Earth Pressure Balance Machine Cutterhead Torque Modeling: Learning from Machine Data

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ABSTRACT
This paper characterizes earth pressure balance machine (EPBM) torque within the context of a physical model using data from a recent Seattle metro-sized (6.44 m diameter) tunnel project. The paper examines the ability of relatively simple physical models to capture torque, and characterizes relative influence of geology, soil conditioning, pressure and other parameters on measured torque. The physical torque model developed for the analysis grossly overestimates the realized torque by 50 – 500%, even with assumed shear strength reductions of 50% due to disturbance and conditioning. The shear strength reduction required to fit the model with measured torque were 65-70% reduction for sand and 80-85% for silt and clay.

INTRODUCTION
Cutterhead torque is one of the main driving parameters TBM operators take into account when advancing an EPB machine (EPBM) (Ates et al. 2014). Accurate prediction of cutterhead torque is crucial to the design and operation of an EPBM. In addition, cutterhead torque may hold information about the ground conditions. Therefore, there is motivation to understand how the cutterhead torque is influenced by geological conditions.

A number of performance models such as Rostami et al. (1996) and Cigla & Ozdemir (2000) exist in hard rock TBM tunneling that are used to predict operational parameters such as cutterhead torque, thrust force, advance rates and so on, but the same is not true in soft ground pressurized face tunneling. The hard rock models have an understanding of the relationship between TBM performance and ground properties. The same is not true for pressurized face TBMs as very little research has been performed to relate the ground conditions to machine parameters such as cutterhead torque. Often when high cutterhead torque is encountered, the TBM operator will alter driving parameters such as reducing the advance rate, addition of soil conditioning agents at the TBM face, and increasing cutterhead rotation speeds. These adjustments are often done at the operator’s discretion, and not based on the understanding of the mechanics or soil-structure interaction of the TBM and the ground or how the TBM parameters directly influence the cutterhead torque.

An empirical model \( T (kN-m) = \alpha D^3 \), where \( D \) (m) is the cutterhead diameter and \( \alpha \) is an empirical constant ranging from 9-25 kPa, is often used in the design of torque capacity for EPBMs (Krause 1987). This method disregards geological parameters and is a function of the TBM diameter and an empirical coefficient. More recently, Shi et al. (2011) and Wang et al. (2012) developed analytical expressions based on a physical model to predict EPBM torque. These approaches attempt to relate the geological conditions with cutterhead torque. The limitation in these developments is that expressions were developed using laboratory data, specifically from a 1.8-m diameter EPBM test rig. Such expressions have not been applied to field size TBMs and ground conditions.

This paper presents the results of an investigation of EPBM torque estimation using a combination of analytical modeling and field data. A modified Shi model is employed to account for arching-reduced overburden stress and face pressures, as well as reduction in shear strength due to soil conditioning. The analytical model is examined using data from the 2011-13 University Link (U-Link 230) metro tunnel construction project in Seattle, WA.
BACKGROUND

University Link U230 and Hitachi Zosen EPBM

The University Link (U 230) twin tunnels are located within areas of glacial and non-glacial sediments in Seattle, Washington (Geotechnical Baseline Report, 2009). The geological profile along the tunnel is shown in Figure 1 below. The ground cover above the tunnel crown ranges from 13 feet (4 m) to about 130 feet (40 m) with varying ground water table (GWT) hydrostatic head. Exploration borings show at least three types of deposits will be encountered, from both glacial and non-glacial cycles, which consists of clays (blue soil group), silts (turquoise soil group), and sand and tills (yellow/yellow 2 soil group) in various combinations, densities and consistencies. The soil properties of the U 230 project can be found in Table 1.

Table 1: U 230 Average Soil Properties (Geotechnical Baseline Report, 2009)

