Performance of different diameter Double Shield TBMs: experiences from the excavation of exploratory tunnel and main tubes of the Italian lot Mules 2-3 – Brenner Base Tunnel

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ABSTRACT: The Brenner Base Tunnel is a 64 km long underground railway connection under construction between Italy and Austria. The project mainly consists of two main one-track tunnels and a central exploratory tunnel 12 m below them. Considering that the three tunnels intersected the same rock masses and fault zones, the paper analyses the scale factor displayed by selected machine parameters in relation to the tunnel diameter, TBM characteristics and rock mass conditions. Final considerations about the performance of the three TBMs, also in the context of comparable case-histories, are addressed.

Keywords: Brenner Base Tunnel (BBT), Double Shield TBM (DS-TBM), Exploratory Tunnel (ET), Main Tunnels (MT), Key Performance Indicators (KPI), scale factor.

1 INTRODUCTION

The BBT is a system of underground structures currently being excavated to build a high-speed railway connection between the town of Fortezza (Italy) and the city of Innsbruck (Austria). The project mainly consists of two main tubes (MT) and an exploratory tunnel (ET) excavated in advance (Figure 1). The 14.2 km long Italian stretch of the ET, already completed in January 2022, was driven by a DS-TBM with a cutterhead diameter of 6.85 m. The main tunnels are currently being excavated by two twin DS-TBMs with a larger diameter of 10.71 m; in particular, on 9th January 2023 the excavations of the east and west MTs, respectively, were 95 % and 75 % complete.

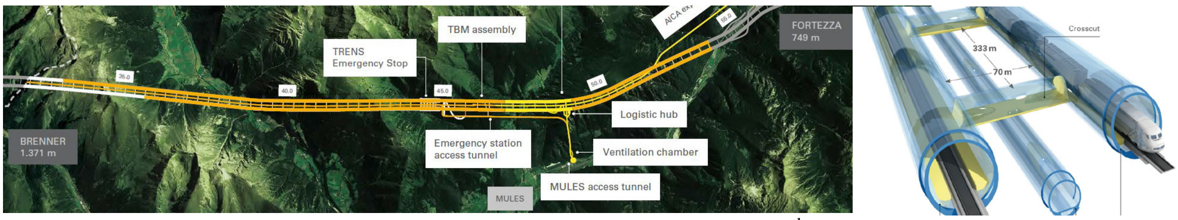

Figure 1. Tunnel layout and status of the works Mules 2-3 lot (Italy) on 9th January 2023 (www.bbt-se.com).

2 GEOLOGICAL AND GEOMECHANICAL CONDITIONS

The tunnels were driven under extremely complex geological-geomechanical conditions, with overburdens varying between 700 and 1,700 m. The forecast and as built geological models are shown in Figure 2: the tectonic units are labelled above the profile and the single litho-stratigraphic units are represented by the different colours (Skuk et al. 2023).

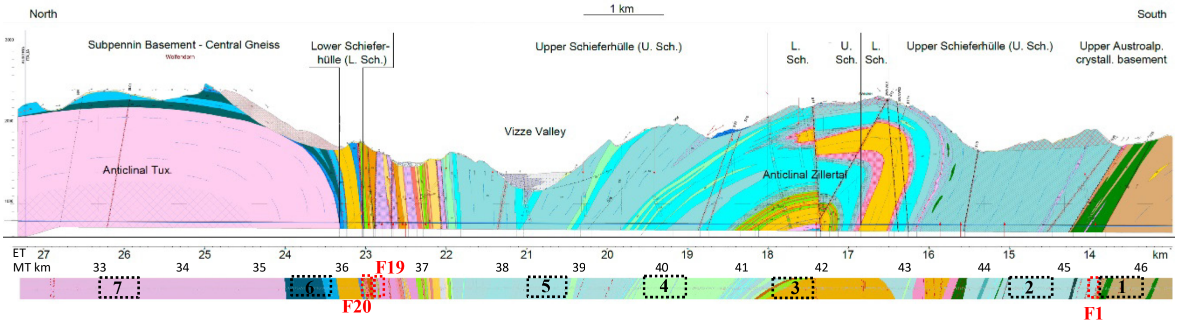

Figure 2. Forecast (upper graph) and as built (lower graph) geological models showing the analysed homogeneous zones 1-7 (black rectangles) and faults zones F1, F19 and F20 (red rectangles).

