Return of experience following the excavation of “La Maddalena Reconnaissance Gallery” - TBM performance prediction in the Ambin Massif

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ABSTRACT: The geological and geotechnical context of the rocky massif of “La Maddalena Reconnaissance Gallery” and the results of excavation with an “open type” TBM are presented, with particular reference to the stretch between ch. 3+045 and 7+020 with overburden constantly over 1000 m, up to a maximum of 2000 m. Based on the registered data of the machine and the geomechanical characteristics of the rock mass collected during the tunnel boring, the real TBM excavation progress, total and net, and the advance values predicted by some empirical models, commonly used to forecast the TBM performance on the basis of the traditional rock mass classification indices, are compared. The consequent critical analysis of the applicability of the empirical approaches to the excavation performance parameters prediction within the Ambin Massif represents an interesting base of knowledge, which is made available for the design of future excavations in similar geomechanical contexts.

1 INTRODUCTION

“La Maddalena Reconnaissance Gallery”, executed between 2014 and 2017 to collect geomechanical information for the design of the future Turin-Lyon transalpine railway base-tunnel, is 7,020 m long. Its final section crosses, for almost its entire length, the crystalline bedrock of the Ambin Massif.

The study refers to the tunnel part excavated under a high overburden, involving the geometrically and structurally deeper geologic unit of the Ambin Massif, named the Clarea Complex (CLR), mainly composed of micaschists and gneiss.

In particular, the gallery section of about 4,000 m excavated in the period May 2015 - February 2017, included between ch. 3+045 and the final ch. 7+020, where the overburdens are consistently over 1,000 m, up to a maximum of about 2,000 m, has been examined.

From the data collected during the construction, the net and gross advancement of the TBM have been analysed and compared with the forecasts deduced from empirical methods, such as Bieniawski rock mass excavability (RME) indicator and Barton Q index.

In addition, possible correlations between the geomechanical RMR and Q indices classifying the mass and the net progression rate recorded by the tunnel boring machine have been looked into.

2 GENERAL CONTEXT

La Maddalena Reconnaissance Gallery is a natural tunnel near La Maddalena location, within the Municipality of Chiomonte (TO), Italy. The excavation was carried out using traditional methods until ch. 0+198; further on a mechanised method was implemented, using an open-type TBM. The tunnel extends to ch. 7+020. The altitude of the tunnel at the entrance is about 670 m above sea level. The TBM nominal diameter of excavation is 6.30 m. The internal measurements and shapes of the tunnel were fixed during the design phase, considering the requirements of the reconnaissance gallery excavation phase, with reference to the subsequent construction phases and the operation. Within the tunnel, in large side chambers, an accumulation basin and a redirection area for the water intercepted during excavation are located at ch. 4+130 and ch. 2+805, respectively. The elevation profile of the tunnel is: uphill for the first 1,500 m, with an approximate 0.34% slope, then drops downhill with a max slope of 3.32% for about 1,600 m. In the last 3,500 m circa, the section is uphill with a max slope of about 1.118% (Figure 1).

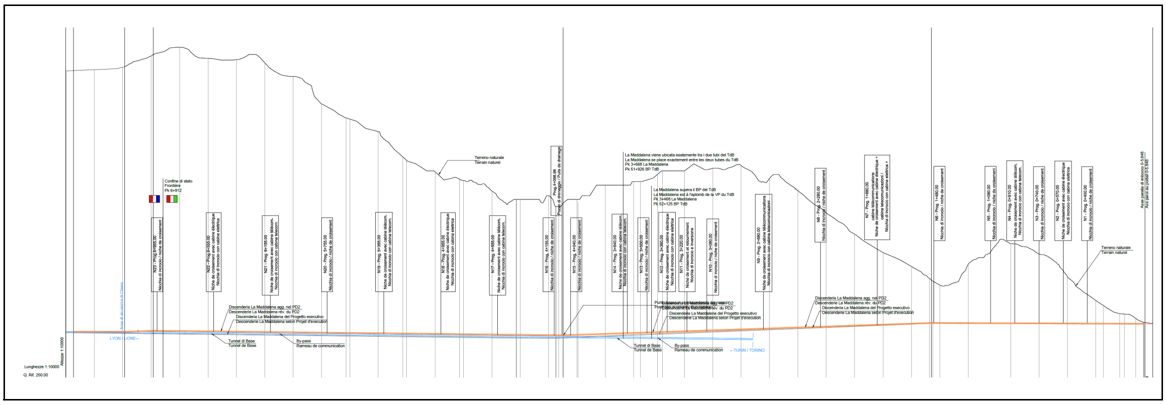

Figure 1. Elevation profile of the gallery.

