on a mechanical excavator.

The data acquisition system includes dynamometer, amplificator and personnel computer. The data acquisition card includes eight independent channels and monitors and collects data from the dynamometer. Data sampling/recording rate is adjustable up to 50,000 Hz. The recorded data is evaluated by a custom macro program.

2.2 *Horizontal drill rig*

The horizontal drilling rig is equipped with an electric motor of 132 kW and it is full hydraulic controlled. It is designed to have a maximum torque of 3500 kgm, a penetration rate of 0–60 m/h, maximum bit weight of 50 t and a maximum lateral thrust of 20 t. The experimental table may be easily accommodate the rock specimen in size of $1.5 \times 1.0 \times 1.0$ m. The rotational speed may be adjusted between 0–40 rpm or 0–80 rpm by connecting two hydraulic motors in series or parallel (Ergin et al, 2000, Kuzu et al, 1999).

2.3 *Small scale rock cutting rig*

This cutting test on small rock samples is discussed in details by McFeat and Fowell. The test results, which may be classified as index values, are evaluated according to previously accumulated field performance data (McFeat-Smith, Fowell, 1977–1979, Balci, 2004).

3 LABORATORY AND FIELD STUDIES TO IMPROVE THE PERFORMANCE OF TBM'S AND PERFORMANCE PREDICTION MODEL

One of the main factors governing the cutting efficiency of a tunnel boring machine is the optimum chip failure occurred between the cutting grooves during the cutting process and the laboratory full scale cutting tests give the unique opportunity to observe the chip failure under controlled conditions. As a basic rule of rock cutting mechanics, specific energy, defined as the energy consumed per unit volume of the excavated rock, is optimum for a given s/d (cutter spacing/cutting depth) ratio. Cutter spacing is a constant value of a TBM cutting head, which dictates that for a given rock formation the laboratory predetermined cutting depth will determine the optimum thrust force values of the excavating machine. In the light of these main rules, an intensive laboratory full scale cutting test program was planned to obtain the relationship between cutting depth and cutter force values, specific energy and s/d ratio for different type of cutters for Tuzla tunnel.

The compressive strength of the rock sample tested was $579 \pm 56\,\text{kg/cm}^2$, and tensile strength was $36 \pm 3\,\text{kg/cm}^2$

The relationship between rolling force, cutting force, thrust force and depth of cut, for unrelieved cutting for CCS disc cutter are shown in Figure 2.

Thrust force (FT mean thrust force, F'T mean peak force) may be defined as vertical cutter force; rolling force (FR mean rolling force, F′R mean peak rolling force) and cutting force may be defined as horizontal cutter forces.

The relationships between specific energy values and s/d (cutter spacing/cutting depth) ratios are given in Figure 3.

3.1 *Steps followed for machine performance prediction*

Steps followed for machine performance prediction are as follows; determine the basic characteristics of the TBM to be considered for the specific job (number of cutters, cutter spacing, thrust and torque available etc.), use full scale cutting test results to obtain specific energy values for optimum s/d (cutter spacing/cutting depth) ratio, obtain optimum thrust value of the machine using cutting depth – thrust force graph from number of cutters and mean rolling force, calculate the torque of the machine for a predetermined cutting depth, calculate the possible power consumption of the machine, calculate the possible excavation rate using optimum specific energy values and the estimated power consumption (Bilgin et al, 1999).

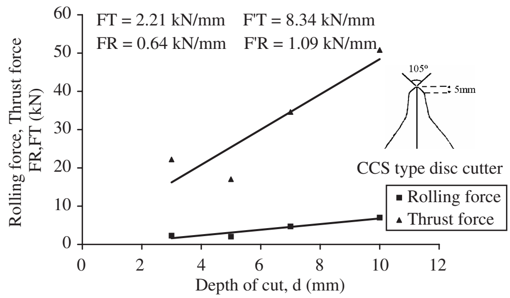

Figure 2. The relationship between rolling thrust forces and depth of cut.

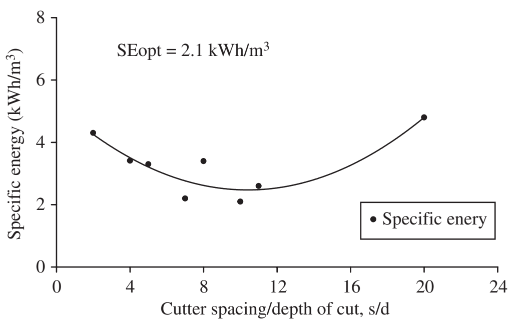

Figure 3. The relationship between specific energy and s/d ratios.

