PERFORMANCE PREDICTION AND COMPARISON WITH IN-SITU VALUES OF A TBM: A CASE STUDY OF OTOGAR-BAGCILAR METRO TUNNEL IN ISTANBUL

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INTRODUCTION

Istanbul is a very fast developing city with more than 14 millions of population. Tunnelling activities like metro, sewerage and water tunnels are increasing tremendously and at the end of 2009 it is planned that around 23 TBMs with different diameters will be working in the city. The total cost of the current tunnelling projects is calculated to be around 10 Billion US Dollars. The geology of Istanbul is complex for tunnelling projects due to tectonic activities, faults, dacite and andesite dykes and several joint sets causing many serious problems during tunnel excavations. A great effort is spent by the authors of this paper to collect data concerning the performance of mechanized excavation systems related to geology and rock mass properties in order to have guidelines for the future tunnel projects. The results of the research carried out for Otogar-Bagcilar Metro line are evaluated in this respect. The general alignment of the metro tunnel is given in Figure 1.

This study is about determination of some design parameters and performance prediction of tunnel boring machines (TBM) using full-scale rock cutting test in the main rock formation encountered in Otogar-Bagcilar Metro Tunnels. 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. A rock sample with minimum size of 1.0 x 0.5 x 0.7 m is obtained from Kirklareli Formation (fossilated limestone) along the tunnel line. The rock sample is subjected to full scale laboratory cutting tests with different depth of cut and cutter spacing values using a 15 inch (381 mm) V-Type disc cutter. Cutter forces, i.e., thrust force, rolling force, and specific energy values are recorded for each cut. In the second stage of the study program the in situ performance of the Lovat TBM is recorded and at the end the predicted performance values are compared with field values and some recommendations are presented to tunnel contractors and practicing field engineer.

EXPERIMENTAL TECHNIQUES, PROCEDURES AND LABORATORY STUDIES

Mechanical properties of the rocks tested

Uniaxial compressive strength, Brazilian tensile strength and density of the rock samples are performed based on ISRM suggestions (Brown, 1981). Uniaxial compressive strength tests are performed on trimmed core samples having a length to diameter ratio of 2. The loading rate is applied within the limits of 0.5-1.0 kN/s. Brazilian tensile strength tests are conducted on core samples having a length-to-diameter ratio of 1. Geomechanical parameters of the rock samples used in laboratory tests are given in Table 1.
Table 1. Physical and mechanical properties of the fossilated limestone

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>2.41 ± 0.04</td>
</tr>
<tr>
<td>Uniaxial compressive strength (kg/cm$^2$)</td>
<td>319.0 ± 148</td>
</tr>
<tr>
<td>Brazilian tensile strength (kg/cm$^2$)</td>
<td>39.4 ± 15.0</td>
</tr>
<tr>
<td>Cerchar abrasivity index</td>
<td>0.75 ± 0.4</td>
</tr>
</tbody>
</table>

Description of full scale cutting rig and rock cutting test

The full scale cutting rig established in the laboratories of ITU Mining Engineering Department and used in the experiments is given in Figure 2a. The box accommodating the rock samples up to 1.0 x 0.5 x 0.7 m can be moved horizontally to adjust cutter spacing and depth of cut is adjusted by a hydraulic cylinder by vertical movement. The aluminum dynamometer equipped with strain gauges has a capacity of 50 tons of thrust force (Bilgin et al., 1999; 2006). The following parameters used in evaluating V type disc cutting performance are illustrated in Figure 2b.

$s$ : Cutter Spacing, cm  
$d$ : Cutter Penetration, cm  
$FR$ : Mean Rolling Force, kgf  
$FN$ : Mean Thrust Force, kgf  
$FR'$ : Peak Rolling Force, kgf  
$FN'$ : Peak Normal Force, kgf  
$SE$ : Specific Energy, kWh/m$^3$

Experimental procedure and the results

A V-type disc having diameter of 15 inches is used in rock cutting experiments. The cutter spacing is kept at 7.5 cm throughout the experiments. The experiments are realized in unrelieved mode where there is not any interaction between the cutters and in relieved mode where there is interaction between cutters. The cutting results are summarized in Figures 3 and 4 (Bilgin et al., 2008).
Fig. 2. General schematic view of the full-scale rock cutting rig (a) and design parameters of disc cutters (b)

Figure 3. The relationships between s/d (cutter spacing / cutter depth of cut) ratio and specific energy for cutting limestone (spacing=75 mm).