In terms of planimetric layout, the tunnel initially is straight for 300 m, followed by a bend of 1,500 m radius of curvature, then another straight section of about 1,600 m and a bend of 1,000 m radius of curvature, to finally continue straight on to the end. Starting from about ch. 3,670 the reconnaissance gallery is aligned with the two tubes of the future base tunnel (Figure 2).

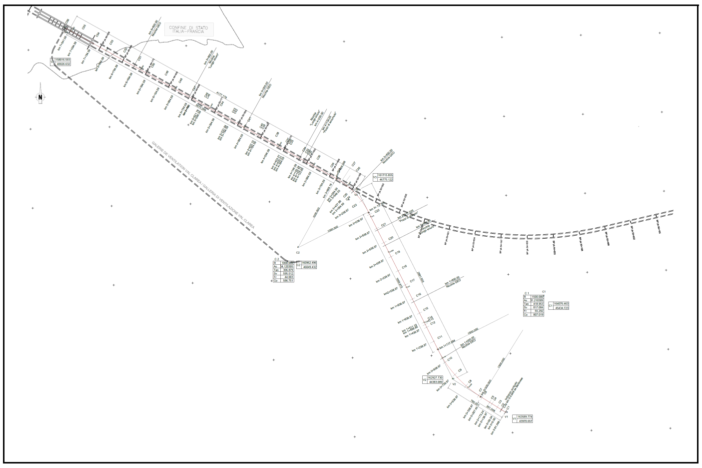

Figure 2. Planimetric layout of the gallery.

3 GEOLOGICAL AND HYDROLOGICAL CONTEXT

The reconnaissance gallery for almost its entire path crosses through the crystalline underbed belonging to the tectonostratigraphic unit of Mont d'Ambin.

Only for a limited section, near the entrance, for about the first 120 m, the excavation involves slope quaternary deposits (fluvioglacial deposits and undifferentiated glacial deposits) and, subsequently, up to ch. 0+198, a series of lithotypes that can be classified as cargneule (ca), dolomite rock with intercalation of talc and talcschist (do) and carbonatic-phyllitic schists, micaschists with chlorite (GCC). Starting from ch. 0+198, it continues on in the Ambin Massif, first crossing aplite gneiss (AMC) with jadeite (up to ch. 1+148) and, following that, albite gneiss and quartz-conglomeratic micaschist belonging to the Ambin Massif (AMD). In the following section, from ch. 1+350 up to the end (ch. 7+020), the reconnaissance gallery exclusively crosses the geometrically and structurally deeper unit of the Ambin Massif: that is the Clarea Complex (CLR), which is uniformly characterised by minute gneiss and micaschist with biotite, muscovite, glaucophane, garnet, quartz and albite in a grey-bluish colour with a layered structure due to the presence of stretched out lenses and layers of metamorphic quartz. As anticipated, the present paper is focused on the exploratory tunnel stretch between ch. 3+045 and ch. 7+020 (the section framed in red in the following figure), in which the overburdens are consistently above 1,000 m, with a maximum of about 2,000 m in the final sector (Figure 3).

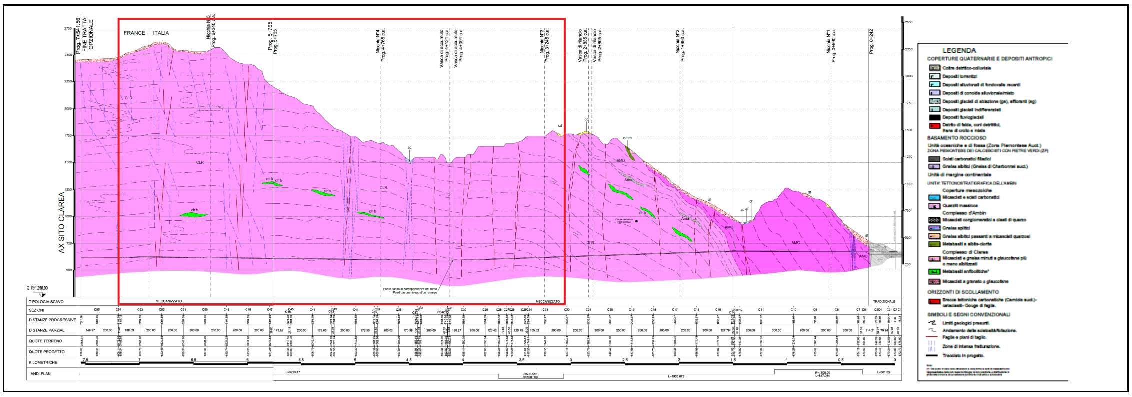

Figure 3. Geological and geomechanical profile of the tunnel.