To investigate the influence of TBM diameter and characteristics, seven 500 m long homogeneous zones from a geological and geomechanical point of view were selected (Figure 2, Table 1). Each of them was characterised by regular excavation conditions in terms of rock-cutterhead interaction and observed ground behaviour, which strongly depend on intact rock strength (UCS, BTS) and abrasiveness (CAI), properties and orientation of main discontinuities and tunnel overburden.

Table 1. Geological and geomechanical data of the analysed zones.

Zone	equ. km MT-E	Over-burden	Tectonic / Stragraphic unit	Main lithologies	Rock mass description		RMR [-]	R1 [MPa]	UCS [MPa]	BTS [MPa]	CAI [-]	Ground behaviour / Notes
Zone 1	45903	1037	Upper Austroalpine / Crystalline basement	Micascists	Low to medium fractured, sub-vertical schistosity against drive (strike ±⊥ TA), no H2O	μ	52	63.8	75.0	6.3	3.8	Block failure, face and cavity, subordinated minor squeezing
	45403	1193				σ	8	18.1	5.0	0.8	0.5	
Zone 2	44803	1050	Upper Schieferhülle / Bündnerschists	Calcareous scists, undifferentiated	Low fractured, sub-vertical schistosity with drive (strike ±⊥ TA), no H2O	μ	54	46.9	41.0	3.9	2.7	Small block failure, face and cavity
	44303	966				σ	7	21.7	18.0	1.3	0.4	
Zone 3	41853	1469	Lower Schieferhülle / Kaserer FM	Micaschists, metaarcoses	Low fractured, sub-horizontal schistosity (variable strike), no H2O	μ	59	51.6	71.0	9	3	Face mainly stable Cavity minor to medium squeezing
	41353	1355				σ	6	19.4	15.0	1.5	0.3	
Zone 4	40303	1229	Upper Schieferhülle / Bündnerschists	Prasinites, greenschists	Low fractured, schistosity dipping 40-70° with drive (strike ±⊥ TA), 1 H2O inflow (4l/s)	μ	72	151.5	105.0	6.5	2.1	Small block failure, face and cavity
	39803	1189				σ	8	43.7	30.0	2.5	1.1	
Zone 5	38803	636	Upper Schieferhülle / Bündnerschists	Calcareous scists, marbles	Low to medium fractured, schistosity dipping 50-70° with drive (strike ±⊥ TA), no H2O	μ	61	71.3	98.0	7.2	2.0	Block failure, face and cavity
	38303	616				σ	4	11.5	22.0	2.2	0.7	
Zone 6	35903	983	Lower Schieferhülle / Schwarzkopf FM ?	Quartzites, quartzitic scists, small graphitic phyllites interlayers	Low fractured, sub-vertical schistosity against drive (strike ±⊥ TA), no H2O	μ	61	73.1	73.5	7.1	4.9	Block failure, face and cavity
	35403	1189				σ	8	30.5	31.0	3.4	0.4	
Zone 7	33500	1573	Subpennine Basement / Central Gneiss	Granitic gneiss, subordinated biotitic scists	Compact, partly sub-horizontal foliation plus 2-3 joint sets, 1 H2O inflow (1 l/s)	μ	73	163.2	199.0	10.3	5.1	Local spalling and/or local gravity induced failure, face and cavity
	33000	1629				σ	10	33.2	27.0	0.3	-	
F1	45403	1193	Upper Schieferhülle / Bündnerschists	DZ: high fratured calcareous scists; CZ: cataclasite	Fault TSW1 dipping 60-70° against drive (strike ENE-WSW), no H2O	μ	42	26.3	-	-	-	Minor squeezing for DZ+CZ
	45303	1197				σ	6	13.0	-	-	-	
F19	36553	853	Upper Schieferhülle / Aigerbach FM	DZ: disturbed marbles, anhydritic-cloritic schists; CZ: kakirites, (fault gouge), rauwacke, gypsum	Fault Vi-5-535 dipping sub-vertical against drive (strike W-E ±⊥ TA), H2O inflow East MT (3-6 l/s)	μ	36	31.9	-	-	-	Instability of face and cavity for CZ
	36453	894				σ	7	11.3	-	-	-	Instability of face and cavity plus water inflow for CZ in the MT-W
F20	36403	913	Upper Schieferhülle / Aigerbach FM	DZ: disturbed anhydritic-cloritic schists; CZ: kakirites, (fault gouge), rauwacke, gypsum	Fault Vi-5-755 dipping sub-vertical against drive (strike W-E ±⊥ TA), no H2O	μ	33	23.4	-	-	-	Instability of face and cavity for CZ
	36303	982				σ	5	11.6	-	-	-	*** RMR / R1 values representative for DZs of faults**