The TBM, which was in consideration for possible use in Tuzla–Dragos Tunnel was a double shielded Robbins 165-162/E 1080 machine, having diameter of 5 m, number of cutters 36, rotational speed 6 rpm, maximum thrust force 785 t, cutting head power 600 HP.

3.2 *Machine performance prediction*

- Optimum specific energy value from Figure 3 is SE = 2.1 kWh/m^3
- Optimum s/d value from Figure 2 is found to be between 8 and 10
- From machine specification cutter spacing is s = 7.5 cm
- For s/d = 8; d = 7.5/8 = 1 cm
- For s/d = 10; d = 7.5/10 = 0.8 cm
- From Figure 2 for CCS cutter type F′T = 8.34 kN/mm
- For d = 8 mm, total machine thrust is 36 × 8 × 8.34 = 2400 kN
- For d = 10 mm, total machine thrust is 36 × 10 × 8.34 = 3000 kN
- Total machine thrust must change between 2400 kN and 3000 kN
- Torque of the machine calculated from Table 1 using Equation 1:

$$\sum_{i=1}^{i=n} r_i XFR \tag{1}$$

where n = number of cutters; $r_{i=}$distance from the cutter to the center of the cutting head; FR is mean rolling force obtained from Table 1; for cutting depth of 8 and 10 mm.

- Torque for the cutting head for d = 8 mm, 36 × 1.375 × 8 × 0.64 = 253 kNm
  Torque for the cutting head for d = 10 mm; 36 × 1.375 × 10 × 0.64 = 317 kNm
- Expected power of the machine

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

In this Equation 2; P is in kW, N rpsec, T torque in kNm.

- Expected power of the machine for cutting depth of 0.8 mm.

$$P = 2\pi \frac{6}{60} x317\,kW ; P = 200\,kW$$

- Expected power of the machine for cutting depth of 10 mm.

$$P = 2\pi \frac{6}{60} x253\,kW ; P = 160\,kW$$

$$Net\,excavation\,rate(m^3/h) = k\frac{P(kW)}{SE(kWh/m^3)} \tag{3}$$

where k is energy transfer ratio, which is estimated to be around 0.7∼0.8, for the below calculations k = 0.8 is taken.

- Net excavation rate = 60∼70 m^3/h

In competent rock an average machine utilization factor of 30% and 16 hours working time per day will result a daily advance rate of

$$\frac{16hx60m^3x0.3}{hx\pi\frac{25}{4}m^2} \cong 15\,m/day$$

The predicted excavation rate is for competent rock, it is obvious that the geological discontinuities will increase the net excavation rate to a certain level and high amount of RQD or water income in rock formation with high amount of clay will decrease the daily advance rate due to regional collapses, face instability and chocking the cutters etc. These factors effected tremendously the advance rate of the TBM during Tuzla-Dragos tunnel drivages.

During field studies it is observed that the actual values were very close to predicted values (Bilgin, 1999).

4 FIELD STUDIES TO CREATE PERFORMANCE PREDICTION MODELS FOR ROADHEADERS AND IMPACT HAMMERS

Roadheaders and impact hammers have been widely used both in civil and mining industries since 1970. A contractor is always interested in predicting the machine performance prior to starting a tunnel project that will definitely define the tunnel drivage economy. The past few research works were focused on the prediction of the performance of roadheaders or TBM's from laboratory rock cutting tests. The work originated in Newcastle Upon Tyne University dealt with the correlation of in-situ data with the results of core cutting tests (McFeat-Smith, Fowell, 1977–1979). In that study the specific energy obtained from small scale rock cutting test was the key factor in the machine performance prediction. A more realistic model was developed by using full scale rock cutting test results in Earth Mechanics Institute of Colorado School of Mines by Ozdemir (Rostami, Ozdemir, Neil, 1994, Cigla, Ozdemir, 2000, Cigla, Yagiz, Ozdemir, 2001). However, the work described in this paper differs from the two previously mentioned in the fact that it is based on the statistical interpretation of the field data that has been collected since 1988 from different sewerage tunnels in Istanbul.

The model described in this paper only deals with the one aspect of performance prediction, i.e. instantaneous cutting rate defined as net cutting rate obtained when the machine is in cutting mode (Bilgin et al, 1988, Bilgin et al, 1990, Bilgin et al, 1997). The improved equations are stated below:

For roadheaders

$$ICR = 0.28P(0.974)^{RCMI} \tag{4}$$

For Impact hammers

$$ICR = 4.24P(RCMI)^{-0.567} \tag{5}$$

$$RCMI = \sigma_c \left(\frac{RQD}{100}\right)^{2/3} \tag{6}$$

Table 1. Actual and predicted cutting performance of roadheaders and impact hammers in selected zones in Istanbul Metro.

