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Standardized Determination of a Normalized Thrust per Cutter for TBM Performance Evaluation

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Abstract

Over the past few decades, several performance indicators have been developed to assess the impact of geological conditions on Tunnel Boring Machine (TBM) performance. These indicators primarily focus on accurately calculating the thrust force per cutter (TpC) required for a disc cutter to penetrate a specific type of rock. However, existing models make simplifying assumptions that overlook crucial factors—such as the loss of thrust in the gauge cutter area—and assume that the cutter is always aligned parallel to the tunnel axis. This article presents a new disc cutter model that accounts for stress variations in fractured rock masses. The model integrates both linear and nonlinear Penetration Prediction Models (PPMs) and introduces a loss factor to adjust for thrust losses due to the curvature of the cutterhead. This stress-dependent correction improves the accuracy of thrust force calculations. It allows for more reliable back-calculations of penetration rates, surpassing the limitations of existing models, such as the Colorado School of Mines' approach, which only applies to intact rock masses. A key aspect of this model is its ability to account for thrust loss resulting from the curvature of the gauge cutter area and the cutterhead diameter. Considering these geometric factors, the model provides a more detailed and accurate estimation of thrust loss in each cutter's direction of load transmission. Based on the cutterhead's geometry and the rock mass's geological conditions, this refinement significantly enhances the precision of penetration rate predictions and improves the overall reliability of field performance indicators.

Keywords

TBM, Performance Prediction, Penetration Rate, Thrust per Cutter, Cutterhead

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1 Performance Characterization of a TBM's performance

Understanding the performance characterization of a Tunnel Boring Machine (TBM) is crucial for optimizing its efficiency and effectiveness during excavation. The TBM excavation process is typically divided into two main stages: the start-up phase and the ongoing excavation phase, which includes deceleration and stroke completion (Wannenmacher, 2023). To initiate cutting, the cutterhead must overcome the TBM's mass inertia during the start-up phase. The TBM's mechanical characteristics predominantly influence this phase and the friction between the cutterhead, the rock surface, and the surrounding ground conditions. Once initial acceleration is achieved, the focus shifts to maintaining optimal performance throughout the excavation stroke. In the ongoing excavation phase, the operator must carefully balance the applied thrust and cutterhead revolutions to optimize energy efficiency and maximize performance. A common misconception in TBM tunneling is the unbiased back-calculation of penetration rates. However, achieving accurate performance characterization requires careful consideration of several factors. Direct comparisons between encountered and predicted penetration rates, or cross-referencing such data, often lead to biased results and misleading correlations. Correcting any data errors in the first step of pre-processing is essential to back-calculating characteristic performance data. Additionally, the stroke must be adequately segmented into the two distinct phases of the excavation process: start-up and continuous excavation. While deceleration is less critical for performance analysis, the initial phase is crucial for understanding nonlinear thrust-penetration interaction. Continuous excavation is the primary phase for evaluating TBM utilization and establishing key performance indicators, such as the Field Penetration Index (FPI) (Klein et al., 1995), the Torque Ratio (Radončić et al., 2014), and the Theoretical Advance Force (Heikal et al., 2021). An unspecific or improper data allocation across these phases can significantly distort the results, leading to inaccurate performance evaluations. Therefore, a precise phase-based analysis is crucial for meaningful back-calculations and performance optimization.