Figure 4. The relationships between depth of cut and laboratory normal, rolling forces and specific energy for cutting limestone in relieved mode (spacing=75 mm).
ESTIMATING PERFORMANCE PARAMETERS OF THE TBM

The rolling force, normal force and specific energy values are obtained for different cutter spacing (in this study 75 mm) and depth of cut values. Machine specifications such as thrust, torque and power are estimated based on the cutter forces. The net cutting rate of TBM is estimated based on the relationship between optimum s/d ratio and specific energy.

Determination of TBM thrust

Total thrust equation (1) can be used to estimate TBM thrust force.

\[ FT = N_c \cdot FN \cdot f_L \]

where:

- \( FN \): mean thrust force one disc cutter (kgf/disc)
- \( f_L \): a coefficient for frictional losses; usually 1.2
- \( N_c \): number of discs (46 for this TBM)

As seen from Figure 3, optimum s/d ratio is obtained as 6.3. This indicates that optimum depth of cut (d) per revolution of cutterhead is 12 mm (Optimum s/d = 6.3, for s = 75 mm, d = 75 / 6.3, d = 12 mm). From Figure 4 for 12 mm depth of cut mean thrust force and peak thrust force are found to be 9843 and 17151 kgf, respectively. Mean and peak thrust forces of the TBM is calculated as follows.

\[
\sum_{n=1}^{46} FN = 46 \times 9843 \times 1.2 = 543339\, kgf = 543t = 5325\, kN
\]

\[
\sum_{n=1}^{46} F'N = 46 \times 17151 \times 1.2 = 946735\, kgf = 947t = 9278\, kN
\]

Determination of TBM torque

Total torque equation (2) can be used to estimate TBM torque

\[ T = \frac{N_c \times FRx D_{TBM} x f_L}{4} \]

where:

- \( T \): cutterhead torque (kgm)
- \( FR \): mean rolling force for one disc cutter (kgf/disc)
- \( D_{TBM} \): diameter of the cutterhead (6.52 m)
- \( f_L \): a coefficient for frictional losses; usually 1.2

For optimum s/d, mean rolling force and peak rolling force are found to be 1225 kgf and 2610 kgf, respectively from Figure 4. Mean and peak torque values of the TBM may be calculated as follows.

\[
T = \sum_{n=1}^{46} FRx \frac{D_{TBM}}{4} x f_L
\]

\[
T = \sum_{n=1}^{46} F'Rx \frac{D_{TBM}}{4} x f_L
\]

\[
T = \sum_{n=1}^{46} 1225x \frac{6.52}{4} x 1.2 = 110221\, kgm = 1080\, kNm
\]

\[
T = \sum_{n=1}^{46} 2610x \frac{6.52}{4} x 1.2 = 234837\, kgm = 2301\, kNm
\]
**Determination of TBM power**

The power in optimum cutting conditions is calculated by taking the mean values of torque. The power requirement of TBM may be calculated with Equation (3) as follows.

\[
P = 2\pi \frac{RPM \cdot T}{60}
\]

where;
- \( P \): cutting power (kW)
- \( RPM \): rotational speed of cutterhead (3.2 rpm in this study)
- \( T \): cutterhead torque (kNm)

\[
P = \frac{2\pi \times 3.2 \times 1080}{60} = 362\text{kW}
\]

**Determination of net cutting rate and daily advance rate**

Rostami observed a method to calculate net cutting rate of TBM using optimum specific energy obtained from laboratory rock cutting tests. This method uses machine installed power, total system efficiency and the specific energy required a particular rock type with a certain type of tool (Rostami et al., 1994). Net cutting rate [Equation 4] and daily advance rate [Equation 5] and their calculations are given below.