The rock strength and abrasiveness data taken from the detailed design documents are integrated in Table 1 by as built data from all three tunnels: i.e., lithologies, main discontinuities, RMR index and its partial rating R1, the field estimated rock uniaxial compressive strength.

In addition, three 100 m long stretches crossed by major (predicted) fault zones with different ground response were also analysed. Namely, the F1 fault was driven through by the TBMs with high advance rates and applying mainly a partial regripping advance mode, while the F19 and the F20 faults (the largest of the construction lot) required rock mass pre-consolidation measures and the use of exceptional advance modes (single shield, partial regripping, low revolution-high torque gear etc.). The fault F19 was characterized by water inflows only in the west MT between 3 and 6 l/s, where additional drainage tubes were installed.

3 TBM EXCAVATION OF TUNNELS WITH DIFFERENT DIAMETER

3.1 Main technical features of the DS-TBMs

The main technical features of the three double-shield TBMs designed by Herrenknecht are summarised in Table 2. There are remarkable differences in length and weight of the machines, cutterhead diameter and in the nominal values of installed power, thrust, torque and rotational speed. However, there are similarities in the shield geometry (e.g. shield length, overbore) and cutterhead design (e.g. cutter diameter and spacing, load per cutter). The two possible drives of both large- and small-diameter machines are a high revolution speed-low torque gear (range I) and a low revolution speed-high torque gear (range II), with different values of torque against speed.

Table 2. Main technical features of the ET DS-TBM S-1054 and MT DS-TBMs S-1071 / S-1072.

Technical features	S-1054 Exploratory Tunnel	S-1071 / S-1072 Main Tunnels
Machine length / weight	270 m / 1300 t	220 m / 2800 t
Main drive power	2,800 kW	4,200 kW
Thrust main cylinders (nr.)	42,750 kN (10)	95,000 kN (18)
Thrust auxiliary cylinders (nr.)	57,000 kN (16)	112,815 kN (38)
Shield + Cutterhead length	12,000 mm	12,480 mm
Conicity / Extended overbore	95 mm / 224 mm	115 mm / 224 mm
Cutterhead boring diameter	6,850 mm	10,710 mm
Rotational speed	0 – 9,05 rpm (range I)	0 – 5,11 rpm (range I)
	0 – 4,50 rpm (range II)	0 – 2,55 rpm (range II)
Nominal torque	5,247 kNm (range I)	13,601 kNm (range I)
	10,574 kNm (range II)	27,524 kNm (range II)
Cutter nr. / diameter / spacing	41 / 19 " / 90 mm	64 / 19 " / 90 mm
Contact thrust / Load per cutter	13000 kN / 317 kN	20160 kN / 317 kN

3.2 Factors influencing TBM excavation

The factors influencing the operational parameters and the performance of a TBM can be divided into three groups: geological and geomechanical factors (C_g), mechanical factors (C_m) and human factors (C_h) (Armetti 2018). Geological and geomechanical factors are highly variable during the 14 km long tunnel excavations. Mechanical factors related to the machine geometry and characteristics are supposed to be constant during the advance, considering the daily maintenance implemented. The human element is influenced by the experience of the TBM operator and his team and had a significant effect on the crossing of critical geological areas such as fault zones. In this paper the influence of the first two factors is investigated, as the human element is difficult to assess.