Under the hydrogeological profile, the entire length of the reconnaissance gallery crosses rock masses that are characterised by fracturing permeability that is the underground circulation of water is substantially controlled by the fracturing density, the interconnectivity of the joints and the localised presence of persistent, permeable discontinuities. During excavation, no areas with significant concentrated water flows have been encountered, except for a few limited passages with permeations along fault lines and intense fracturing zones, however, with limited short-term peak flow rates.

4 TBM CHARACTERISTICS

The tunnel boring machine was designed according to the expected geological conditions and the several activities requested for geological and investigative purposes, for the consolidation of the cavity, and for high levels of productivity even in unfavourable environments. The TBM used belongs to the family of "high-performance machines in hard rock formations". It can be divided into three structural components consisting of an operational section (cutterhead, bulkhead and main beam), the gripping section (the thrust and gripping system), and the drive section (electric motors with gearboxes, gearwheel and main bearing, collection blades on the head and a conveyor belt). The potential presence of poor-quality materials, with different characteristics and problems, such as the investigative purpose of the tunnel, have influenced the set-up of the machine in terms of the power available to the head and its structure and powering overall. That led to the creation of two main work zones in which targeted consolidations and geological investigations could be carried out. The machine has thus been designed with two separate work zones, named L1 (as close as possible to the head ,about 6 m from the front) and L2 (about 40 m from the front). The distance between the boring front and the area where the supports were installed has determined the design choices in terms of the excavation sections. The following table lists the main characteristics of the tunnel boring machine (Table 1).

Table 1. TBM main characteristics

Cutterhead		Technical specs	
Boring diameter:	6.30 m	Max operational thrust	13,667 kN
N. of cutters:	43	Max thrust capacity	14,200 kN
		N. of motors	7
		Cutterhead power	2,205 kW
		Cutterhead rotation speed	0 – 9.3 revs/min.
		Thrust cylinder stroke	1,830 mm
		Recommended cutterhead pressure	310 bar
		Nominal system pressure	345 bar

The excavation parameters were recorded by an Automatic Data Detection and Recording System able to read, display and collect the most important parameters. The Automatic System then extracted the data collected, so it could be continuously recorded, monitored, processed and compared to the data coming from surveys and monitoring.

5 GALLERY EXCAVATION SECTIONS

On the basis of the geological and geomechanical study of the rock mass, a series of excavation and consolidation sections that could be applied in the various scenarios according to the RMR index and tunnel overburdens has been defined in the design stage, together with a criterion for their application.

Sections with occasional bolts were then adopted (sections F1 and F2), referring to the best geomechanical conditions expected along the reconnaissance gallery stretches with RMR values above 60 (class 2), and with systematic bolting (F3a-b-c and F3c_1) or single ribs (FMV) for intermediate geomechanical situations with RMR values between 51 and 60 (Class 3).

In the lower-rated geomechanical contexts with RMR values below 51 (Classes 3 and 4), where a higher fracturing degree in the mass and more evident plastic deformations are present, the sections made up of metal panels with double ribs were planned for (sections F4 and F5). Lastly, to limit rockburst phenomena, specific sections were designed (sections F4_1 and F5_1) that reinforce the shapes and increase the frequency of the metal panels that constitute sections such as F4 and F5.

6 DATA COLLECTED DURING THE EXCAVATION PHASE: GEOMECHANICAL CLASSIFICATION OF THE MASSIF AND ADVANCE OF THE TBM

6.1 *Geomechanical classification of the massif*

In terms of geomechanical characteristics, in the stretch being examined between ch. 3+045 and ch. 7+020, the rock masses crossed through were found to be good (RMR classes 2 and 3), showing weakened characteristics only at short sections along faults or intense fracturing zones (RMR class 4).

The following figure (Figure 4) lists the subdivision into RMR classes and the trend of the relative index as the reconnaissance gallery advances.

The micaschists of the Clarea Complex (CLR) have shown average σ_c strength around 100 MPa, accompanied by an accentuated mechanical anisotropy due to the typical markedly schistous texture of the lithotype.