<table>
<thead>
<tr>
<th>Soil Group/USCS Classification</th>
<th>Sat. Unit Weight ($kN/m^3$)</th>
<th>Friction Angle, $\phi$ (°)</th>
<th>At-Rest Lateral Earth Pressure Coefficient, $K_o$</th>
<th>Cohesion, $c'$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purple/ CL-CH</td>
<td>20.1</td>
<td>33</td>
<td>0.8</td>
<td>13</td>
</tr>
<tr>
<td>Turquoise/ ML</td>
<td>19.6</td>
<td>37</td>
<td>0.8</td>
<td>0</td>
</tr>
<tr>
<td>Yellow 2 / SM</td>
<td>19.9</td>
<td>39</td>
<td>1.2</td>
<td>23.9</td>
</tr>
<tr>
<td>Yellow / SP-SM, GM</td>
<td>19.9</td>
<td>39</td>
<td>0.37</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 1: Tunnel geological profile (top, Irish 2009) and geology at the face (bottom). Ground cover and groundwater table elevation above crown shown. Tunneling conducted right to left.
A 6.44 m (21.1 ft) diameter Hitachi Zosen EPBM shown in Figure 2 was used to construct the 3800-feet (1160 m) twin tunnels. Both the northbound (NB 2011) and the southbound (SB 2012) tunnels were launched from the Capital Hill station. Tunneling was performed right to left in Figure 1 and all subsequent Figures. Eight variable frequency drive electric motors rotate the cutterhead. The equipped cutterhead torque (cutterhead torque at 100% capacity) for the EPBM was approximately 3107 kN-m at a max cutterhead rotation speed of 2.2 RPM. There are five independently controlled injection ports located on the cutterhead for ground conditioning and six pressure sensors on the back of the excavation chamber to measure muck pressures. The opening ratio, $\eta$, of the cutterhead is 45%.

**Modified Cutterhead Torque Estimation Model**

The cutterhead torque estimation model proposed by Shi et al. (2011) was modified and used for the analysis. For ease of comparison, we followed their notation with modifications noted. Shi et al. (2011) proposed eight components of cutterhead torque (Figure 3), three of which they deemed insignificant, namely the torque due to the summation of individual tool cutting ($T_4$) and torque due to the main bearing and sealing ($T_7 + T_8$). The remaining five components of total EPBM cutterhead torque $T_{EPB}$ are presented in equation (1.1) where $T_1$ is the frictional torque on the front surface of the TBM cutterhead, $T_2$ is the frictional torque on the perimeter surface of the cutterhead, $T_3$ is the frictional torque on the back surface of the cutterhead, $T_5$ is shearing torque on cutterhead openings, and $T_6$ is torque of agitating the ground by mixing bars and cutterhead to main bearing struts.

![Figure 3: Cutterhead torque components](image)
Frictional torque on the front surface of the TBM cutterhead is estimated in equation (1.2):

$$T_1 = \frac{\pi D^3}{12} s' \mu_1 (1 - \eta)$$

where $s'$ is the effective lateral support pressure at the face (average at the centerline is used for simplicity), $\mu_1$ is the coefficient of friction between the TBM cutterhead and sheared conditioned soils, and $\eta$ is the opening ratio of the TBM cutterhead (here 0.45). $T_1$ is derived by integrating the product of cutterhead-soil interface shear stress (that varies from crown to invert) and radial position of each infinitesimal area, over the area of the cutterhead face. Pore water pressure (PWP) is neglected as it offers no shearing resistance. $s'$ can be estimated from field data or limit equilibrium methods as described later. $T_1$ has been modified from Shi et al. to incorporate arching reduced stresses (Shi’s laboratory model did not generate arching and therefore was not needed in the original framework).

Frictional torque on the perimeter surface of the cutterhead is estimated using equation (1.3) where $t$ (m) is the thickness of the cutterhead surface and $\mu_2$ is the perimeter shield steel – soil interface friction coefficient at the circular face (see Figure 3). $T_2$ employs the effective chamber pressure $s'$ as an estimate of the average normal stress acting at the shield – soil interface.

$$T_2 = \frac{\pi D^3}{2} s' \mu_2 t$$

Frictional torque on the rear of the cutterhead is estimated in equation (1.4), where similar to equation (1.2), $T_3$ is derived by integrating the product of cutterhead-muck interface shear stress (that varies from crown to invert) and radial position of each infinitesimal area, over the area of the cutterhead. The cutterhead rear - muck interface friction is the product of the interface friction coefficient $\mu_3$ and the lateral effective bulkhead lateral stress. We assume that the effective bulkhead stress and effective face support pressures are similar and reasonably represented by $s'$.

$$T_3 = \frac{\pi D^3}{12} s' \mu_3 (1 - \eta)$$

The muck – cutterhead rear surface interface friction stress is the product of the interface friction coefficient $\mu_3$ and the lateral effective bulkhead stress. We assume that the effective bulkhead stress and effective face support pressures are similar and reasonably represented by $s'$.

The torque required to shear across the cutterhead openings is estimated in equation (1.5):

$$T_5 = \frac{\pi D^3}{12} k_4 s' \mu_4 \eta$$

where $\mu_4$ is the shear strength coefficient of the conditioned soil in the openings and coefficient $k_4$ is an integration parameter related to the opening area distribution. For the particular TBM used in this project, the V-shaped opening yields a $k_4 = 0.35$ ($k_4$ is not the face opening ratio).

