

INFLUENCE OF ROCK MASS PROPERTIES ON TBM PERFORMANCE PARAMETERS IN THE CENTRAL GNEISS UNIT OF THE BRENNER BASE EXPLORATORY TUNNEL (ITALY)

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ABSTRACT

Rock mass characteristics, including uniaxial compressive strength and quartz content of the intact rock material, as well as the number, spacing, and orientation of joints, play a pivotal role in the performance of tunnel boring machines (TBMs). Various researchers have proposed TBM performance prediction models that have gained widespread acceptance in the literature and have been extensively utilised over the years. This study aims to analyse data collected from the hard rock TBM excavation of the Northern Italian stretch of the Brenner Base Exploratory Tunnel within the Central Gneiss unit. To this end, statistical analyses were conducted to explore relationships between intact rock and rock mass properties and the actual TBM data recorded during the excavation. Furthermore, the study compared penetration rates derived from performance prediction models based on rock and rock mass properties with actual penetration data, highlighting the extent to which the models align with real observations.

Keywords: TBM performance, prediction models, rock mass properties.

INTRODUCTION

The development of hard rock tunnel boring machines (TBMs) over the years, despite their high initial investment costs, has enabled more efficient excavation compared to conventional tunnelling methods, especially in favourable geological conditions and for tunnel lengths exceeding 1.5-2 km (e.g., Salimi et al. 2022). Their ability to operate in diverse rock mass conditions while ensuring fast and safe excavations represents a key advantage. Correct machine selection is therefore essential, highlighting the importance of performance prediction models. These models play a crucial role in tunnel design by aiding in the selection of the most suitable machine type and specifications. Over the years, numerous models have been developed to estimate TBM penetration rates, generally classified into two main categories: theoretical and empirical methods (Hamidi et al. 2010).

Theoretical performance prediction models are developed through an in-depth analysis of the rock fragmentation process using mechanical tools. These models are based on results from fullscale laboratory tests, such as linear cutting tests and punch penetration tests. They focus on identifying the forces acting on the cutter, which determine the thrust, torque, and power requirements of the TBM. Theoretical models typically combine key properties of the intact rock, such as uniaxial compressive and tensile strengths, with cutter spe-

cifications, including diameter, spacing, tip width, and the thrust applied to each cutter. The models proposed by Gehring (1995) and by Rostami & Ozdemir (1993) of the Colorado School of Mine are among the most widely applied in this category.

Empirical models, on the other hand, are based on extensive databases from tunnelling projects, typically compiled by university research groups and regularly updated with data from new excavations. Since TBM performance is influenced by a variety of factors and field conditions, there is a continual need to develop new models. Some models, proposed by Bruland (1998) and Yagiz (2008), focus on rock mass characteristics, while others, such as those by Barton et al. (2000), Innaurato et al. (1991), Ribacchi & Lembo Fazio (2005) and Hassanpour et al. (2011), explore correlations with rock mass classifications commonly used in rock mechanics (Armetti et al. 2018).

THE CASE HISTORY

The Brenner Base Tunnel (BBT) is a 55 km long railway tunnel that connects two countries. It runs through the Eastern Alps, between Innsbruck (in Austria) and Fortezza (in Italy). The entire tunnel system spans over 230 km, including an Exploratory Tunnel, two Main Tunnels, as well as cross passages, emergency stations, and access tunnels.

The 6.85-metre diameter Exploratory Tunnel is located between the two Main Tunnels and 12 metres deeper, with the purpose of investigating the geological and geomechanical conditions in advance, as it is excavated first. The Exploratory Tunnel will also be used for water drainage and maintenance during the operation of the tunnel (Boldini et al. 2018).