Hence the generic TBM parameter of the main tunnel, called KPI_{MT}, is related to that of the exploratory tunnel, KPI_{ET}, as $KPI_{MT} = C \cdot KPI_{ET} = (C_g+C_m) \cdot KPI_{ET}$.

4 ANALYSIS OF THE TBM PARAMETERS

4.1 Relevant Key Performance Indicators (KPI) and global scale factor

The most relevant KPIs to describe the excavation process at the tunnel face are the total thrust force [kN], the penetration per revolution [mm/rpm] and the torque [MNm], recorded by sensors at 3 second intervals. In order to avoid spikes and non-significant instant recordings, an average of these values over a single TBM advance was considered in the next calculations. The cutterhead rotation speed [rpm], guaranteed by the torque generated by the main drive motors, and the total thrust force, exerted by the main cylinders, are regulated by the operator of the TBM to guarantee a rate of penetration within the range 30-50 mm/min. The penetration per revolution is the effect produced during the excavation by the simultaneous translation and rotation of the cutterhead.

A first analysis of KPI values along the three tunnels was carried out to find a global scale factor C between the ET and the MT TBMs (see paragraph 3.2). In this case, the coefficient C only reflects the influence of the mechanical factors (i.e. $C = C_m$), since all data are considered without any distinction among the different zones. Figure 3 shows, as an example, the values of the thrust force recorded for the three TBMs, indicating a value of $C_m = 2.0$.

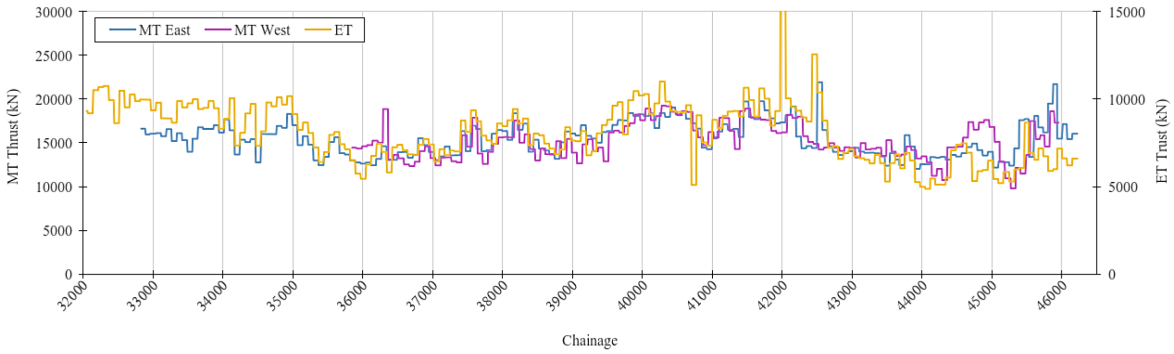

Figure 3. Averaged thrust values of the three TBMs along entire tunnel length.

4.2 Scale factor in geological homogeneous zones and fault zones

The scale factor C for the thrust force, identified as the KPI with the highest correlation with the main characteristics of rock and rock mass (i.e. RMR, R1 and UCS), is shown in Figure 4 for the seven homogeneous zones and the three fault zones defined in Table 1. For the sake of comparison, the dashed lines refer to the value of C_m identified in the previous paragraph: as such, the vertical distance between each symbol and the dashed line identifies the influence of the geological and geomechanics characteristics, i.e. the value of C_g.

The graphs show an indirectly proportional relationship with the RMR, R1 and UCS values, thus indicating that in low-quality zones the larger TBM should guarantee an adequately thrust force (i.e. $C_g > 0$) to counteract shield friction and local face instabilities, higher than that calculated by theorical considerations based on the TBM characteristics. This situation is amplified in fault zones, where the TBM with a larger diameter has greater difficulty in advancing due to the rock mass behaviour (more pronounced block instability, deeper stress induced failure etc.). On the contrary, high-quality zones display an opposite trend (i.e. $C_g < 0$). In fact, the minimum value of C is reached for rock masses with high UCS/R1 (100-200 MPa) and RMR (75-85) values because larger diameter TBMs typically adopt limited thrusts to reduce cutting edge wear and overload, and therefore cutterhead maintenance, to ensure an adequate daily production. The larger degree of correlation is obtained with the RMR value: this means that the thrust force parameter is particularly connected with the overall characteristics of the rock mass identified by the RMR itself.