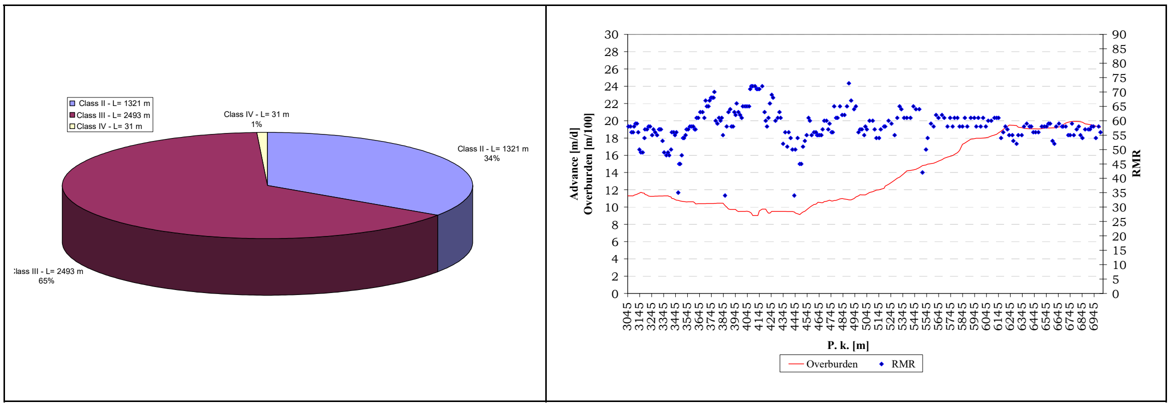

Figure. 4. Massif quality between p.k. 3+045 ÷ 7+020 – Bieniaswski RMR class – Percentage breakdown (a) – Sampled RMR and progression of the tunnel overburden (b).

6.2 *Progress of the tunnel boring machine - Total advance (TA) and net advance (NA).*

In the period May 2015 (ch. 3+045) - February 2017 (ch. 7+020), the tunnel boring advances were between a max. of 280 m in April 2016 and a min. of 45 m in August 2015, a month in which repairs were done on the TBM, with an average of about 190-200 m per month. The following figure (Figure 5) illustrates the gross monthly progress in m/month, called Total Advance (TA), which includes stoppages for maintenance, surveys, repairs of collapses s, etc. which took place in the time span considered. The same figure indicates, month by month, the use percentage of the tunnel boring machine.

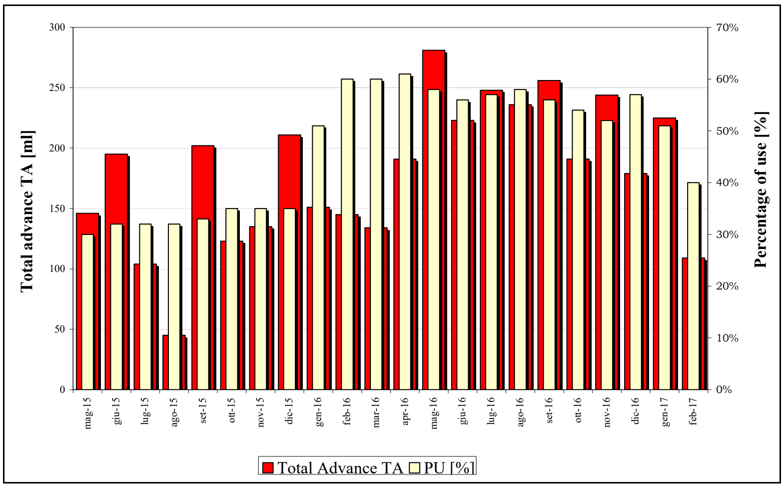

Figure 5. Monthly progress (Total advance TA) of the TBM and relative percentage of use (PU)

An adjustment was made to the gross monthly advance TA numbers to account for the slow-downs and stoppages of the TBM which were necessary for the systematic execution of the geological studies taking place at the boring front, so as to bring the case in question to a “classic” mechanical excavation in which the effective boring time is a sum of the excavation, regripping and towing of the backup. The gross TA values were then increased by a percentage equal to the relationship between the time required for the execution of the geological studies and geotechnical investigations and the theoretical monthly times, generally about 4% on average. The average daily TA in the period of reference resulted about 6.5 m.

Starting from the aforementioned total advance (TA) values, the relative net advance (NA) numbers were calculated, multiplying the TA values for the actual machine use coefficient (subtracting the time required to carry out maintenance, repairs and surveys). The average daily net advance (NA) in the period of reference came to about 17.5 m. Below is a representation of the Total Advance TA (Figure 6) and the Net Advance NA (Figure 7) in m/day, monthly averaged, in the section studied. To be fully exhaustive, the tunnel overburden and the detected RMR values are also indicated.

