A new parameter for TBM data analysis based on the experience of the Brenner Base Tunnel excavation

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Abstract. Tunnel boring machine (TBM) operational data can be seen as a function of three main influences: the machinery of the TBM itself, the way the TBM is operated, and the excavated rockmass. Whereas the processing of TBM data must be done by computer-aided methods, the interpretation is typically done visually and is highly dependent on the user’s prior experience. One way is to inspect the raw data itself, and another is to inspect computed parameters (specific penetration, specific energy or torque ratio). Either way, the goal is to find distinctive patterns that indicate changes in the rock mass conditions, and therefore it is crucial to find parameters that bear as much information as possible. The goal of this paper is to introduce the new parameter “theoretical advance force” ($F_{N,\text{theo}}$) that was developed in the course of systematic analysis of TBM operational data from the exploratory tunnel Ahrental-Pfons (part of the Brenner Base tunnel project). $F_{N,\text{theo}}$ is back-calculated from the measured cutterhead torque and the measured penetration. The theoretical advance force shows very promising results with the data at hand, yielding more pronounced and well-defined patterns that correlate better with the encountered rockmass conditions than several other common parameters.

1. Introduction

The Brenner Base Tunnel (BBT) is a railway tunnel that is currently under construction and connects the cities of Innsbruck (Austria) and Fortezza (Italy). With 120 km of main tubes – railway tunnels, a 61 km long exploratory tunnel and 49 km of other tunnels (e.g., crosscuts) the tunnel system is considered to be the longest in the world today [1]. A part of BBT’s exploratory tunnel on the Austrian section is driven by an open gripper tunnel boring machine (TBM, figure 1) and will be used for logistics and maintenance after the construction. It also offers a geological forecast for the excavation of the main tunnel tubes [2]. To achieve this goal, the data collected from the 16.7-km long exploratory tunnel Ahrental-Pfons is thoroughly analyzed [3]. Innsbrucker Quarzphyllite; and lower and upper Schieferhülle are the main lithological units encountered in the excavation [4].

A significant part of the exploratory tunnel's knowledge derivation process is the analysis of the TBM operational data. During the advance, several parameters (e.g., cutterhead torque, advance force, etc.) are continuously recorded. The TBM operational data constitutes an uninterrupted archive of the encountered rockmass conditions. TBM data analysis aims to find distinctive correlations between the data and the different encountered geological conditions. In addition to the TBM’s standard parameters, Bergmeister et al. and Reinhold et al. [2] [3] use additional parameters such as specific
energy [MJ/m³] after Teale [5], specific penetration [mm/rot/MN], or the theoretical torque [MNm] and torque ratio after Radoncic [6].

A drawback in the above-given parameters is that they are all dependent on the recorded advance force that is generated by the TBM’s thrust cylinders. The advance force is, however, heavily influenced by the hardly determinable effect of the shield friction. Consequently, the advance force associated with the drilling process is a blurred signal of processes on the tunnel face and the TBM’s shields directly contacting the tunnel wall. To illustrate, the penetration achieved by the TBM is basically a result of both measured cutterhead torque and machine’s advance force. But, part of the latter force is dissipated in confronting the shield friction and pulling the back-up system. This phenomenon limits the ability of the aforementioned parameters to describe rockmass conditions at the tunnel face, since the amount of lost advance force is highly correlated with the conditions around the shield.

Figure 1. Open gripper tunnel boring machine used in the exploratory tunnel ‘Ahrental-Pfons (BBT SE, 2021).

The aim of this study is to introduce a new parameter called the “theoretical advance force” \( F_{N,\text{theo}} \) and several derived parameters. \( F_{N,\text{theo}} \) is an attempt to elicit the exerted thrust in the drilling process from the machine’s total thrust. To the author’s knowledge, no similar parameter has been published before. Section 2 gives a brief description of the TBM operational data and the used rockmass classification system followed by the data pre-processing procedure and the computation of \( F_{N,\text{theo}} \). Section 3 states the results of the paper’s approach compared to other “standard” TBM parameters. The paper is then concluded with a discussion and an outlook on future studies in section 4.

2. Methodology
The study’s approach is to investigate the validity of the new presented parameters in the analysis of the TBM advance data. As mentioned in the introduction, the common goal of the analysis is to find solid correlations between the TBM data and the driven rockmass.