Good correlations were also found for the scale factor of the penetration per revolution, which shows a positive proportionality with the values of RMR, R1 and UCS (Figure 5; C_m, indicated again by the dashed line, is here equal to 1.2). In this case the best correlation is obtained with the UCS parameter, thus indicating that this KPI strongly depends on intact rock strength.

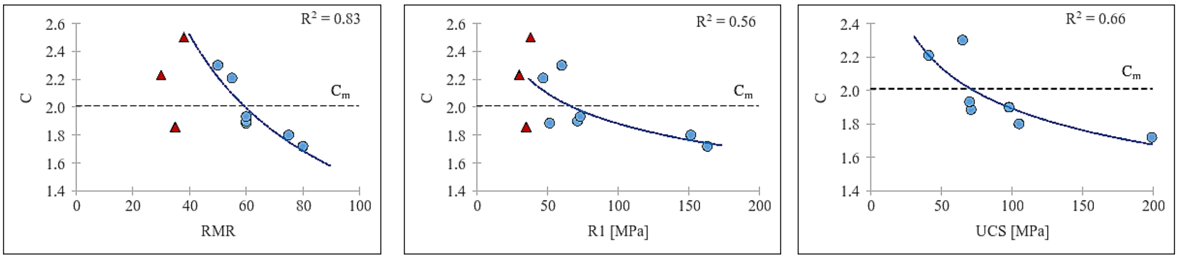

Figure 4. Correlation between the scale factor C for the thrust force and averaged values of RMR, R1 index and UCS of the analysed homogeneous and fault zones (respectively identified by blue circles and red triangles).

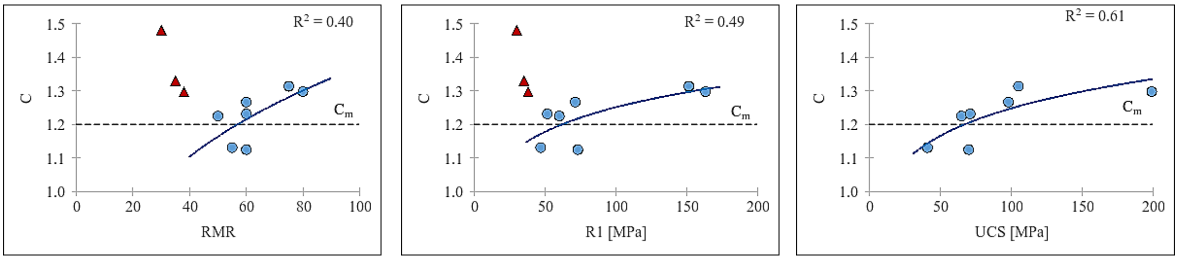

Figure 5. Correlation between the penetration scale factor C and averaged RMR, R1 Index and UCS values of the analysed homogeneous and fault zones (respectively identified by blue circles and red triangles).

In good quality rock, with high UCS values, TBMs with larger diameters obtain higher penetration values (i.e. $C_g > 0$), as the available major contact thrust is distributed to a smaller number of cutters on face area. The chipping process may also be facilitated due to the higher number of joints and schistosity planes, with narrow spacing and higher aperture due to more pronounced decompression related to the larger area of the face. In fault zones, exceptional penetration values are recorded for large diameter TBMs caused by the global instability of the face and the larger applied thrusts.

No relevant correlations were observed for the relative torque scale factor. The torque is the force that the engine must guarantee to maintain a fixed rotational speed, therefore it depends on the driving style of the operating team and the power of the machine. It was observed that in the ET the rotational speed was frequently modified to keep the torque at a low value, while in the MTs (especially in the eastern tunnel) its speed was kept as constant as possible, in order to take advantage of the larger power of the motors. However, it was also observed that in fault zones, where unstable face behaviour causes backflow of material in and above the cutterhead and the drive takes place in range II mode, the larger diameter TBMs reaches the maximum value of the C scale coefficient.