This study focused on the Northern Italian stretch of the BBT Exploratory Tunnel, between chainages km 23+988 and 27+273, examining the influence of intact rock and rock mass properties on TBM performance. To achieve this, correlations between Rock Mass Rating (RMR), and Geological Strength Index (GSI) of the Central Gneiss unit and various performance parameters (penetration rate, instantaneous cutting rate, specific energy, boreability index, power consumption and specific penetration) were analysed. Furthermore, theoretical penetration rate calculations were conducted using selected performance prediction models, and the results were compared with the actual measured penetration rate during the excavation of this specific stretch.

Geological and Geomechanical Conditions

In the geological forecast model, the Central Gneiss unit consisted of two main rock mass types, coded as GA-ZG-G-1z (Central Gneiss – Granitic Gneiss: medium to coarse-grained granitic gneiss) and GA-ZG-S-1z (Central Gneiss – Schists: biotitic schists). These were described as predominantly good, and subordinately fair, in terms of rock mass quality according to Bieniawski's classification (i.e., classes II and III), and characterized by high resistance and abrasiveness of the matrix. The geological documentation produced during the excavation works confirmed that the encountered rock mass types corresponded well to the forecast, in terms of mineralogy (mica, schist, quartz and feldspar contents), intact rock strength and abrasiveness, geological structures (schistosity/foliation and joint sets), and rock mass quality. The as built lengths of the zones are provided in Table 1.

As part of the geological documentation, periodic rock classifications were carried out by the geologists from both the Site Supervision team of the Owner Company (BBT) and the Contractor (BTC), resulting in GSI and RMR ratings. Figure 1 presents an overview of all GSI and RMR values. However, the more extensive BBT dataset was used in the following analysis.

Table 1. As built lengths of the zones excavated within the Central Gneiss unit.

Zone	Length (m)	Length (%)
GA-ZG-S-1z	375.56	11.43
GA-ZG-G-1z	2909.60	88.57
Total	3285.16	100

TBM Characteristics and Parameters

A double-shield (DS) Tunnel Boring Machine manufactured by Herrenknecht was used for the excavation of the Exploratory Tunnel. The key technical specifications are listed in Table 2.

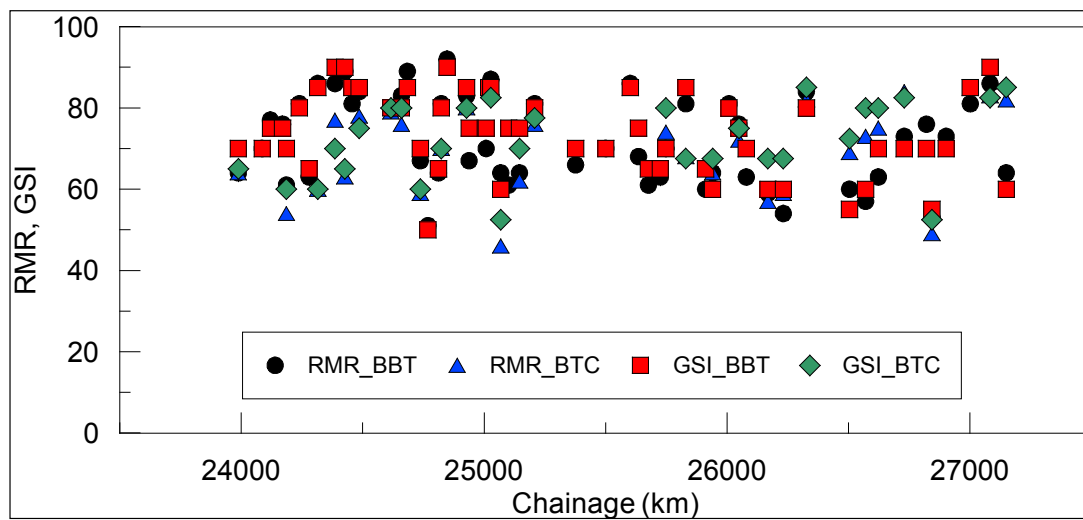


Figure 1. GSI and RMR ratings for the Central Gneiss unit.