The torque required to rotate the mixing bars and cutterhead frame pedestals (struts) is estimated using equation (1.6):

$$T_6 = s' \mu_1 D_b L_b n_b R_b + s' \mu_4 D_p L_p n_p R_p$$

where $R_b$ and $R_p$ (m) are the distances between the mixing bar or pedestal and the centerline of the shield, respectively; $D_b$ and $D_p$ (m) are the transverse dimensions of the mixing bar and pedestal, respectively, $L_b$ and $L_p$ (m) is bar/pedestal’s length, respectively, and $n_b$ and $n_p$ (m) is the number of bar/pedestals. $\mu_1$ is the
friction coefficient between the bars/pedestals and muck. The cutterhead frame pedestal and mixing bar on the U 230 TBM are shown in Figure 4.

![Figure 4: Cutterhead driving levers (a) and articulating bars (b) that mix muck in the chamber](image)

Equations (1.1) - (1.6) provide a rational framework for estimating cutterhead torque. The use of simplified formulas, however physically related, is somewhat limited and may potentially miss some important aspects. For example, equations (1.2), (1.3), (1.4) and (1.5) do not expressly account for the irregular shapes of the cutterhead surfaces (front, rear and perimeter). This can be somewhat accounted for within the surface - soil frictional coefficients $\mu$ as defined in equation (1.7), where the angle of internal friction of the formation soil $\phi'$ is reduced due to soil conditioning and disturbance due to cutting ($R_i$) and due to the roughness/irregular shape of the specific cutterhead surface – front, rear, perimeter ($f_i$).

$$\mu_i = \tan(f_i R_i \phi')$$  \hspace{1cm} (1.7)

The product $R_i \phi'$ conveys the reduced shear strength of the disturbed and conditioned soil interacting with the cutterhead front face, rear face, and perimeter (assuming $R_i < 1$). We assume here that the soil interacting with the cutterhead front face, rear face and perimeter is disturbed and conditioned similarly. This assumption holds if the mixing zone between the cutter tips and the cutterhead face (nominally 10-20 cm) consists of conditioned soil with similar behavior to that in the excavation chamber and that this conditioned soil infiltrates the annulus at the cutterhead perimeter. The latter assumption is consistent with the findings of DiPonio et al. (2012). In this particular project, 4 inch (100 mm) of overcut was used so it is deemed reasonable that the annulus created is filled with disturbed and conditioned soil. The values of $R_i$ and $f_i$ are further addressed in the Results section. Finally, we assume that interface shearing resistance is dominated by friction and that $c'$ is negligible.

RESULTS

The measured cutterhead torque (summation of 8 VFD motors) and other key EPBM parameters are presented in Figure 5 for both NB and SB tunnels. All the data were recorded every 5 seconds using an Arigataya (ver. 3.0) Data Collection System. A ±5 point window (11 data points in total) moving average was conducted to smooth the data to reduce significant variations in raw data. The data presented below are ring averages. Realized torque was greater in the granular soil formations (2-2.5 MN-m), followed by the silts (1-1.5 MN-m) and then clay (~1 MN-m). These values are reasonably comparable to published torque levels encountered in similarly sized EPBMs used in glacial Seattle soils (McLane, 2014). The high torque observed from 0-300 ft occurred during tunneling through controlled density fill under Interstate 5 and will not be considered here. A comparison of torque to interpreted face geology from the GBR suggests the granular soil boundary to be around 800 ft instead of 500 ft, and the silt/clay
boundary to be closer to 2200 ft instead of 2000 ft. Cutterhead torque was reasonably similar in the NB and SB tunnels within the sand and silt soils (except 50-300 ft where NB was higher). NB torque was lower in the clay between 400 and 1000 ft. Some operational differences make a direct comparison between NB and SB torque levels challenging. For example, the TBM conveyor system for SB tunnel was modified significantly based on the experience gained during the excavation of the NB tunnel. This modification increased the muck flow, which was the limiting factor for production during the excavation of NB tunnel, and made torque the limiting factor during the excavation of SB tunnel resulting in an increase in the torque through this section in SB tunnel. Centerline bulkhead pressure is shown in Figure 5 and will be used in the model-predicted torque below (less pore water pressure). Because bulkhead pressure would not be available during the EPBM design phase when equipped torque is determined, Figure 5 also shows the limit face pressure estimated from the Jansecz and Steiner (1994) silo theory model using a factor of safety = 1.3 (presented is effective plus hydrostatic head based on Figure 1). This model matches the data well and is based entirely on geotechnical parameters that would be available during EPBM procurement. The background colors in Figure 5 displays the geological profile of the tunnel as described in Figure 1.

