The Performance Prediction of a TBM in Tuzla - Dragos Sewerage Tunnel

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ABSTRACT: This paper deals with a detailed field and laboratory study concerning Tuzla-Dragos Sewerage Tunnel in İstanbul. First a brief description of the project is given and later the results of full-scale cutting tests, realized in the laboratory for performance prediction of a full-face tunnel-boring machine, are summarized. The equipment used for the tests is developed under NATO TU-Excavation Project in İstanbul Technical University, Mining Engineering Department. Rock samples were collected from tunneling side and different type of roller cutters and a conical bit were tested in the laboratory conditions and the performance of TBM was predicted using Specific Energy values obtained from cutting tests. In the second stage of the research program the in situ performance of the Robbins TBM is recorded and at the end the predicted performance values are compared with field values and some recommendations are made to tunnel contractors and practicing field engineer.

1 INTRODUCTION

The use of tunnel boring machines for underground construction has been increasing steadily for the last 30 years. However the efficient and economic use of these high capital cost machines, necessitates an intensive side and laboratory studies. The proper and correct machine performance prediction basically depends on the quality and quantity of the geological and geotechnical data collected before making the final decision. Several empirical and semi-empirical models were used in the past for TBM performance prediction, most widely used models being those developed by EMI (Earth Mechanics Institute of Colorado School of Mines), The University of Trondheim and Norwegian Institute of Technology (Lislerud 1988, Nilsen&Özdemir 1993, Rostami&Özdemir 1994, Johanessen 1995). Following these pioneering works, full scale laboratory rock cutting tests were used to predict the performance of a TBM which was planned to be operated in one the sewerage tunnels in Istanbul. The predicted and measured performance values of this machine are compared in this paper and some recommendations are made for further effective use of the full-scale rock-cutting test.

2 DESCRIPTION OF THE TUNNEL PROJECT

2.1 *General Outline*

Tuzla-Dragos Sewerage Tunnel, situated in the Asian Side of Istanbul, is a part of a complex project covering the area of Kartal-Pendik and Tuzla. Tunnels completed by STFA Construction Company are found between X-X3 shaft and Kemiklidere pump station and have a total length of 6490m and final diameter of 4.5m. The plan of the project area is shown in Figure 1. The tunnels between X1-X3 and K1 shafts are opened with Robbins TBM Model 165-162 having a diameter of 5m. Typical cross section of the TBM driven tunnel is illustrated in figure 2.

2.2 *Geology*

The main rock formation in the area is Lower Devonian aged Kartal formation composed of shale and limestone. In the upper levels there is Pliocene aged Belgrad Formation of sand, gravel and silt, and Quaternary aged sediments. Diabase dykes of Cretaceous ages cut Kartal Formation in several places. The tunnels between X1-X3 and K shafts are mainly driven within limestone and shale. Limestone of gray-blue in color is in medium thickness, sandy and fractured in several places, shale of dark gray-black in color is carbonated, mainly jointed and laminated.

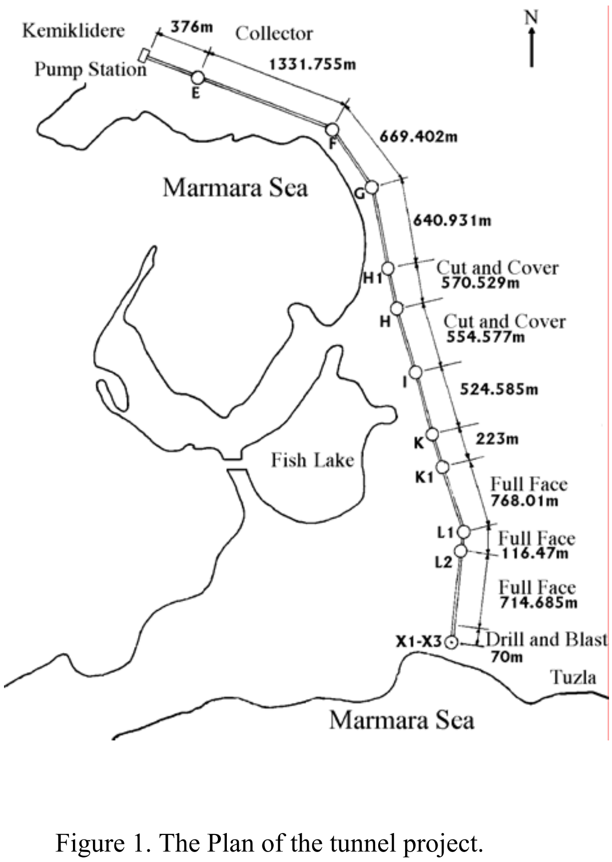


Figure 1. The Plan of the tunnel project.