\[
ICR = k \times \frac{P}{SE_{opt}}
\]

where;
- \( ICR \): net cutting rate (m³/h)
- \( P \): power consumed in optimum condition (kW)
- \( k \): energy transfer ratio from cutterhead to tunnel face usually taken as 0.8-0.9 for TBMs (Rostami et al. 1999)
- \( SE_{opt} \): optimum specific energy (kWh/m³)

\[
ICR = 0.8 \times \frac{362\text{kW}}{3.5\text{kWh/m³}} = 83\text{ m³ / h}
\]

\[
DAR = \frac{ICR \cdot a \cdot h \cdot \text{MUT} \cdot 4}{\pi \cdot D_{TBM}^2}
\]

where;
- \( DAR \): daily advance rate (m/day)
- \( ICR \): net cutting rate (m³/h)
- \( a \): working shifts per day
- \( h \): working hours per shift
- \( \text{MUT} \): machine utilization time (%40)
- \( D_{TBM} \): diameter of the cutterhead (6.52 m)

\[
DAR = \frac{82.7 \times 2 \times 10 \times 0.4 \times 4}{\pi \times 6.52^2} = 20 \text{ m / day}
\]
FIELD STUDIES AND TBM PERFORMANCE

Otogar Bagcilar Metro Tunnel is a part of the transporting project of the European part of Istanbul. The 6.52 m diameter mixed ground earth pressure balance (EPB) tunnel boring machine is used to excavate at Guney Sanayi Station in Basaksehir, Bagcilar Metro tunnels during this study. The geological conditions of the general area consisted of soft ground, primarily clays, silts and sands. Between Basaksehir and Bagcilar stations the geology is called Kirklareli Formation. The Kirklareli formation is represented by hard and dense limestone and includes some fossils. The tunnel was excavated using shielded Lovat TBM of which cutterhead and design parameters are shown in Figure 5 and technical specifications of are given Table 2.

![Figure 5: Lovat TBM cutterhead and design parameters](image)

### Table 2. Basic technical specifications of the TBM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine diameter</td>
<td>6.52 m</td>
</tr>
<tr>
<td>Number of Cutters</td>
<td>8 centre + 30 single + 8 corner = 46</td>
</tr>
<tr>
<td>Total thrust capacity</td>
<td>780-1355 tons</td>
</tr>
<tr>
<td>Cutterhead Drive</td>
<td>Electric Motors</td>
</tr>
<tr>
<td>Cutterhead Power</td>
<td>1160 kW</td>
</tr>
<tr>
<td>Cutterhead Rotational Speed</td>
<td>0-3.2 rpm</td>
</tr>
<tr>
<td>Cutterhead Torque</td>
<td>2610-3597 kNm</td>
</tr>
<tr>
<td>Thrust Cylinder Stroke</td>
<td>1.5 m</td>
</tr>
<tr>
<td>TBM Weight (approx.)</td>
<td>567 tons</td>
</tr>
<tr>
<td>Average cutter spacing</td>
<td>75 mm</td>
</tr>
</tbody>
</table>

The TBM performance data is recorded continuously by the contractor, Gulermak-Dogus Joint Venture using a data acquisition system equipped within the TBM. The field data analyzed in this study is collected during excavation of the tunnel in Kirklareli Formation.

The operational parameters of the TBM such as rotational speed, torque, advance rate, and thrust are recorded by the machine data logger and analyzed as ring by ring. Analyzed data includes totally 262 rings at 16 days (366.8 m) in Guney Sanayi station. All the analyzed data is summarized in Table 3.
Table 3. TBM field data parameters