4.3 TBM performance

The TBM performance can be analysed through two calculated KPIs, namely the rate of penetration ROP related to the effective boring time (excavation length / excavation time) and the advance rate AR (excavation length / total working time). Figure 6(a) shows that ROP values are correlated with RMR values following a quadratic trend, already observed in other tunnels excavated in similar rock mass conditions (Sapigni et al. 2002). More specifically, the larger-diameter TBMs display a higher vertex in comparison to that estimated for the ET; in contrast, ROP values are higher for the low-diameter TBM for RMR values above 75 and below 40.

The correlation between ROP and AR values is displayed in Figure 6(b). The figure shows that high ROP values occur in poor rock masses where exceptional advance modes are required (single shield or partial regripping mode), thus associated with lowest AR values. In addition, low AR values also occur in high quality rock masses, typically combined with low ROP values. The best performance in terms of AR is achieved by the larger-diameter TBMs in the intermediate conditions, i.e. RMR= 40-75, due to the larger thrust force and penetration per revolution and due to the larger length of the lining segments, which reduce the total regripping times.

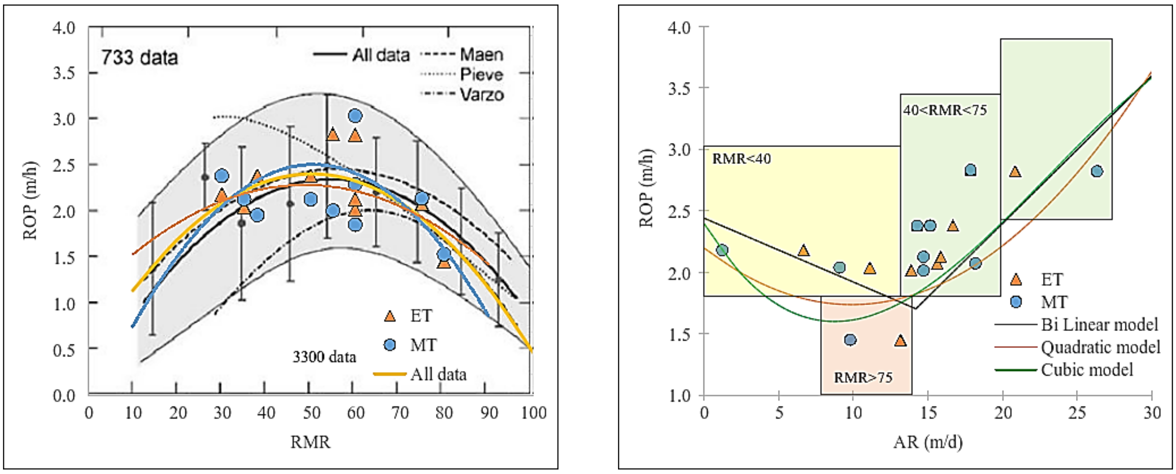

Figure 6. Correlation between ROP and RMR values (left, modified from Sapigni et al. 2002) and between ROP and AR values (right).

5 CONCLUSIONS

The paper shows an analysis of the main KPIs of the excavation process, i.e. thrust force, penetration per revolution and torque, recorded for a total excavated length of 38 km, carried out to identify the scale factor between the MT and ET TBMs and to assess the influence of mechanical TBM characteristics and geological/geomechanical conditions. The data interpretation indicates that:

- a global scale factor related to TBM characteristics was clearly identified for the three investigated tunnels, thus indicating the possibility of employing the recorded machine parameters of the ET, excavated in advance, to optimize the design and the construction of the MTs;
- variations from the global scale factor were observed for several homogeneous and fault zones due to the influence of geological and geomechanical conditions. These were found to be well correlated with intact rock and rock mass properties and can be easily explained considering the excavation behaviour of different-size TBMs;
- the TBMs of the lot Mules 2-3 reached ROP values consistent with those measured in similar tunnelling projects;
- in terms of AR values, the smaller-diameter TBM was characterized by a better performance in the extreme ranges of RMR values (i.e. < 40 and > 75), while comparable productions to those of the larger-diameter TBMs were recorded for good quality rock masses (i.e. 40 <RMR <60);
- more in general, the study highlights how crucial is to determine the scaling factor and in particular, on the basis of which parameter it can be properly - and usefully - defined.

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