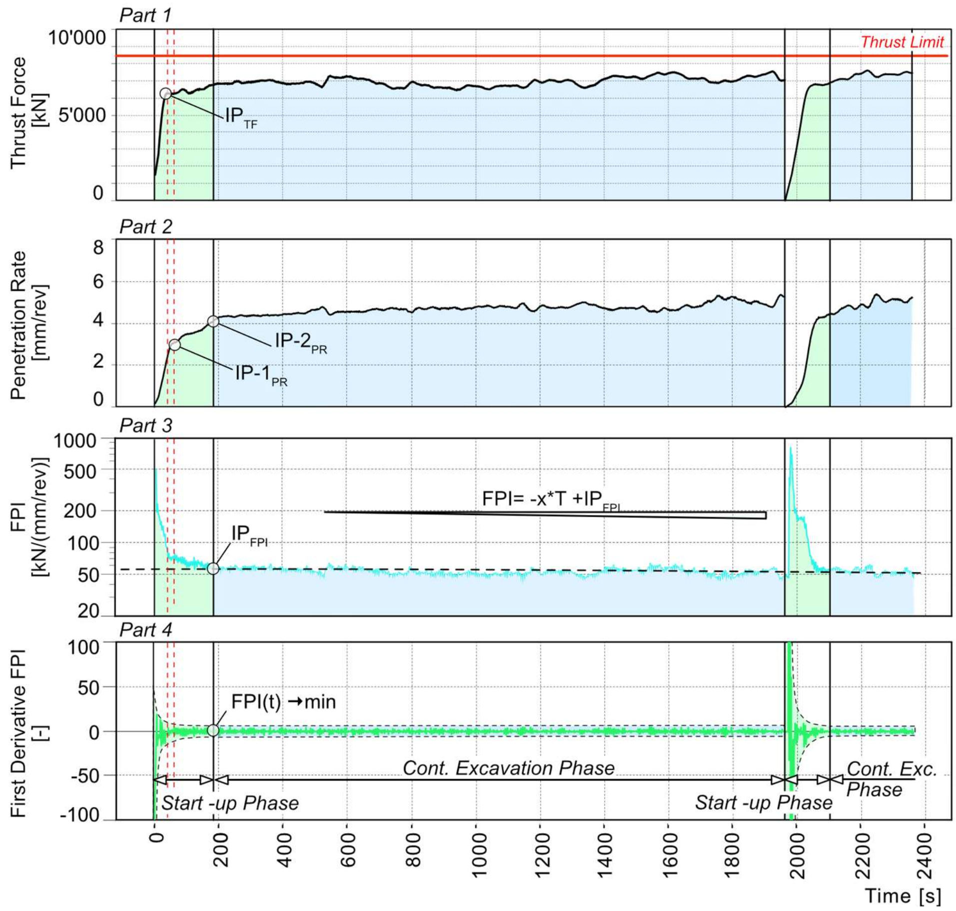

Figure 1.1-1.4: Compilation of the TBM performance data and determination of the start-up and excavation phase based on TBM data based on the first derivative of the Field Penetration Index.

The transition from the start-up phase to continuous excavation is best described by a damped oscillation from the first derivative of the FPI, influenced by frictional forces and vibrations inherent in the excavation process. The thrust force reaches a first inflection point (IP_{TF}), characterizing the reach of the plateau of continuous thrust propulsion. However, the TBM’s advance rate is still accelerating and is linked to overcoming frictional resistance. Two inflection points ($IP\text{-}1_{PR}$ / $IP\text{-}2_{PR}$) often characterize the penetration rate's increase before reaching a plateau. The later inflection aligns with the FPI slope (IP_{FPI}), approaching a near-constant value, signaling the shift to a stable, continuous excavation phase. The first derivative of the FPI, which represents the rate of change of force, provides a clear indicator of the system's evolving dynamics. The amplitude of oscillations, initially varying, gradually decays as the process stabilizes. This decay envelopes the oscillatory amplitude, which reaches a minimum range of approximately +/- 4 units, marking the completion of the transition. The first derivative of the FPI forms an envelope with exponential amplitude decay (see equation 3).

$$FPI(t) = FPI_{min} + \left(FPI_0 - FPI_{min}\right) \cdot e^{-kt} \tag{3}$$

This approach—using the first derivative of the FPI—enables a more sophisticated and comprehensible evaluation of TBM operations. It allows for accurate segmentation of the excavation process and better decision-making in real-time monitoring and operational adjustments, as shown in Figure 1. A distinct mechanical model for back-calculating cutting forces has been developed based on a comprehensive analysis of TBM data from the two main excavation phases. This model is designed for stable tunneling conditions where face integrity exceeds 90 % and focuses on a systematic method for evaluating "steady" cutting forces incorporated into PPMs (Wannenmacher, 2023). The face integrity refers to the percentage of failed rock mass and the excavation face. Figure 2 illustrates the structured methodology for determining the normalized thrust per cutter. This method accounts for factors such as frictional losses, variations in cutter orientations, and the reduction in thrust due to fractured rock mass conditions. By integrating these critical variables, this approach provides a more accurate and especially standardized calculation of cutter loading for each stroke, enhancing the precision of force predictions and operational performance.