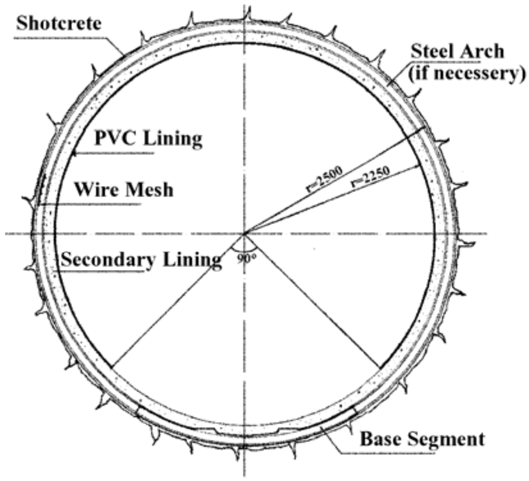


Figure 2. Typical cross-section of TBM driven tunnel.

3 LABORATORY CUTTING TESTS

3.1 *Main objectives*

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.

3.2 *Description of the full-scale cutting rig*

The general view of the full-scale cutting rig is given in Figure 3.

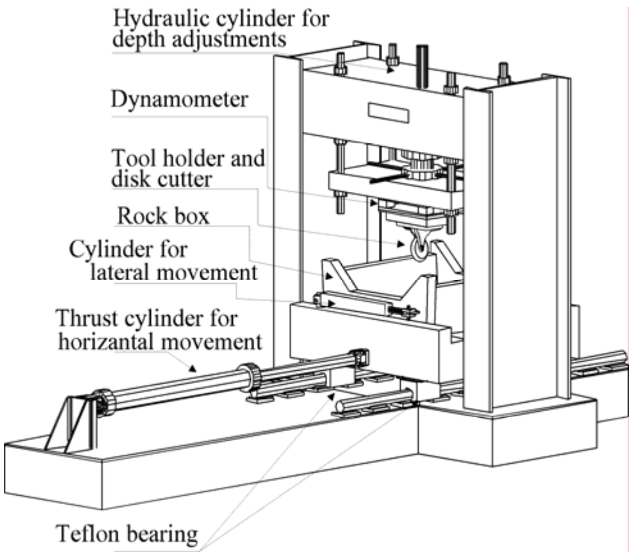


Figure 3. The general view of the full-scale cutting rig.

The rig is designed and manufactured within the NATO-TU Excavation Project with a tremendous technical help from EMI, Colorado School of Mines. It can accommodate rock samples up to 0.7x0.7x1 m in size. An high quality aircraft aluminum block equipped with strain gages is used as a dynamometer to record thrust forces up to 50 tons and rolling forces up to 20 tons and a data acquisition system, which is used to record the cutter forces in three directions. The hydraulic cylinders can move the rock samples in horizontal and lateral directions for adjusting cutter spacing and realizing the cutting action. The rock samples are casted within rock boxes in order to eliminate pre-failure of the rock specimen. The cutter is fixed with a tool holder directly to the dynamometer.

3.3 *Test procedure and results*

A Sandvik S 35/80H type conical bit and two different types of disc cutters were used throughout the experiments for comparative studies. The profiles of V type and constant cross section discs are shown in Figure 4.

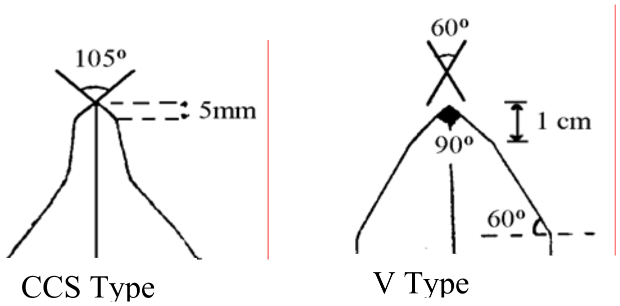


Figure 4. The profiles of V type and constant cross section disc cutters

The compressive strength of the rock sample tested was 579±56 kg/cm^2, and tensile strength was 36±3 kg/cm^2

The relationship between rolling force, cutting force, thrust force and depth of cut, for unrelieved cutting for different cutters are shown in Figure 5 and 6 and the mean values are summarized in Table 1.