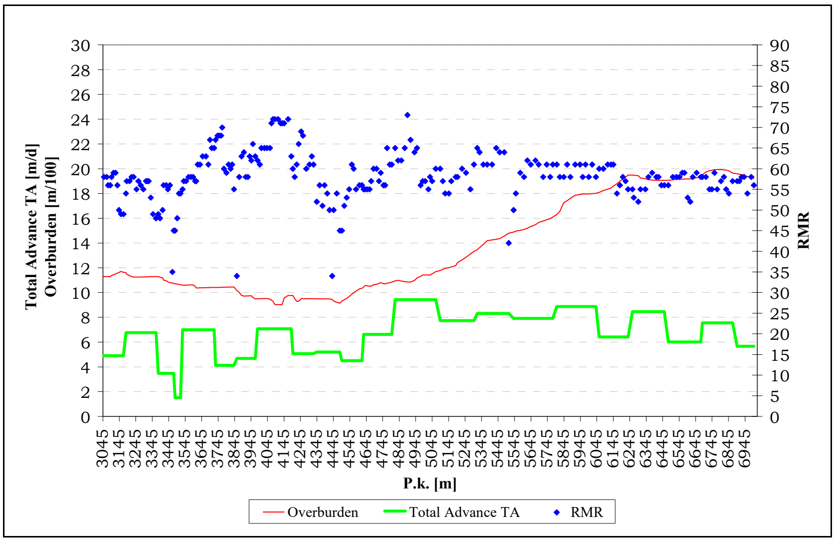

Figure. 6. Total advance TA

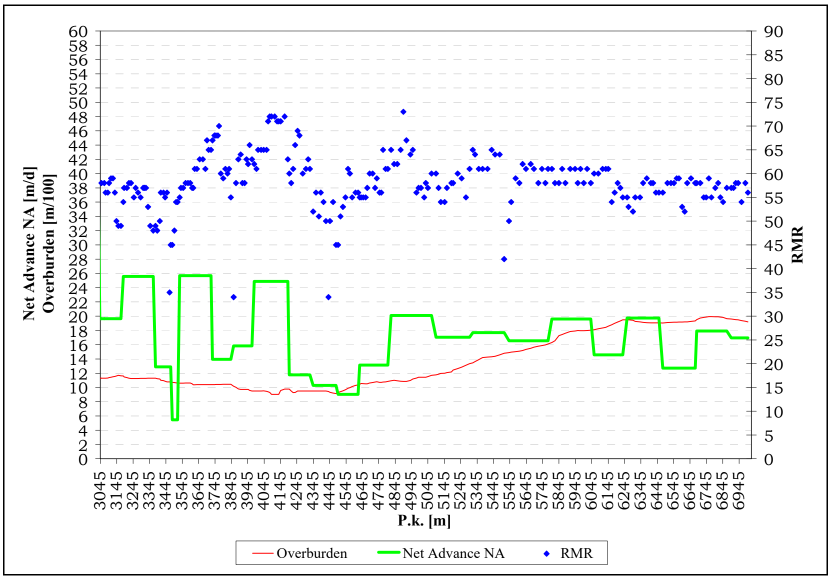

Figure. 7. Net advance NA

7 THEORETICAL ADVANCE OF THE TBM BASED ON GEOMECHANICAL INDICES AND COMPARISON WITH THE MEASURED ADVANCE

7.1 *Theoretical advance values calculated from Bieniawski rock mass excavability (RME) index*

During excavation, some systematic geostructural measurements were taken in the cavity about every 10 m. The geomechanical data collected during excavations were then used to calculate Bieniawski rock mass excavability (RME) values, thereby obtaining the ARA_T (Theoretical Average Rate of Advance) and ARA_R (Real Average Rate of Advance) parameters, the latter being analogous to the Total Advance TA, which are forecast indices of theoretical and real advancement, respectively.

Bieniawski correlations developed for open TBMs were used for this purpose:

$$ARA_T = 0.839 \times RME - 40.8 \qquad (1)$$

for terrains with σci >45 MPa and for RME<55 ARA_T=6 m/day

$$ARA_R = ARA_T \times F_E \times F_A \times F_D \qquad (2)$$

where FE= Factor of Crew efficiency= 0.7÷1.2; FA= Factor of team adaption to terrain=1.0, FD= Factor of tunnel diameter = 1.59

The FE values corresponding to Bieniawski minimum and maximum values, 0.7 and 1.2 respectively, were considered. The same index was also adopted with the value of 1 (which is about the average).

The following figure illustrates the RME values and the minimum, maximum and average ARA_R values, in m/day, monthly averaged, in the section being studied. For a direct comparison, the actual Total Advance TA numbers are shown as well (Figure 8).