2.1. TBM data and geological indication
The TBM under consideration is recording different parameters with an interval of 10 seconds during the advance. Some of these parameters are: cutterhead torque [MNm], total advance force [kN], penetration [mm/rot] and pressure of crown-support-cylinder left & - right [bar].
At the exploratory tunnel Ahrental-Pfons, an experience-based classification system called “geological indication” (GI) was developed to categorize the rockmass (figure 3). Considered parameters for identifying the GI are mainly focused on discontinuity properties (i.e. orientation, degree of fracturing, roughness characteristics etc.) and the presence of fault-material and deformation characteristics. Table 1 shows the different encountered GIs after Reinhold et al. (2017) [2].

Table 1. Definition of the classification system classes (Ahrental-Pfons exploratory tunnel) after Reinhold [2].

| Class | Short description |
|-------|-------------------|
| 1 green | good rock mass, with minor interface influence |
| 2 yellow | rock mass with minor faults or unfavorable discontinuities |
| 3 orange | squeezing rock mass, high degree of fracturing (parallel to schistosity), weakened rock |
| 4 red | rock mass in geotechnically heavily relevant fault zones |

2.2. TBM data pre-processing
As the original TBM data involves noise, outliers and data points at the same location (standstills etc.), the following pre-processing steps were taken to enhance the “readability” of the TBM operational data:
- eliminating all the records that have a penetration value = 0, which caused by the machine standstills;
- removing outliers caused by peaks in values appear after the machine’s system loose breaks or irrelevant values because of sensors’ malfunction. Since the data is normally distributed (figure 2), the detection of the outliers is performed according to the z-value scores. Therefore, data points with z-values score > 3 are discarded [7];
- Applying a rolling mean with a window width = 70 data points on the line plots for better visualization (figure 3).
2.3. Computation of theoretical advance force

The theoretical advance force $F_{N,\text{theo}}$ is calculated from the cutterhead’s measured torque ($T$) and the penetration ($P$) recorded by the TBM, which is inspired by Radoncic [6] who computes the theoretical torque based on the TBM’s penetration and advance force. The computations of Radoncic are themselves based on the Colorado School of Mines model [8] [9]. In case of the exploratory tunnel Ahrental-Pfons, it is assumed that 46 cutter discs are active during the cutting process. Consequently, as shown in equation (1), $T$ can be represented as the summation of the individual torque products done by cutter discs plus the additional torque ($T_0$). Each torque product is simply the multiplication of the tangential force on each cutter disc $F_{\text{tang}}$ (assumed to be equal for all cutters) by its corresponding distance to the centre of the cutterhead $r_i$. Where $T_0$ is the torque exerted against the internal friction; and against the contact between the calliper cutters and the tunnel wall.

$$T = \sum_{i=1}^{46} (F_{\text{tang}} r_i) + T_0$$

**Figure 2.** Kernel density estimation [7] and histograms of some selected raw parameters. The data shows a statistical normal distribution.

**Figure 3.** Different parameters with the GIs encountered between chainage 1450 and 1550 (along 100 m of exploratory tunnel). The noise in the background resembles the data after eliminating the outliers and the unreasonable values, and the solid line resembles its moving average.
The calculation sequence is to compute the tangential force $F_{tang}$ as given in equation (2), then derive the normal force $F_n$ on each of the cutter discs from the relationship governing the normal force $F_n$, tangential force $F_{tang}$, penetration $P$, and the cutting angle $\alpha$ (figure 4).

$$F_{tang} = (T - T_0) \cdot \left( \sum_{i=1}^{46} r_i \right)^{-1}$$

Figure 4. (a): 3D illustration of the resultant cutting force. (b): torque product as the multiplication of the tangential force on the cutter disc by the distance to the centre of the cutterhead, (c): the assumed relationship between normal force, tangential force, penetration, disc cutter radius and the angle $\alpha$ (modified after Radoncic [6]).

The cutting angle $\alpha$ is estimated from the penetration $P$ and the cutter radius $R_{DC}$ as follows:

$$\alpha = \cos^{-1} \left[ (R_{DC} - P) \cdot (R_{DC})^{-1} \right]$$

The normal force $F_n$ for each cutter is calculated as:

$$F_n = F_{tang} \cdot \left[ \tan \left( \frac{\alpha}{2} \right) \right]^{-1}$$