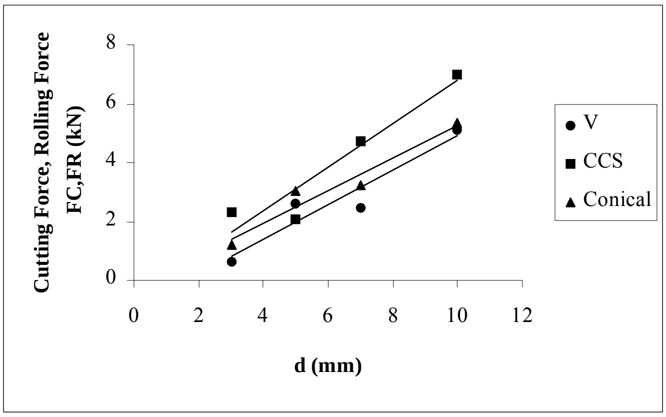


Figure 5. The relationship between rolling force and depth of cut

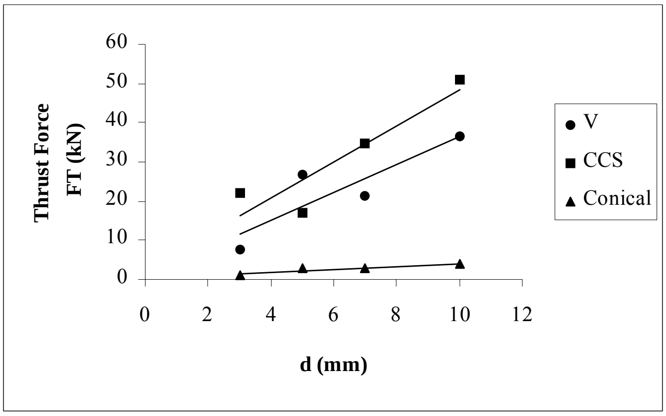


Figure 6. The relationship between thrust force and depth of cut

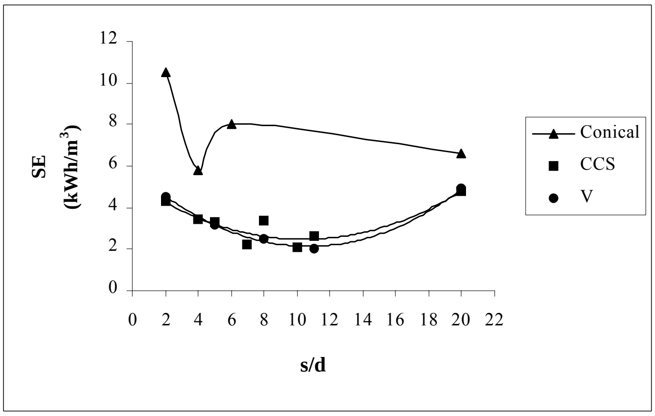
Table 1. The summary of the cutting test results

Type of cutters	Conical bit	V type	CCS type
F_T (kN/mm)	0.44	3.65	5.21
F'_T (kN/mm)	1.78	5.84	8.34
F_R, F_C (kN/mm)	0.49	0.40	0.64
F'_R, F'_C (kN/mm)	1.57	0.72	1.09

In Table 1 F_T is mean thrust force, F'_T is peak thrust force, F_R is mean rolling force, F'_R is peak rolling force for disc cutters, F_C and F'_C is mean and peak cutting forces for conical bit tested.

Thrust force may be defined as vertical cutter force; 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 7.

Figure 7. The relationship between specific energy and s/d ratios

As seen in Figure 7 the optimum specific energy values for conical bits are obtained for s/d ratio of 4 and for V profile and CCS profile discs the optimum values are obtained for s/d ratios of between 8 and 10, with relevant specific energy values of 5.8 kWh/m^3 and 2.1 kWh/m^3. As a long discussion between the responsible persons of the construction company and research team, the CCS disc cutters were chosen for the tunnel excavation since they have longer cutting life and necessitated as lowest specific energy values as than the other cutters.

4 TBM PERFORMANCE PREDICTION IN A COMPETENT ROCK

4.1 *Steps followed for machine prediction*

Steps followed for machine 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.