Zone	Excavator	Compressive strength MPa	RQD	Actual ICR m^3/h	Predicted ICR m^3/h
A	Roadheader	80	40	28	24
B	ATM 75	76	25	35	34
C		88	70	14	12
D	Roadheader	102	40	16	22
E	ET 250	94	30	25	31
F		110	60	11	12
G	Impact	118	70	10	11
H	Hammer	120	80	8	10
I	BRH 250	85	30	14	18

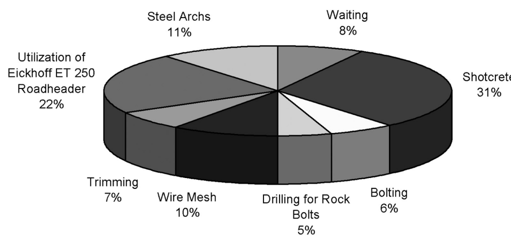

Figure 4. Overall performance of tunnel drivage in Taksim platform tunnel 2.

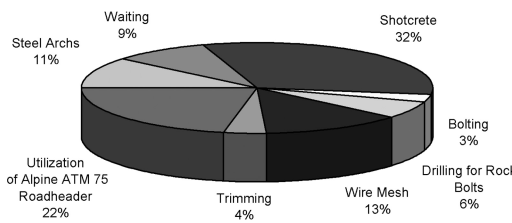

Figure 5. Overall performance of tunnel drivage in Taksim platform tunnel 1.

However it should be emphasized that equation 3 is improved using Schmidt hammer values (Bilgin et al, 2002).

In these equations; ICR = Instantaneous or net cutting rate in m^3/h; P = Cutting power of the machine in HP; $RCMI$ = Rock mass cuttability index; σ_c = Uniaxial compressive strength in MPa, RQD = Rock quality designation.

Different zones in Istanbul Metro were used to compare actual values and predicted values of net cutting rate as using Equations 4, 5 and 6. It is clearly seen from the relevant table 1 that the predicted values are

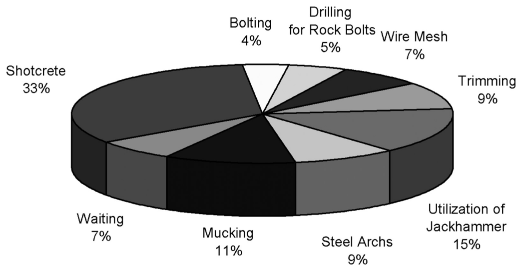

Figure 6. Overall performance of tunnel drivage in Levent line 2 tunnel.

very close to the actual values of net cutting rates suggesting that the model described by (Bilgin et al, 1996) is valid for both spiral and drum head roadheaders.

Overall performance of roadheaders and impact hammers are given in Figures 4–6.

5 STUDIES ON CREATING A MODEL TO PREDICT THE PERFORMANCE OF TUNNELING MACHINES UNDER STRESSED CONDITIONS

In the past, different models on performance prediction of different excavation machines were developed based on site observations, laboratory small- and full-scale cutting tests. However, it is important to note that none of these models takes into account the rock stresses for machine performance prediction.

First cutting experiment carried out by Pomeroy in different coal samples showed that a modest level of stress can close up the cleats in coal, making it more difficult to cut (Pomeroy, 1958). However it is reported by Roxborough and Phillips that experiments undertaken on a rock which was largely free of discontinuities, confining stress up to 200 kg/cm^2 was found no measurable effect on cutting force, normal force and specific energy (Roxborough et al, 1981). These studies are pioneering in their field and limited in number and only to unrelieved cutting conditions. During realization of the research programme described in this paper, it is decided that some laboratory rock cutting experiments under stressed conditions should be carried out in order to make clearer this phenomenon. A numerical model should also be run to support the findings of rock cutting experiments under stress conditions.

Several samples were needed for relieved and unrelieved cutting experiments. Two artificial materials, plaster and concrete were used during experiments to keep constant the homogeneity characteristic of the test material.

The stress analyses were performed using software 'Franc2D/L' (Swenson et al, 1997). It is a crack propagation simulator for two-dimensional layered structures. The finite element method is used in Franc2D/L to compute the stresses and displacements in an arbitrary structure subjected to arbitrary boundary conditions. The material is assumed to be linear elastic. Franc2D/L needs a pre-generated (initial) mesh. The initial meshes were developed using software 'Casca' (Swenson et al, 1997), which is distributed together with Franc2D/L.