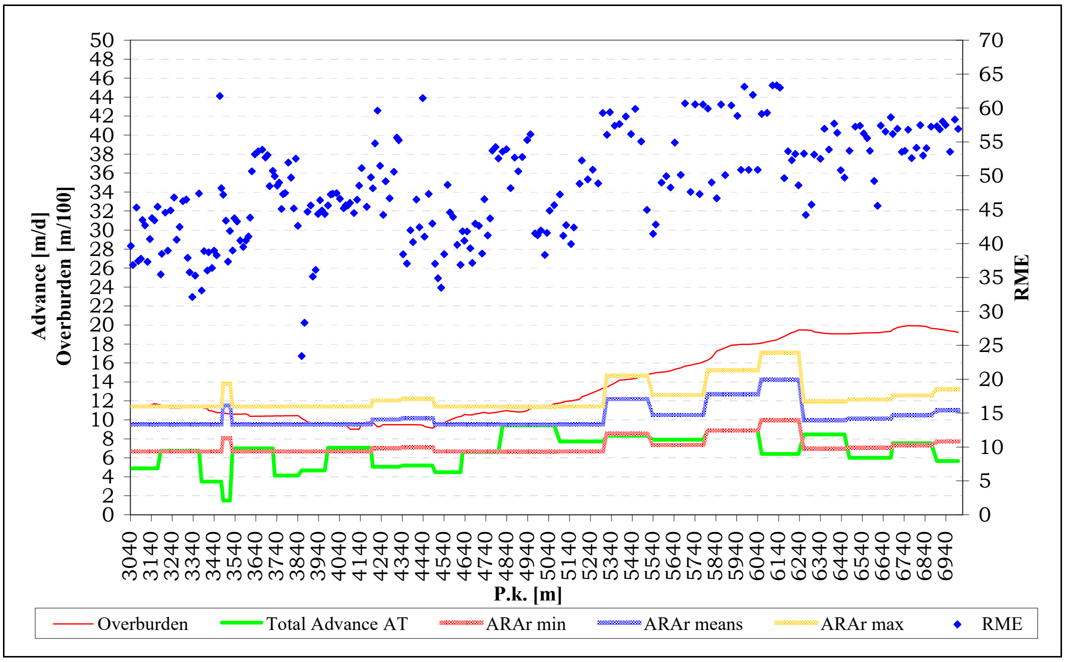

Figure. 8. Monthly Real Average Rate of Advance (ARA_R), calculated based on the RME (Rock Mass Excavability) index and Total Advance TA between ch. 3+045 ÷ 7+020

The average daily values of the Real Average Rate of Advance in the period of reference varied between around 7 m/day (ARA_{Rmin}) and 12 m/day (ARA_{Rmax}), compared with actual measured Total Advance TA values of about 6.5 m.

There is thus a good correspondence between the estimated ARA_R values and those actually measured for the Total Advance TA, especially as far as the minimum values provided by the Bieniawski correlation are concerned.

7.2 *Theoretical advances calculated based on Barton QTbm model*

The values of Barton Q parameter of the mass were calculated based on the geomechanical data collected during excavation. The Qtbm was then elaborated and used to obtain the Penetration Rate (PR) and Advance Rate (AR) parameters via the following formulas:

$$PR \approx 5 \cdot (QTbm)^{-0.2} \qquad (3)$$

$$AR \approx 5 \cdot (QTbm)^{-0.2} \cdot T^m \qquad (4)$$

$$T = 5 \cdot \left(\frac{L}{PR}\right)^{\left(\frac{1}{1+m}\right)} \qquad (5)$$

where T = the time necessary to bore a tunnel with length L, m = the negative coefficient that represents the AR decrease over time.

Based on the AR values, it was then possible to calculate the theoretical net average monthly advance in m/day, considering the real TBM excavation hours. In Figure 9 below, the values of Barton Q index and the theoretical average monthly advance numbers in m/day, calculated on the basis of the QTbm index for the section studied, a dimension analogous to the Net Advance (NA) parameter, are represented.