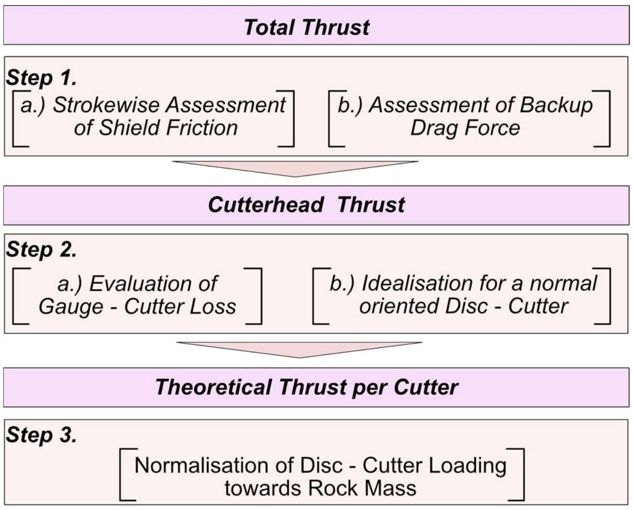

Figure 2: Flowchart for determining the idealized typically oriented acting thrust per cutter within fractured rock mass conditions.

2 Step 1: Determination of an idealized normal oriented Thrust per Cutter

Determining a consistent thrust per cutter, aligned perpendicular to the tunnel face, requires accounting for fluctuating frictional forces during each stroke and the forces needed to mobilize the backup system throughout excavation. This evaluation establishes the total thrust acting on the cutterhead. The next step involves examining how the gauge design of the cutterhead and the surrounding rock mass conditions influence the cutter loading. The cutterhead's geometry, along with the arrangement of the mounted cutters, introduces a specific loss factor for the gauge disc-cutters, reducing the overall thrust transmitted to the cutters mounted on the cutterhead. Normalizing the disc-cutter loading is necessary when reviewing the initial TpC within the PPM, as the TpC forms the basis for estimating penetration rates (PRs). However, a more nuanced approach is required when tunneling through fractured rock, which enhances the indentation process of the disc cutter (Büchi, 1984). Specifically, a reverse-engineering technique must be applied to account for the differential stress concentrations at the contact point between the disc cutter and the fractured rock mass. This adjustment allows for a more accurate representation of cutter performance under these complex conditions.

Step 1 a.): Determination of the Cutterhead Thrust

The TBM experiences varying frictional losses throughout the different phases of a stroke, which are closely tied to the cutting process. During the start-up phase, a specific static friction (f_s) is overcome within the first few seconds of excavation. This is followed by a gradual reduction in kinetic friction ($f_{k,initial} \rightarrow f_{k,min}$) towards an initial minimum value at the beginning of the stroke as the machine transitions to the steady-state excavation phase. In the excavation phase, frictional losses may also decrease slightly due to the formation of a shear plane from fines or the presence of water, which can act as a lubricant in the invert (see Figure 1- Part 3., decay of the FPI). Nelson (Nelson, 1983) estimated the frictional loss for the cutterhead to be 10 to 15 % of the cutterhead thrust during excavation, which aligns rather well with actual observations. A more refined method for assessing frictional losses involves examining the deviation of cutterhead torque relative to cutterhead thrust during the start-up phase (Schlicke et al., 2024b). This torque deviation typically coincides with the beginning of the TBM's acceleration phase, marking the transition from static to kinetic friction, as shown in Figure 3. Since the exact moment of onset cannot be determined due to current data recording frequency limitations, a specific transition range must be acknowledged, from f_s to initial kinetic friction f_k.