And, the theoretical advance force $F_{N, theo}$ which is the summation of the normal force $F_n$ acting on each cutter disc is:

$$F_{N, theo} = 46 \cdot F_n$$

$F_{N, theo}$ represents the part of the advance force acting on the tunnel face during the drilling process without the effect of shield friction. Therefore, $F_{N, theo}$ can be used to further investigate the effect of the shield friction. Similar to the torque ratio computed by Radoncic [6], the advance force ratio (R) in equation (6) represents the ratio between the theoretical advance force and the recorded total advance force $F_{N, rec}$. Moreover, equation (7) yields the difference between the measured advance force ($F_{N, rec}$) and the theoretical advance force $F_{N, theo}$. The advance force loss $F_L$ resembles the amount of advance force exerted to overcome the friction around the shield and pulling the machine’s back-up system. Lastly, the effect of the shield friction $F_F$ can be computed as the difference between $F_L$ and the force required to pull the back-up system $F_B$, equation (8). However, due to absence of records of $F_B$ in the present dataset, we only present the results of $F_L$. 

$$F_{N, theo} = 46 \cdot F_n$$
By using $F_{N, theo}$, parameters that are dependent on the recorded advance force can be recalculated (e.g., specific penetration). In the next section, the effect of substituting the theoretical advance force in the specific penetration’s calculation besides the results of the new derived parameters are presented.

### 3. Results

Figure 5 shows the results of the new parameters compared to some common parameters over the geological section, and the assigned GIs, between chainage 2290 to 2335 including the fault zone ESI-f9240. Detailed information about the fault zone can be found in reference [2] and, figure 6 displays the distribution of the results (violin plot) over more extended tunnel section (chainage 0-6000).

From both figures, it can be seen that the theoretical advance force shows less values than the total measured advance force, and the theoretical advance force achieves very well correlation with the GIs. Along the inspected area in figure 5, the theoretical advance force decreases with approach to the fault zone until it reaches its minimum at chainage 2317.5 approximately, then increases again after having passed the fault zone to reach its highest in GI1. The violin plot (figure 6) gives descending medians and interquartile ranges of the theoretical advance force values from GI1 to GI4. Moreover, the density of the records is clearly different especially between (GI1,2) and (GI3,4).

The recalculation of the specific penetration yields a general increase in the values, and an obvious enhancement in the correlation with the encountered geologies can be observed (figure 5 and 6). In figure 5, the behavior of the specific penetration changes especially in the fault zone. Where the ‘standard’ specific penetration suddenly decreases approaching the center of the fault zone without retrieving, the recalculated specific penetration further increases.

The advance force loss gives a satisfactory correlation with the GIs (figure 6). In figure 5, the advance force loss shows its highest values at the core of the fault zone, and responds almost similarly to the total measured advance force.

Figure 6 demonstrates that the advance force ratio has a better correlation with the GIs than the advance force loss and more distinctive values in the GI4. Moreover, within the example section given in figure 5, the advance force ratio shows the same behavior described above regarding the theoretical advance force.

\[
R = \frac{F_{N, theo}}{F_{N, rec}} \quad (6)
\]

\[
F_L = F_{N, rec} - F_{N, theo} \quad (7)
\]

\[
F_P = F_L - F_B \quad (8)
\]
Figure 5. The investigated parameters with longitudinal geological section and geological indications, chainage 2290 to 2335.

4. Discussion
The results have further strengthened our confidence that our approach provides additional insights in the analysis of the TBM advance data. However, an important limitation in the computation of the theoretical advance force may have influenced the results obtained. The resultant force acting on the cutter disc is assumed to be acting through the symmetry axis of the cutting angle $\alpha$. This assumption yields very narrow values range of the term $\tan\left(\frac{\alpha}{2}\right)$, see equation (4). As a result, the theoretical advance force is highly dependent on the measured torque. This downside hinders the ability of the theoretical advance force to pronounce the normal force acting on the face. It is also important to stress that in areas where face instabilities occur, the friction effect around the shield can not be discriminated from the face effect on the cutterhead.
Notwithstanding these weaknesses, the theoretical advance force achieved remarkable outcomes, which can be seen in the enhancement of the specific penetration, and in the expression of the shield friction effect. Furthermore, the shield friction can be widely investigated by using both of the advance force ratio and the advance force loss. Explained shortly, the advance force ratio can help indicating the rocks mass encountered however the advance force loss can reflect its conditions.

This work has gone some way towards more comprehensive TBM advance data analysis. Which would lend it well for use by the means of modern applications in rock mass characterization like machine learning. At the same time, we see this study as the first step for the theoretical advance force, and more accurate results can be achieved with better approaches. Therefore, additional future work is planned to investigate the possibility of estimating the theoretical advance force based on the TBM recorded shield pressure.

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