4.2 *Specifications of the TBM selected for TUZLA – DRAGOS tunnel drivage.*

The TBM, which was in consideration for possible use in Tuzla – Dragos Tunnel was a double shielded Robbins 165-162/E 1080 machine. The tool configuration of the cutting head is shown in Figure 8 and machine specifications are given in Table 2

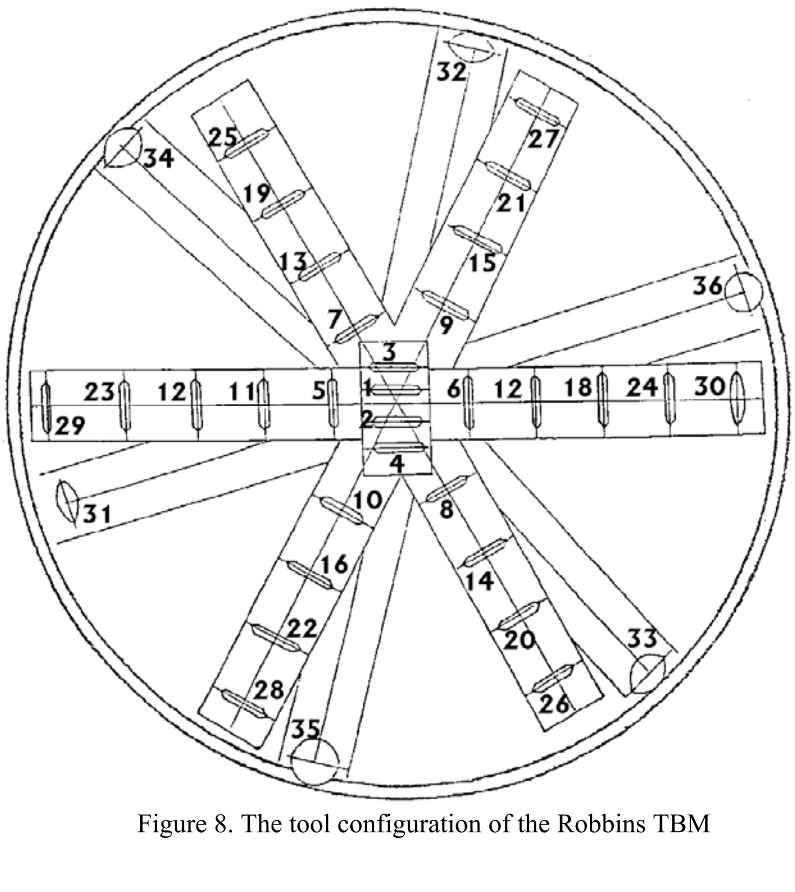


Figure 8. The tool configuration of the Robbins TBM

Table 2. The specification of the Robbins 165-162 / E1080 TBM

Property	Values
Machine diameter	5.0 m
Number of cutters	36
Rotational speed	6 rpm
Normal thrust force	471 tons
Maximum thrust force	785 tons
Cutting head power	600 HP
Power of the miscellaneous pumps etc.	285 HP
Conveyor belt capacity	476 m^3/h
Electrical transformer	1000/380V-50Hz

4.3 *Machine performance prediction*

- Optimum specific energy value from Figure 7 is SE=2.1 kWh/m^3
- Optimum s/d value from Figure 7 is found to be between 8 and 10
- From machine specification cutter spacing is s=7.5cm
- For s/d= 8; d=7.5/8=1cm
  For s/d=10; d=7.5/10=0.8cm
- From Table 1 for CCS cutter type F'_T=8.34 kN/mm
  For d=8mm, total machine thrust is 36×8×8.34=2400 kN
  For d=10mm, total machine thrust is 36×10×8.34=3000 kN
- Total machine thrust must change between 2400 kN and 3000kN

$$\sum_{i=1}^{i=n} r_i x F_R \qquad (1)$$

- Torque of the machine

In this equation n= number of cutters, r_i= distance from the cutter to the center of the cutting head, F_R is mean rolling force obtained from Table 1, for cutting depth of 8 and 10 mm.

- Torque for the cutting head for d=8mm, 36x1.375x8x0.64= 253kNxm,
  Torque for the cutting head for d=10mm; 36x1.375x10x0.64= 317kNxm.
- Expected power of the machine

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

In this equation P is in kW, N rpsec, T torque in kNxm.