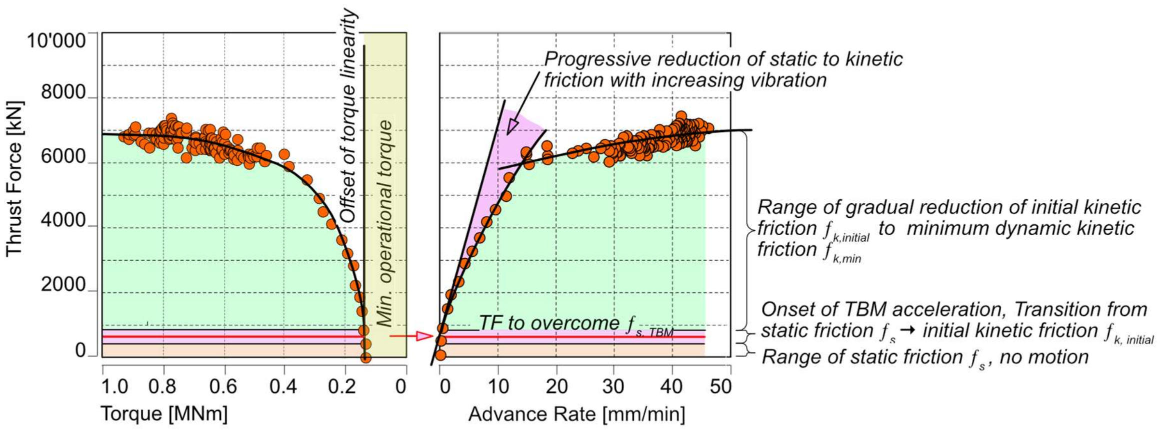

Figure 3: Determination of the TF to overcome TBMs shield friction, based on the onset of the minimal operational torque and the onset of motion (acceleration) by overcoming static friction.

The advance rate exhibits a pronounced non-linear trend during the start-up phase, gradually decreasing and transitioning to a linear trend once the TBM reaches the steady-state "constant" cutting phase. This non-linear behavior is primarily attributed to reduced sliding friction, further influenced by increased cutterhead vibrations and a transition from subcritical crushing to chipping. In contrast to the frictional losses of the cutterhead, the thrust required to move the backup system is monitored by TBM data acquisition systems. While the backup system's total weight is higher than the cutterhead's, the required thrust is insignificant to the overall force balance, as the backup system is usually roller-based (Figure 2, Step 1b.).

3 Step 2: Determination of the Cutterhead Specific Loss Factors

3.1 Step 2a.): Evaluation of Gauge Cutter Loss

The design of the gauge area in the cutter head enables a smooth transition towards optimized excavation of the tunnel periphery to achieve the final tunnel profile. This transition is facilitated by the curvature of the cutter head, which typically covers a radial range of 30-60 cm, depending on the tunnel size. The gauge cutter area is characterized by an increasing inclination of the disc-cutters from an axial orientation. The curvature of the cutterhead in the gauge area leads to a deviation of the proportional normal force (F_N) in the direction of the load transmission of the total proportional TpC. This deviation is influenced by the angle ζ of the disc-cutter (see Figure 4: right side) towards the direction of the load transmission. The lateral oriented side force (F_S) counteracts and decreases the F_N. The right side of Figure 4 illustrates the F_S in the gauge cutter area, showing that it increases with distance towards the center of the TBM axis and the angle ζ. The F_S depends on the tangential deviation of the disc-cutter to the tunnel axis; as it increases with the angle ζ, the F_N decreases with the angle ζ. The rolling force (F_R) solely depends on the resulting TpC and is not affected by the cutter's tangential inclination. The deviation of the disc cutters continuously increases with the distance from the center, and the stepwise increase in the angle depends on the layout of the cutterhead (Wannenmacher, 2023).