<table>
<thead>
<tr>
<th>Date</th>
<th>Total ring</th>
<th>Total excavation time (minute)</th>
<th>RPM (rev/min)</th>
<th>Torque (kNm)</th>
<th>Thrust (kN)</th>
<th>ICR (m³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008-10-25</td>
<td>18</td>
<td>821</td>
<td>2.7</td>
<td>2514</td>
<td>14638</td>
<td>62</td>
</tr>
<tr>
<td>2008-10-26</td>
<td>12</td>
<td>537</td>
<td>2.6</td>
<td>2639</td>
<td>15904</td>
<td>63</td>
</tr>
<tr>
<td>2008-10-27</td>
<td>7</td>
<td>153</td>
<td>2.8</td>
<td>2030</td>
<td>10769</td>
<td>130</td>
</tr>
<tr>
<td>2008-10-31</td>
<td>17</td>
<td>718</td>
<td>2.9</td>
<td>1933</td>
<td>11576</td>
<td>67</td>
</tr>
<tr>
<td>2008-11-01</td>
<td>22</td>
<td>904</td>
<td>3.0</td>
<td>2002</td>
<td>12634</td>
<td>69</td>
</tr>
<tr>
<td>2008-11-02</td>
<td>7</td>
<td>238</td>
<td>3.0</td>
<td>2074</td>
<td>14391</td>
<td>83</td>
</tr>
<tr>
<td>2008-11-03</td>
<td>22</td>
<td>702</td>
<td>2.9</td>
<td>1789</td>
<td>10431</td>
<td>89</td>
</tr>
<tr>
<td>2008-11-04</td>
<td>25</td>
<td>718</td>
<td>2.9</td>
<td>1918</td>
<td>10646</td>
<td>99</td>
</tr>
<tr>
<td>2008-11-05</td>
<td>19</td>
<td>655</td>
<td>3.0</td>
<td>1968</td>
<td>13631</td>
<td>82</td>
</tr>
<tr>
<td>2008-11-06</td>
<td>7</td>
<td>307</td>
<td>3.0</td>
<td>2164</td>
<td>15044</td>
<td>65</td>
</tr>
<tr>
<td>2008-11-08</td>
<td>12</td>
<td>417</td>
<td>3.0</td>
<td>1818</td>
<td>13008</td>
<td>81</td>
</tr>
<tr>
<td>2008-11-09</td>
<td>22</td>
<td>758</td>
<td>3.0</td>
<td>1979</td>
<td>12495</td>
<td>82</td>
</tr>
<tr>
<td>2008-11-10</td>
<td>19</td>
<td>759</td>
<td>3.0</td>
<td>2075</td>
<td>13307</td>
<td>71</td>
</tr>
<tr>
<td>2008-11-11</td>
<td>17</td>
<td>808</td>
<td>3.0</td>
<td>2184</td>
<td>14764</td>
<td>60</td>
</tr>
<tr>
<td>2008-11-12</td>
<td>18</td>
<td>849</td>
<td>3.0</td>
<td>1890</td>
<td>15562</td>
<td>60</td>
</tr>
<tr>
<td>2008-11-13</td>
<td>18</td>
<td>877</td>
<td>3.0</td>
<td>1872</td>
<td>8015</td>
<td>58</td>
</tr>
<tr>
<td>AVERAGE</td>
<td></td>
<td>2.9</td>
<td>2053</td>
<td>12926</td>
<td>76</td>
<td></td>
</tr>
</tbody>
</table>

The average instantaneous cutting rate is found 76 m³/h in the field at 2.9 rev/min of the cutterhead. The net cutting rate is very close to the predicted TBM performance values of the laboratory linear rock cutting tests. The average torque and thrust force are found 2053 kNm and 12926 kN, respectively in the field. Peak torque and thrust values of the LCM are close to the field values of the TBM.

CONCLUSIONS
This paper is a typical example to direct application of laboratory full scale rock cutting tests to one of the biggest Metro tunnels project in Istanbul. Full scale rock cutting tests are realized in the laboratory to calculate the basic design parameters of TBM. Field data are collected carefully in order to compare predicted and actual values of TBM operational parameters. Full scale cutting tests with disc cutters are performed for this purpose. The laboratory cutting test results in competent rock formations are in good agreement with actual values. It is proved that laboratory full scale cutting tests are very useful tool in determining design parameters and performance prediction of a TBM for a specific job.

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