Foam injection was greater during SB tunneling along the majority of the alignment. Water injection played an important role in cohesive soil conditioning and was also higher along the SB excavation. The SB advance rate was generally lower than NB; this is therefore reflected in the measured thrust force. SB cutterhead rotation speed was generally higher than NB. The combination of lower advance rate and higher cutterhead rotation speed yielded lower penetration rates (mm/revolution) in the SB tunnel. The lower SB penetration rates did not yield lower torque levels, and is consistent with the notion that torque component $T_4$ is negligible.
The model predicted $T_{EPB}$ is presented in Figure 6 for both NB and SB tunnels together with the measured torque. Here, the effective face pressure and effective bulkhead pressure $s'$ is approximated using the centerline bulkhead pressure data (Figure 5) less the pore water pressure. Estimating the pore water pressure in the chamber is very difficult and is a limitation of this modeling approach. In this analysis, we assume that the PWP reduced the effective stress 20%-50% from the total stress. Interface friction coefficients were calculated using angles of internal friction from Table 1 reduced to reflect the effects of disturbance during cutting plus water and foam conditioning. Various $f_iR_i$ ($i = 1, 2, 3, 5$) combinations are tried to yield the best fit.

Figure 6 shows the torque prediction result when $f_iR_i=0.5$ is adopted. The assumption here is that the combination of cutting disturbance, soil conditioning and irregular surface shapes combine to net a reduction in the interface friction by 50% from the soil’s angle of internal friction ($f_iR_i=1.0$). With this, the model overestimates the torque by 50-100% in granular soils and by 300-500% in the cohesive silt and clay formations, which suggests the variation of soil conditioning’s influence in different soil types. It is worth mentioning that the model grossly overestimates cutterhead torque by 10-15X if the at-rest lateral effective stress from full overburden is used (as proposed in the original Shi et al model).
Several $R_i$ values were investigated for each of the three soil groups ($f_i = 1$ for all cases) to essentially best fit the model to the measured torque. Figure 7 shows the predicted torque response with the adopted reduction coefficients needed for each soil group to fit to measured torque. The $R_i$ values required to model fit the measured torque in sand/gravel were 0.35 (NB) and 0.37 (SB), implying that cutting disturbance plus soil conditioning reduced the shear strength of the sand & gravel/till by 65-67%. This is consistent with laboratory test results done by Alavi Gharahbagh et al. (2014) on sand soils. The $R_i$ values required to model fit the measured torque in the silt and clay formations were 0.15 (NB) and 0.18-0.20 (SB). This suggests that the combination of water and foam injection reduced the clay/silt shear strength by approximately 80%. The pore water pressure during tunneling is an unknown that influences these results. If excess pore water pressure was generated during excavation in saturated clay/silt, this would decrease the effective stress (assuming excess PWP was positive) and decrease the modeled torque. In this case, the estimated reduction in clay/silt shear strength would be less than predicted here.

Finally, a decomposition of the fitted torque tells us the relative magnitude of the five components (Equations 1.1-1.6). The analysis revealed that the torque due to cutterhead front and back face resistance ($T_1$ and $T_3$) accounts for 62% of total torque, and frictional torque on perimeter surface $T_2$ is estimated to be around 24%. Torque caused by soil friction at the cutterhead opening and muck mixing is trivial and only accounts for 9% and 4%, respectively.
The following conclusions can be drawn from this analysis:

- Observed torque on the 6.44 m diameter EBPM was greater in the granular soil formations (2-2.5 MN-m), followed by the silt (1-1.5 MN-m) and then clay (~1 MN-m).
- Torque was mostly similar in the NB and SB tunnel drives despite considerable differences in advance rate, cutterhead rotation speed, penetration rate, thrust force, chamber pressure and foam and water injection ratios. Operational differences makes it difficult to directly compare NB and SB torque.
- The physical torque model developed for the analysis grossly overestimates the realized torque by 50 – 500%, even with shear strength reductions of 50%.
- The shear strength reduction required to fit the model with measured torque were 65-70% reduction for sand ($R_i = 0.35–0.4$) and 80-85% for silt and clay ($R_i = 0.8-0.85$).

It is worth mentioning that the fitting of model parameters using measured torque is an underdetermined problem, meaning there are more unknowns than knowns. This creates uncertainty in the findings that require further research. Specifically, independent estimation of the conditioned soil shear strengths as well as chamber pore water pressure would help to constrain the fitting process.

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