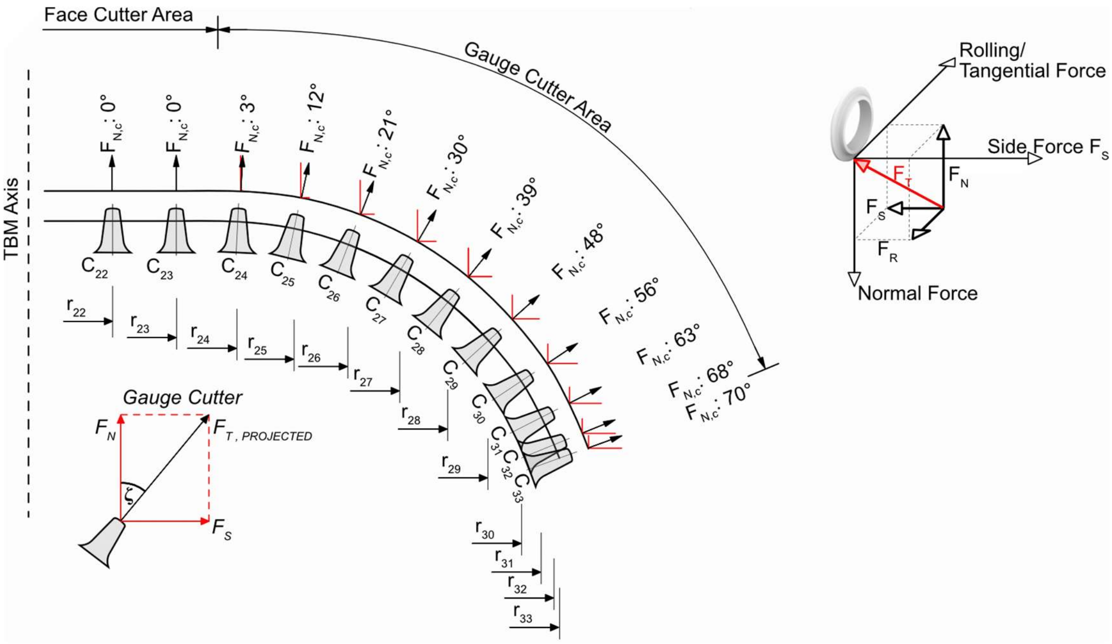

Figure 4: (left side) Illustration of acting cutting forces F_N, F_R, and F_S regarding their installation position (face/ gauge cutter area); (right side) schematic illustration of disc cutters orientation at face and gauge disc-cutter area.

The reduction in forces depends on the ratio of face and gauge cutters, the curvature of the cutterhead, and the number of cutters in the gauge area. The acting forces within the gauge cutter area, depending on the encountered angle ζ, see Eq. 4 & 5.

$$F_N = F_T \cdot cos(\theta/2) \cdot cos(\zeta) \tag{4}$$
$$F_S = F_T \cdot sin(\theta/2) \cdot sin(\zeta) \tag{5}$$

Where F_N Normal thrust per disc-cutter [kN]
F_S Side thrust per disc-cutter [kN]
F_T Acting thrust per disc-cutter [kN]
θ Contact angle of the cutter and rock mass [°]
ζ Tangential deviation angle of the cutter [°]

Figure 5 shows the upper and lower boundaries of the decrease in the normal direction and the increase of lateral disc-cutter loading about the tangential deviation of the disc-cutter. The differences in the decline of the F_N depend on the curvature of the gauge cutter area, which is considered disc-cutter loading.

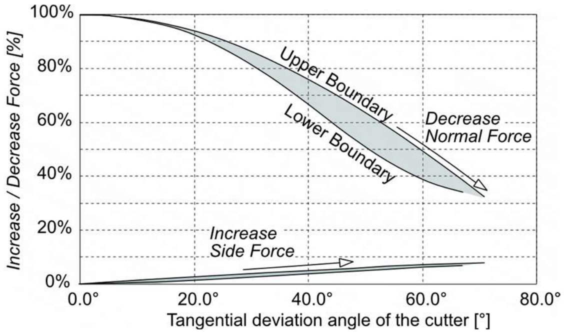

Figure 5: Differences in the behavior of normal and side force acting on a single disc-cutter within the gauge cutter area depending on the tangential deviation angle of the disc cutter towards the tunnel face.

The reduction factor (f_ζ) describes the overall losses of the F_N for the entire cutterhead, typically ranging from 4 to 10 %, related to the geometry of the cutterhead and the arrangement of disc cutters

(Rostami & Chang, 2017). The revised equation for the acting forces on the cutter, considering the loss factor, see Eq. 6.

$$f_{(\zeta)} = \sum_{i=1}^{n_c} F_{n,i} \Big/ F_T \tag{6}$$

Where $f(\zeta)$ Loss factor [-]

The analytical reduction factor aligns with the findings of actual disc-cutter in-situ measurements. Entacher (Entacher, 2013) conducted in-situ force measurements and observed a decay in the acting forces of disc-cutters on the rock mass in the gauge cutter area. Entacher found a reduction of approximately 23 % for the unreferenced position of a gauge cutter. Similar findings were reported by Qi (Qi et al., 2016) based on small-scale Ring Cutter Test (RCT) experiments.