During excavation, various machine parameters were recorded by sensors installed on the TBM. Table 3 shows the average values and range of these parameters for the investigated tunnel stretch.

Table 2. Technical specifications of the DS-TBM used in the excavation of the Exploratory Tunnel.

Technical specifications	S-1054
Machine length / weight	270 m / 1300 t
Main drive power	2800 kW
Thrust main cylinders (n)	42,750 (10)
Thrust auxiliary cylinders (n)	57,000 (16)
Shield + Cutterhead length	12,000 mm
Conicity / Extended overbore	95 mm / 224 mm
Cutterhead boring diameter	6850 mm
Rotational speed	0 – 9.05 rpm (Range I); 0-4.50 rpm (Range II)
Nominal torque	5247 kNm (Range I); 10,574 kNm (Range II)
Cutter nr. / diameter / spacing	41 / 19" / 90 mm
Contact thrust / Load per cutter	13,000 kN / 317 kN

METHODOLOGY

This study analysed the correlations between TBM parameters, including penetration rate (PR), instantaneous cutting rate (ICR), specific energy (SE), boreability index (BI), power consumption (P) and specific penetration (SP), and intact and rock mass parameters, such as RMR, and GSI values.

Table 3. Mean values and range of TBM parameters.

Parameters	Mean Value		Range	
	GA-ZG-S-1z	GA-ZG-G-1z	GA-ZG-S-1z	GA-ZG-G-1z
Thrust force (kN)	8272.42	9464.92	2954.6-10667.5	3487.6-11079.3
Torque (kNm)	1156	1055.43	500-1600	100-1800
Advance rate (mm/min)	35.79	25.32	12-57	5-54
Penetration rate (mm/rev)	6.42	4.45	2-11	1-13
Cutterhead rotation (rpm)	5.63	5.94	3.4-6.4	2.2-7.4
Specific energy (MJ/m ³)	46.49	65.81	11.2-89.3	10.2-135.3
Specific penetration (mm/rev/MN)	0.82	0.52	0.204-3.720	0.092-2.730
Auxiliary cylinder force (kN)	6521.04	8121.42	4116.8-9409.0	2407.8-9792.0
Power consumption (kW)	1264.41	1004.77	674.6-1712.9	88-1928.3

RMR and GSI values were determined at 55 locations and a data regularization process was applied. To this end, five-unit class intervals were defined between 50 and 100 for both RMR and GSI values to account for the intrinsic variability of the rock mass classification indices.

TBM data recorded at the chainages of RMR and GSI locations were considered. Specifically, the average value of these parameters along the corresponding TBM advancement was calculated. Additionally, derived TBM performance parameters were determined using the following equations:

$$SE = \frac{4 \cdot 1000 \cdot P}{PR \cdot rpm \cdot 60\pi \cdot D^2} \quad (\text{Bilgin et al. 2014}) \quad (1)$$

$$ICR = k \frac{P}{SE} \quad (\text{i.e. Exadaktylos et al. 2008}) \quad (2)$$

$$BI = \frac{FN}{PR} \quad (\text{i.e. Hamidi et al. 2010}) \quad (3)$$

where: P is the power consumption (kW), PR is the penetration rate (mm/rev), rpm is the rotational speed (rev/min), D is the diameter of TBM cutterhead (m), k is the energy transfer coefficient (typically ranging in the interval 0.8- 0.9 for TBM), SE is specific energy (kWh/m³), BI is boreability index (kN/cutter/mm/rev) and FN is the normal force (kN/cutter).

Finally, penetration rates were also calculated from the intact rock and rock mass data using the prediction models summarized in Table 4.

Table 4. Overview of selected performance prediction models for TBM performance evaluation.