A shaping machine equipped with a chisel pick having a rake angle of $-5°$ and width of 12.5 mm is used as a cutting rig. Tool cutting, normal and side force are measured using a triaxial piezoelectric. Lateral stresses are given to cutting samples with the aid of hydraulic pistons.

Numerical modeling showed that for unrelieved cutting lateral stresses dramatically decrease tensile stresses around the cutting groove up to a certain level of lateral stresses, in this case, a lateral stress of 1/5 or 1/4 of sample compressive strength in magnitude, causing an increase of around 60 percent in cutter force. However, for relieved cutting the effect of lateral stresses are less apparent, causing an increase in cutter force around 20 or 30 percent more than unstressed conditions. Experimental cutting tests justify the findings of numerical modeling used in this study. These results emphasize that specific energy values found in full-scale relieved cutting tests should be multiplied at least with a factor of 1.3 in performance prediction models, if tunnels under stresses are considered (Bilgin et al, 2000).

6 STUDIES ON THE ENVIRONMENTAL PROBLEMS OF TUNNEL EXCAVATION

The noise measurements in Istanbul Metro Tunneling works Phase 1, were carried out in 4. Levent shaft and associated tunnels of Sisli –4. Levent Line.

It is observed that the main source of the noise at the top of the shaft is ventilator given fresh air to the tunnels. The noise measured 1 m away from the ventilator was $L_{eq} = 88.6$ dBA. At different places of shaft plant the values of $L_{eq} > 80$ dBA were observed.

It is concluded that within a circle having a diameter of 10 m from the center of the ventilator, the daily working time for the workers should be limited to 3–4 hours if it is necessary. Otherwise the ventilator should be in operation under a noise proved environment and earring protectors should be given to the workers.

It is understood that the noise levels of $L_{eq} =$ 91 dBA where the excavators are working and the noise levels of $L_{eq} = 93.5$ dBA where the shotcrete equipment is working, reach to a dangerous level to effect negatively the hearing health of the workers (Okten et al, 1998).

Underground workers usually suffer greatly from the unfavorable environmental conditions of tunnel

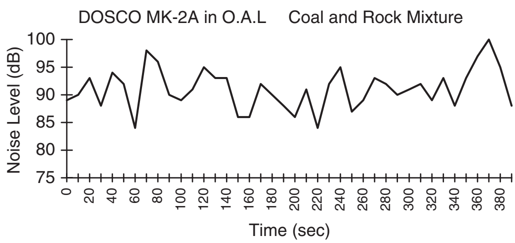

Figure 7. The variation of noise level with time in Middle Anatolian Lignite Mine.

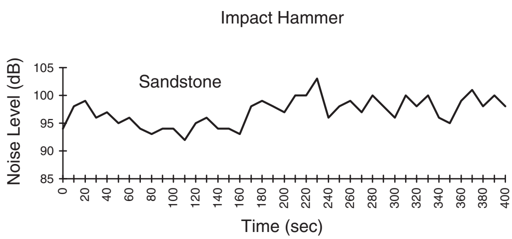

Figure 8. The variation of noice level with time in Istanbul Metro Tunnel.

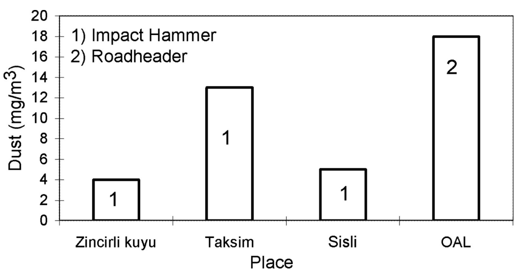

Figure 9. The variation of dust content in air in different tunnels.

projects, i.e., dust, noise, humidity etc. Underground measurements were taken during the past six months in Istanbul Metro Tunnels and Middle Annotation Lignite Mine. This gave an opportunity to compare dust and noise levels encountered in tunnel drivages both with roadheaders and impact hammers. Casella 113, a gravimetric dust collector and RS-103 sound level meter were used for in-situ measurements. The following Figures 7, 8 and 9 are the typical examples emerged from this investigation.

7 CONCLUSIONS

A detailed research programme carried out showed that, optimum specific energy obtained from full scale cutting tests using real life cutter may be used with confidence in predicting net cutting rate of TBM's or any mechanical excavators. However specific energy should be multiplied at least with a factor of 1.3 in performance prediction models, if tunnels under stresses are considered.

It is also demonstrated that rock mass cuttability index defined as a product of rock compressive strength and RQD may be used as a guide in predicting cutting and breaking rates of roadheaders and impact hammers.

Noise and dust are also main factors in an efficient working environment. Noise levels in impact hammers are as high as roadheaders. However dust generation in impact hammer is proved less than in roadheader application.

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