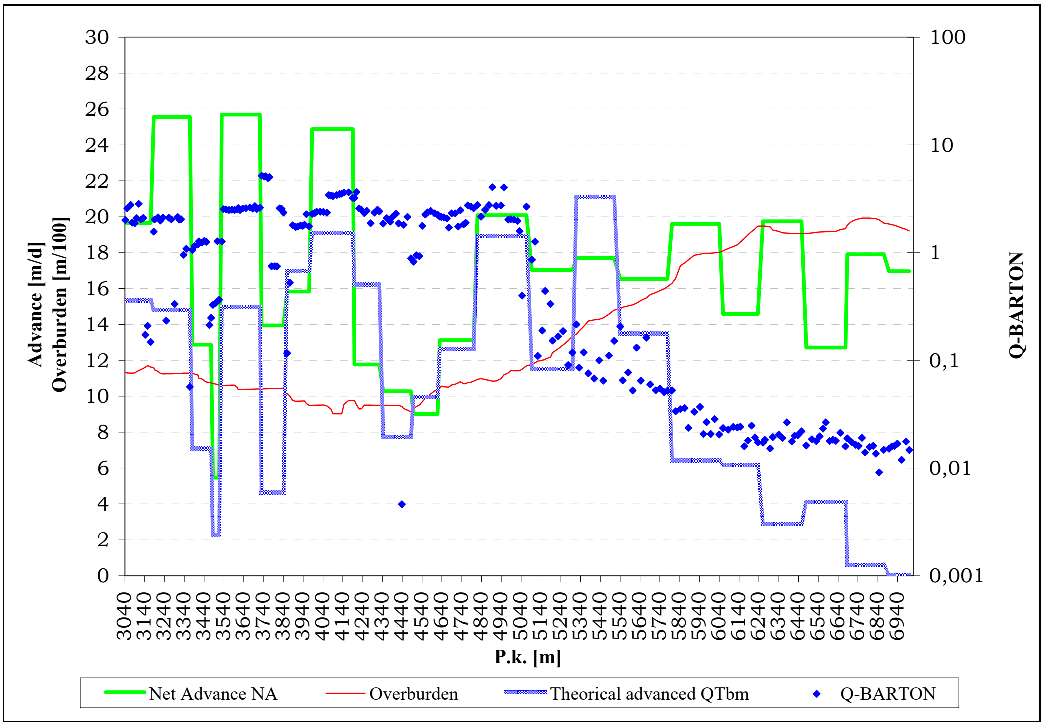

Figure. 9. Theoretical monthly advances(m/d), calculated based on Barton QTbm index and Net Advance (NA) between ch. 3+045 ÷ 7+020

Figure 10 contains the graph that correlates the Penetration Rate (PR) values calculated based on the QTbm values and the ROP provided by the TBM data in the tunnel boring phase.

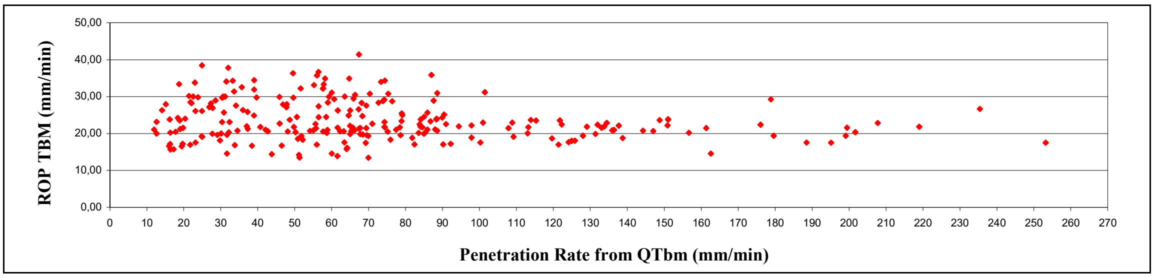

Figure. 10. ROP from the TBM data and PR calculated based on Barton QTbm index between ch. 3+045 ÷ 7+020

The comparison of the theoretical advance values in m/day, monthly averaged, calculated based on the QTbm in the section being studied and the Net Advance (NA) values measured during excavation demonstrates the lack of a clear correlation, especially as the overburden increases, where a decrease in Q linked to the tensile state (and consequently to the theoretical calculated advance) does not correspond to a clear decrease in the measured advance of the TBM. This inconsistency is also clear in the comparison of the theoretical average daily advance value in the period of reference, about 11 m, with the actual net advance (NA) number measured, which is significantly greater at 17.5 m.

Also, a comparison between the Penetration Rate (PR) calculated on the basis of the QTbm index and the ROP provided by the TBM data set does not demonstrate a satisfactory correlation.

8 CORRELATIONS BETWEEN THE MEASURED NET ADVANCES AND THE RMR AND Q GEOMECHANICAL CLASSIFICATION INDICES

The monthly net advance (NA) measured during the excavation were correlated with Bieniawski RMR and Barton Q geomechanical indexes as taken from the massif. The following empirical correlations resulted (Figure 11a and Figure 11b):

$$NA = 0.5192 \cdot RMR - 12.87 \quad \text{(m/day)} \qquad (6)$$
$$NA = 0.8475 \cdot Q + 16.248 \quad \text{(m/day)} \qquad (7)$$

For comparison, the same figure shows also the total advance (TA) numbers, calculated by considering an average machine use (PU) percentage of 40%.