Model	
Gehring (1995)	$PR = \frac{4FN}{\sigma_c} k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5$ $k_1 = 0.475 w_f^{-0.56} \quad \text{with } w_f = \frac{W_f}{\sigma_c}$ $k_4 = \frac{432}{d_c}$
Cassinelli et al. (1982)	$ROP = -0.0059 \cdot RSR + 1.59$ $RSR = 0.77 \cdot RMR + 12.4$
Innaurato et al. (1991)	$PR = 40.41 \cdot \sigma_c^{-0.437} - 0.047 \cdot RSR + 3.15$
Ribacchi & Lembo Fazio (2005)	$SP = 250 \cdot \sigma_{cm}^{-0.66}$ $\sigma_{cm} = \sigma_c \sqrt{\exp\left(\frac{RMR - 100}{18}\right)}$
Hassanpour et al. (2011)	$FPI = 0.053 \cdot RMR^2 - 4.205 \cdot RMR + 92.068$
Hamidi et al. (2010)	$FPI = 9.401 + 0.397 \cdot \log a + 0.011 \cdot J_c^2 + 1.14 \cdot 10^{-5} \cdot RQD^3 + 1.32 \cdot 10^{-8} \cdot \sigma_c^4$
	<p>PR: penetration rate (mm/rev); FN: normal force per cutter (kN); σ_c: UCS of the intact rock (MPa);</p> <p>k_1: correction factor for specific failure energy; k_2: correction factor for spacing and orientation of discontinuities; k_3: correction factor state of stress; k_4: correction factor for cutter diameters $\neq 432$ mm;</p> <p>k_5: correction factor for cutter spacing; W_f: failure energy (Nm); w_f: specific failure energy ($m^3 \cdot 10^{-6}$); d_c: cutter diameter (mm);</p> <p>ROP: rate of penetration (m/h); RSR: rock structure rating; SP: specific penetration (mm/rev)/(kN/cutter); σ_{cm}: uniaxial compressive strength of the rock mass (MPa);</p> <p>FPI: field penetration index (kN/cutter)/(mm/rev); J_c: condition of the joints; a: angle between the discontinuities and the tunnel axis ($^\circ$)</p>

RESULTS

RMR and GSI values demonstrate a strong correlation with the TBM performance parameters (Figure 2), as evidenced by the high R^2 values. Specifically, penetration rate, instantaneous cutting rate, and specific penetration exhibit a strong negative correlation with the RMR index, with a slightly weaker correlation observed for power consumption. The relationship between penetration rate and RMR is consistent with findings by Sapigni et al. (2002), Hamidi et al. (2010), Jain et al. (2016), and Armetti et al. (2018). The penetration rate graph suggests that maximum values are reached for RMR indices in the range of 60-80. The specific energy graph shows a strong positive correlation, highlighting the energy requirements' dependence on the rock mass rating, in line the findings of Exadaktylos et al, (2008) and Celeda et al. (2009). Finally, the boreability index exhibits a strong positive polynomial correlation, similar to the results of previous studies, such as those by Sapigni et al. (2002) and Armetti et al. (2018).

The analysis of the relationship between the GSI and various performance parameters reveals correlations similar to those obtained for the RMR. As GSI values increase, penetration rate and instantaneous cutting rate decrease, while specific energy and boreability index values increase. Power consumption values show a quadratic relationship with the GSI index. Specific penetration rates decrease significantly with rising GSI. Overall, for the encountered rock-mass of good quality ($GSI / RMR \geq 50$) in the considered tunnel stretch, the results highlight the significant influence of rock mass characteristics on TBM performance.

Figure 3 presents a comparison between the measured penetration rates and those calculated by various performance estimation models, revealing significant discrepancies among the models. It can be observed that the models proposed by Gehring (1995), Innaurato et al. (1991), and Hassanpour et al. (2011) generally predict higher penetration rates than those recorded, whereas the models of Cassinelli et al. (1982) and Hamidi et al. (2010) tend to yield lower estimates within a narrower range.

The Cassinelli model remains confined to a range of 1.0–1.6 m/h, which fails to reflect the variability observed in the actual penetration rates (0.7–3.0 m/h). However, the overall trend of the series remains consistent with the recorded penetration rates. Penetration rate calculated with the Cassinelli et al. (1982) model data are plotted on the secondary axis to more clearly illustrate and compare the trends.