3.2 Step 2b: Idealisation for one Disc Cutter

Overcoming frictional losses and the subcritical excavation phase leads to increased torque with increasing thrust (refer to Fig. 2). The torque deviation marks the transition of frictional shield losses and the excavation process (Weh et al., 2012; Wild, 2012; Erharter et al., 2023). The second phase refers to the nonlinearity of the thrust-penetration gradient (TPG), which resembles the Colorado School of Mines (CSM) model's formulation, representing the upper limit of disc-cutter indentation on massive rock conditions at a laboratory scale (Schlicke et al., 2024a). The simplest form of TpC is derived from the quotient of the total thrust acting on the cutterhead (F_C) and the number of disc cutters (no_c) of a cutterhead. See Eq. 7.

$$TpC\ [\mathrm{kN}/c] = F_c \cdot f_{(\zeta)} \Big/ no_c \tag{7}$$

Where F_c Cutterhead Force [kN]
$f_{(\zeta)}$ Loss factor [-]
no_c Number of installed cutters on the cutterhead [-]

4 Step 3: The Influence of Rock Mass Conditions on the Contact Pressure of a Disc Cutter

Rock mass defects are considered within several penetration prediction formulas (Büchi, 1984; Gehring, 1995) by linear approximation. The base penetration rate (PR) is multiplied by a correction factor without consideration of the changed geometrical constraints of cutter indentation and their impact on the stress conditions during ongoing excavation. Therefore, models considering linear approximation of fractured rock mass conditions overpredict the actual TpC. Based on the degree of fracturing, the penetration rate is enhanced, depending on the exact model's correction factor of up to 300 % for very blocky conditions. Rock mass conditions with higher fracturing are potentially exposed to instabilities affecting the TBM's utilization rate and operability. The influence of rock mass fracturing is reported to vary in discontinuity spacing and magnitude of influence to more than 100 % (Wannenmacher, 2023). Based on the disc-cutter's dimensions, the basic formulation adopts a corresponding contact angle (θ) for disc-cutter-induced loading. The angle of the disc cutter defines the contact area for load transmission, which refers to the TpC. Consequently, the degree of fracturing enhances the indentation depth of the disc-cutter, which increases the contact angle and the load transmission area. The average disc cutters' indentation depths per revolution (≈ PR) hold a nonlinear correlation with the contact angle (θ) in degrees, which can be addressed for a new 19" disc cutter ($D_{19"}$ = 483 mm) by the following relationship (Wannenmacher, 2023). See Eq. 8.

$$\theta[°] = 5.5132\sqrt{PR} \tag{8}$$

Where θ Contact Angle [°]
PR Penetration rate [mm/rev]

Based on the enlarged area for disc-cutter loading, the proportional stress reduction, utilizing the basis of Büchi's rock mass correction factor (Büchi, 1984), is shown in Figure 6. The correct computation of the TpC requires an iterative approach considering the actual geological conditions to determine the enhanced TPG regarding the contact angle. Determining the TpC for the fractured conditions is an iterative approach, requiring the calculation of the TPG for the underlying fractured conditions as a first step. The TpC is determined by correlation with the contact angle.

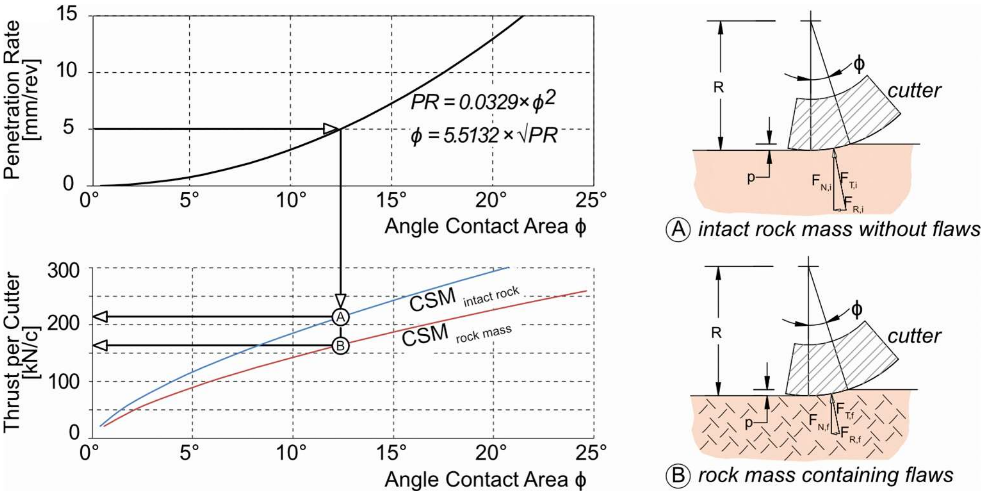

Figure 6: Integrating the impact of rock mass conditions into the CSM model according to Büchi (Buechi, 1984).