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

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

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

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

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

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

$$\frac{16\,h \times 60\,m^3 \times 0.3}{h \times \pi \frac{25}{4}\,m^2} \cong 15\ \text{m/day}$$

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. Due to do complexity of the problem these factors will be discussed in other technical paper, which is planned to be published in Paris, AFTES, international conference (25/28 October 1999).

5 INSITU OBSERVATIONS, COMPARISION OF PREDICTED AND MEASURED PERFORMANCE VALUES

Eleven different zones were chosen for in situ observation of the TBM performance in Tuzla – Dragos tunnel. It is paid a special attention to the fact that the rock formation in selected zones should have similar mechanical properties with those tested in full scale cutting rig. Measured and predicted values are compared in Table 3.

Table 3 Comparison of predicted and measured TBM performance values.

Selected Date	Zone Tunnel (km)	Disc Cutting Depth (mm)	Measured F′T kN./disc	Predicted F′T kN/disc	Measured Net cutting rate m^3/h	Predicted Net cutting rate m^3/h
14.10.1997	172.7	11	73.9	91.3	71	80
15.10.1997	175.3	7	69.8	58.1	49	53
16.10.1997	190.2	8	69.9	66.4	57	61
17.10.1997	194.0	9	72.3	75.1	64	60
28.10.1997	225.6	7	59.3	58.1	49	53
30.10.1997	227.9	10	117.2	83.0	71	70
04.11.1997	251.3	8	111.2	66.4	57	61
11.10.1997	272.1	11	123.7	91.3	71	80
13.11.1997	275.4	9	89.0	75.1	64	60
14.11.1997	275.4	13	126.2	107.8	92	74
18.11.1997	284.5	8	96.0	66.4	57	61

A statistical analysis was carried out in order to see whether the predicted values were significantly different from the actual values. One of the most common test in determining whether one process is different from another is the student's t-Test based on comparison between pair of values. The closer to zero the total of differences lies, the grater the degree of statistical

confidence, which can be attached to the statement that there is no difference between the sets of data.
We reject the hypothesis of no difference and conclude that two sets of data are different when the calculated value of "t" is greater than the tabulated values of "t". The calculated student's t-Test values for thrust force value is 0.096 and for net cutting rate is 0.835, so referring to standard tables of "t" values, we may conclude that we are 95% confident that there is not a statistical difference between predicted and measured values of disc thrust force and net cutting rate.

6 CONCLUSIONS

One of the most important factors effecting the cutting efficiency of a TBM is the proper chip formation between the disc cutters which is dictated by cutter spacing and machine thrust force. Specific energy, defined as the energy consumed per unit volume of excavated rock, is optimum for a given s/d (cutter spacing/cutting depth) ratio. A given cutter depth means a predetermined machine thrust force. As a basic rule of rock cutting mechanics it may be easily stated the proper chip failure is only obtained for optimum s/d ratios. For the performance prediction of a TBM in Tuzla-Dragos sewerage tunnel, full-scale cutting tests were carried in the laboratory in order to obtain the relationships between cutter force and depth, specific energy and s/d ratios. These relationships were latter used to predict net cutting rate of the TBM and the necessary machine thrust values for efficient cutting. In the second stage of the research program the in situ performance of the TBM is recorded, predicted and measured values are compared. It is concluded that there is not a statistical difference between predicted and measured values of net excavation rate and disc thrust force. However it is important to note that full performance of a TBM or daily advance rate is a complex matter which is mainly depend on the cutting efficiency of the machine, job organization, the experience of the contractor, skill of the operator, unexpected geological conditions, machine available time and machine utilization time. The reader of this paper should bear in mind that only net excavation rate in m^3/h (the volume of the rock excavated per hour during the excavation process of the TBM) and optimum cutter thrust forces are predicted within the main frame of the research program.

7 ACKNOWLEDGEMENT

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REFERENCES

Johanessen, O., 1995. *Hard rock tunnel boring*, University of Trondheim, The Norwegian Institute of Technology 165.
Lislerud, 1988. *Hard rock tunnel boring, prognasis and costs*. Tunneling and Underground Space Technology, 3:9-17
Nilsen, B., Ozdemir L., 1993. *Hard rock tunnel boring prediction and field performance*, RETC, Boston: 13-17
Rostami, J., Ozdemir, L.,. Neil, M.D., 1994. *Performance prediction, a key issue in mechanical hard rock mining*. Mining Engineer, 11, 1263-1267.