Both the Gehring (1995) and Innaurato et al. (1991) models predict higher penetration rates than those observed, with the latter showing better agreement. In fact, the Gehring model is limited to $UCS = 100-250$ MPa and $FN = 200$ kN/cutter with its peak points occurring precisely outside its applicability range, specifically when $UCS < 100$ MPa and $FN > 200$ kN/cutter.

The Ribacchi & Lembo Fazio (2005) model exhibits a trend that closely aligns with the measured penetration rates, particularly at values below 40 (mm/rev)/(MN/cutter). However, this model generally provides more conservative and stable estimates compared to the recorded data. Notably, the peak values in the measured data tend to occur in sections where the normal force per cutter (FN) is relatively low or where the penetration rate is higher.

The Hassanpour model is presented on the primary axis, and its values demonstrate both a close alignment with the recorded data in terms of magnitude and a parallelism in overall trend. The fluctuations and peak points observed in the Hassanpour model largely coincide with those in the recorded data. The Hamidi model, shown on the secondary axis due to its relatively lower magnitude, exhibits a trend that is generally consistent with the recorded data, despite the differences in absolute values. The use of a secondary axis allows for a more effective visual comparison of the temporal variations and directional changes between the Hamidi model and the recorded data. Although the Hamidi model tends to underestimate the actual field values, it remains effective in reflecting the overall trend and variations observed in the field measurements. Furthermore, it is observed that the peaks in the actual penetration rates often correspond to intervals where the normal force per cutter (FN) is higher or the penetration rate is lower.