The empirical PPMs (e.g., Gehring, 1995; Alber, 1999; Barton, 2000) consider a linear TpC and disc-cutter indentation formulation. The validity of the base PR is restricted to a normalized TpC of 200 kN, according to Gehring (Gehring, 1995), neglecting any rock mass influence - Gehring-minded rock mass influence with a more than 50 cm spacing for the discontinuities. Since Gehring's basis considers a layered rock mass or partly massive rock mass conditions without accompanying cross-joining, limited relevancy towards blocky rock mass conditions is pertinent. In-situ conditions hardly comply with these premises; either deviating from the underlying assumption of a TpC of 200 kN or presenting fractured rock mass conditions qualifies for an eased penetration accompanied by an increased contact area and likewise an influence of the contact pressure, which is not considered in the PPM. An unbiased comparison of the in-situ PRs against the outcome of PPM for re-examining validity demands a dual process of up-scaling rock mass conditions and normalizing the base PR to normalize the TpC to 200 kN (see Figure 7).

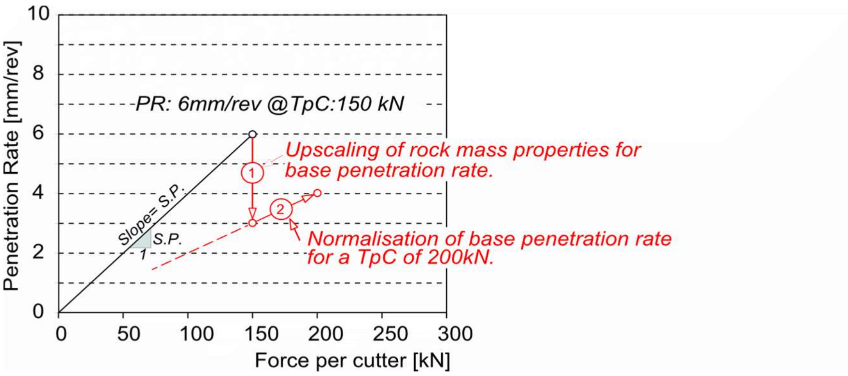

Figure 7: Dual process of scaling the thrust-dependent PR for the PPM of Gehring. The first step includes up-scaling rock mass conditions for the base PR, while the second provides normalization (P_{200}). Note that the linear expression of the TPG refers to the Specific Penetration (SP), which equals the slope.

The up-scaling follows the reverse process of rock mass influence delineated within Gehring's rock mass correction factor. On the other hand, the normalization of the TpC towards the base PR equation considering 200 kN adopts a linear approximation. Nonetheless, only the recorded PR and the ground conditions represent ground truth; steps 1 and 2 already include an unspecified simplification, which implies considerable bias in the system. Therefore, models based on linear TPG must be considered cautiously for back-calculation of TPG.

5 Summary

Advancing the analytical formulation of the base penetration rate is pivotal for enhancing the precision and efficiency of penetration predictions in Tunnel Boring Machine (TBM) operations. This study introduces a refined analytical model employing a stepwise normalization of stress concentrations for a single, normally aligned disc-cutter, effectively capturing the stress conditions within kerfs induced by disc-cutter loading in fractured rock masses. The model also addresses the influence of disc-cutter orientation in the gauge cutter zone on thrust distribution and cutting efficiency, incorporating adjustments for cutterhead curvature, frictional losses, and stress variability. By establishing a standardized and slightly simplified approach, the model ensures consistency in results and fosters a common framework for continuous back-calculation and forward prediction. These advancements improve the accuracy of penetration rate assessments and provide a reliable foundation for optimizing TBM performance, enhancing data-driven decision-making, and mitigating operational risks. Consequently, the research represents a transformative leap in TBM technology, bridging the gap between theoretical predictions and field performance while ensuring greater productivity, efficiency, and adaptability across diverse geological conditions.

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