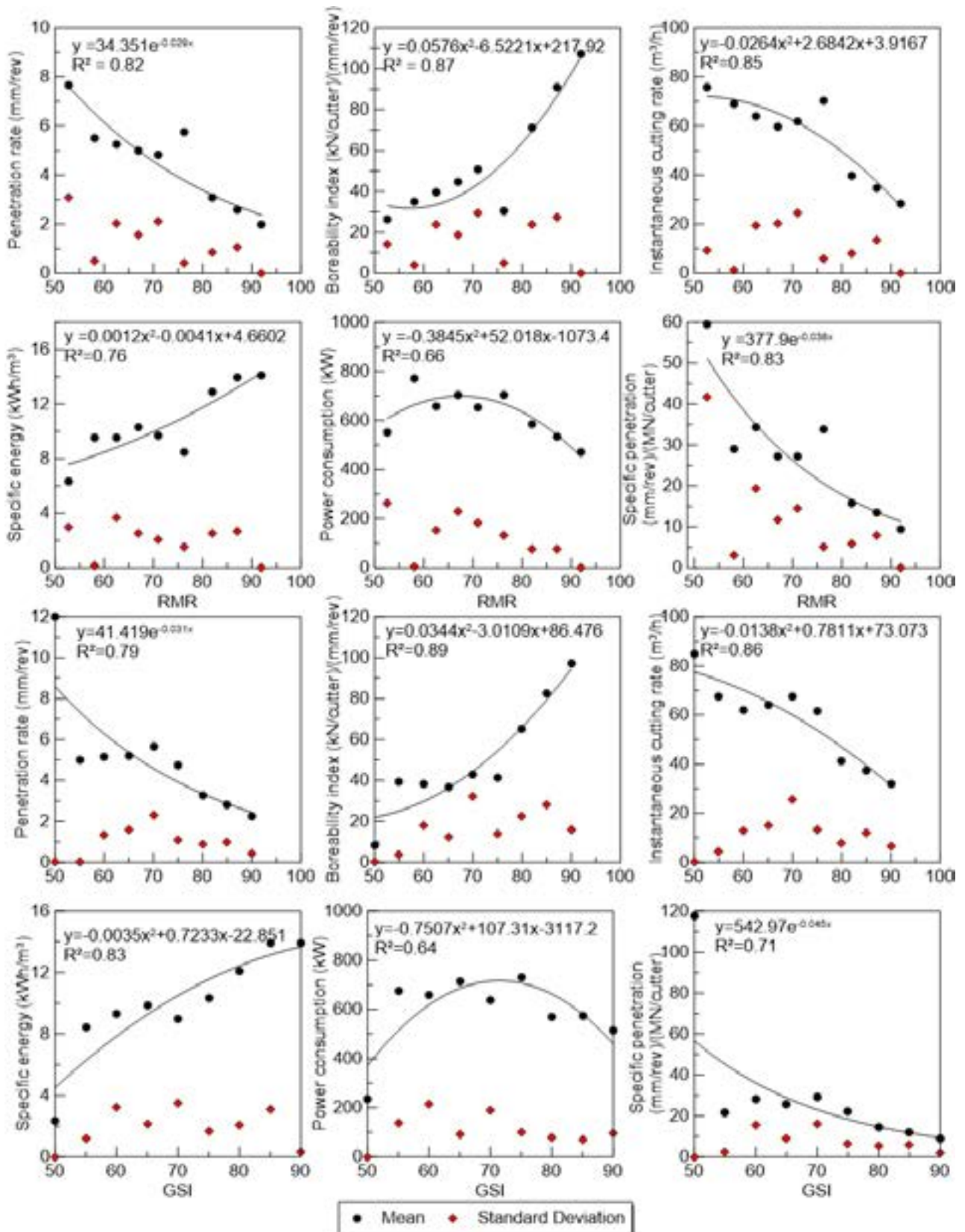


Figure 2. Relationship between RMR/GSI indices and TBM performance parameters.

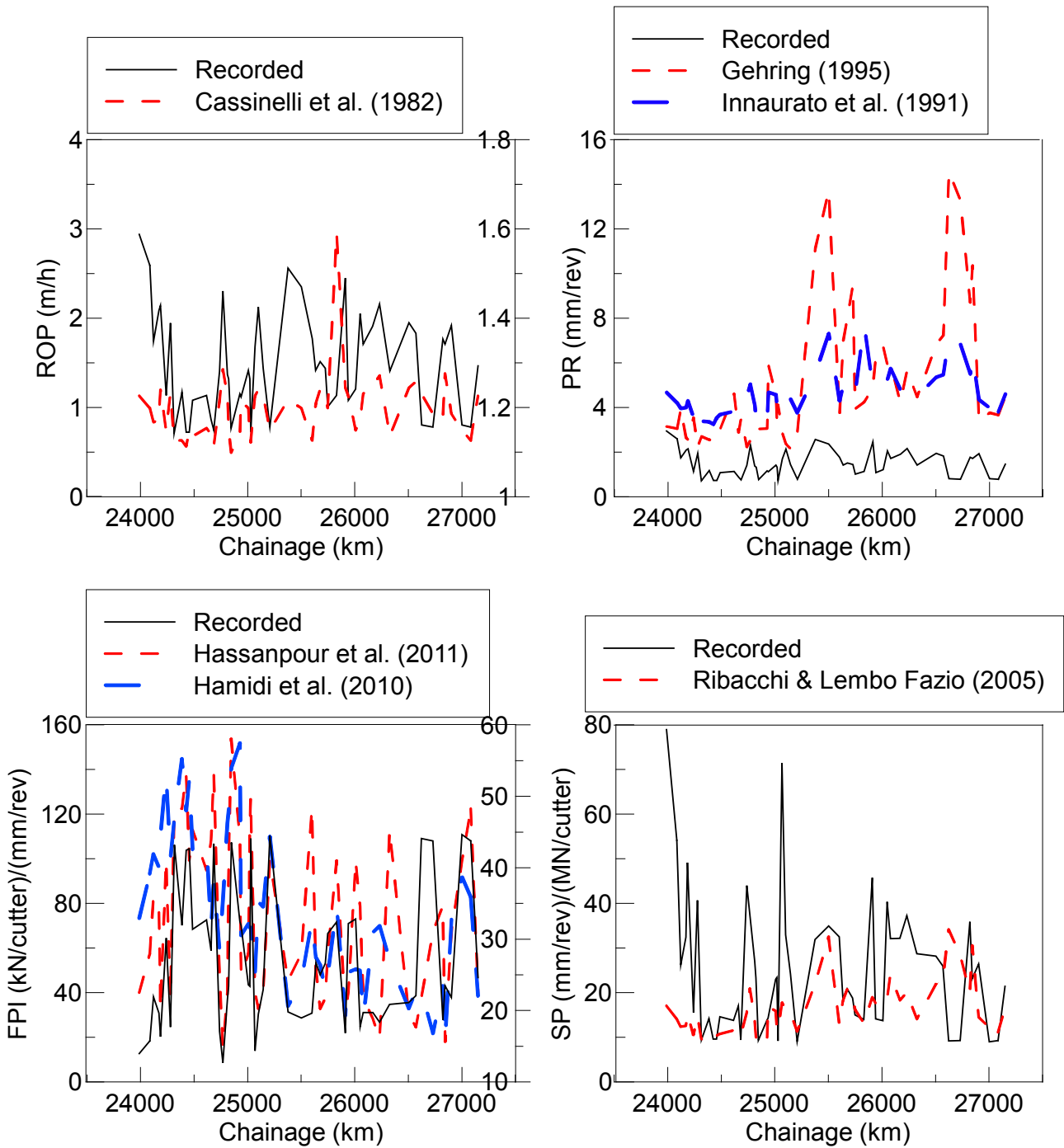


Figure 3. Comparison of actual penetration results with selected performance prediction models.

CONCLUSION

This study investigated the relationship between intact rock and rock mass properties and the TBM performance parameters collected during the excavation of the Brenner Base Exploratory Tunnel in the Central Gneiss unit. This unit is characterised by a predominantly low degree of fracturing and generally stable rock mass conditions ($GSI / RMR \geq 50$). Comprehensive field data, including both intact rock and rock mass characteristics, were statistically analyzed alongside actual TBM operational parameters. Additionally, penetration rates calculated by several prediction models were compared with the measured ones.

The research demonstrated that rock mass quality indices, specifically RMR and GSI, exhibit significant correlations with key TBM performance indicators. The results point out that higher rock mass quality gener-

ally makes the rock more difficult to excavate, and in parallel, it also increases energy and power consumption. However, parameters related to advance, such as penetration, instantaneous excavation speed, and specific penetration, show a decrease in high-quality rock mass. Strong correlations were detected for the rock mass RMR (with R^2 values ranging from 66% to 87%) and GSI (with R^2 values ranging from 64% to 89%) indices.

Furthermore, the study compared actual TBM penetration rates with predictions from established empirical and theoretical models. While some models, such as Hassanpour et al. (2011), closely matched both the magnitude and trend of the recorded penetration rate, others, like Cassinelli (1982), Hamidi et al. (2010) and Ribacchi & Lembo Fazio (2005), provided more conservative or lower estimates but were still effective in capturing general trends when appropriately visualized.

The differences between recorded penetration rates and those predicted by various models arise from a combination of factors, including the inherent variability in rock mass properties, limitations in model assumptions, TBM-specific operational dynamics, and site-specific geological conditions. To enhance prediction accuracy, future studies should focus on integrating more detailed geomechanical data, accounting for real-time TBM operational adjustments, and refining models to better reflect modern TBM technologies and unique site conditions. The findings of this study highlight the critical role of detailed geological and geomechanical characterization in TBM performance prediction and tunnel design. By employing multiple performance models validated against field data, the reliability of TBM selection and operational planning can be significantly improved, leading to more efficient and predictable tunneling outcomes.

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