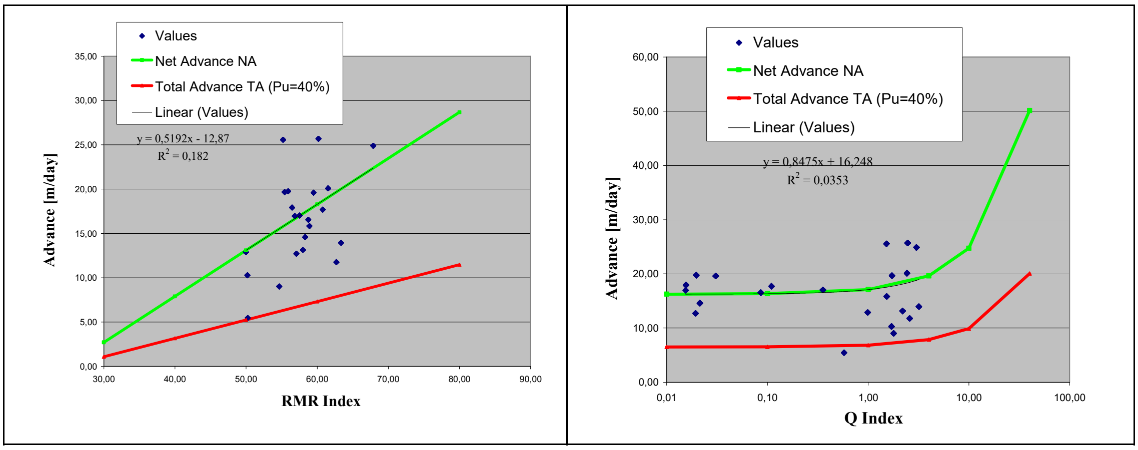

Figure. 11. Correlation between Net Advance (NA) and the RMR (a) and Q (b) indices

The above correlations have generally low determination coefficients, proving that, in the specific case being studied, factors other than the sole geomechanical quality of the mass excavated had a clearly important influence on the machine progress.

In detail, the available data show that, for RMR index values between 30 (Class 4) and 80 (Class 2), the resulting net advance (NA) values are between about 2.5 m/day and 28 m/day, which correspond to total advance TA (PU=40%) numbers between 1 m/day and about 11 m/day.

For Q index values between 0.01 (very poor rock) and 40 (good), the resulting net advance (NA) values are between about 16 m/day and 50 m/day, corresponding to total Advance TA (PU=40%) numbers between about 6 m/day and 20 m/day. It has to be noted that for Q index values below 1, up to 0.01 (poor to very poor rock), the correlation does not highlight a lessening of the TBM advance (in line with what was actually measured), staying just about constant, as a direct result of the elevated overburden and thus of the elevated tensional status.

Also considering the average RMR and Q values measured in the relevant stretch, that is, 58 (Class 3) and 1.30 (poor quality rock) respectively, net advance (NA) values of about 17-17.5 m/day and total advance (TA) values of 6.5-7 m/day are obtained, largely in-line with the detected average advance values of the TBM in the examined section.

9 CONCLUSION

Considering the data obtained during the excavation of La Maddalena Reconnaissance Gallery, the gross and net advance values of the TBM were analysed and processed. The study has focused on the section of the tunnel in which the overburden was consistently in excess of 1,000 m, up to a maximum of about 2,000 m, i.e. between ch. 3+045 and the final ch. 7+020.

Then a comparison has been performed of the measured and estimated advancement numbers, deducible from empirical methods used for the estimation of the performance of an open-type TBM in hard rock, such as Bieniawski Rock Mass Excavability (RME) index and Barton QTbm model.

The obtained numbers show a good correspondence between the predicted values of Bieniawski ARA_R and the actual TA values measured during excavation. This was particularly true in terms of the minimum values estimated using the empirical correlation proposed by Bieniawski. That result seems to confirm that the RMR index, adopted in the planning and execution phase as a base for the design and application of the support-type sections during excavation, and the Rock Mass Excavability (RME) index are sufficiently reliable to characterise the mass and to predict the mechanised excavation advance within the Clarea Complex (CLR).

The same cannot be said for the theoretical advance numbers calculated using Barton model (QTbm), which does not demonstrate a clear correlation with the advance measurements. In particular, a significant decrease in the Q index, which appears when the overburden and thus the in-situ rock stress increases, did not correspond to a significant decrease in the TBM measured progress, as the forecasting model would suggest.

Lastly, possible correlations between the RMR and Q geomechanical indices of the rock mass and the net advance rate measured during excavation were analysed. The resulting correlations, although characterised by low determination coefficients, can still be a useful indication to consider in the planning phase for future excavations in the same geomechanical environment or in other similar contexts.

10 REFERENCE

Barton, N. 1999. *TBM performance estimation in rock using Q TBM.* Tunnels and Tunnelling International, Sept. 1999, pp. 30-34

Barton. N. 2009. *TBM prognoses in hard rock with faults using QTBM methods*. Keynote lecture, Inst. of Min. Metall. International Tunnelling Conf., Hong Kong.

Barton. N. 2010. *TBM prognoses for hard rock with weakness zones, using open-gripper or double-shield solutions.* Keynote paper. Int. Conf. on Underground Constructions, Transport and City Tunnels, Prague.

Barton, N. & B. Gammelsæter, 2010. *Application of the Q-system and QTBM prognosis to predict TBM tunnelling potential for the planned Oslo-Ski rail tunnels.* Nordic Rock Mechanics Conf., Kongsberg, Norway.

Barton, N. 2015. *TBM performance, prognosis and risk caused by faulting.* Plenary lecture, VIIIth S. American Rock Mech. Cong, Buenos Aires, 40

Bieniawski, Z.T, Celada, B, Galera, J.M. and Álvarez, M, 2006. *"Rock Mass Excavability (RME) Index".* Proc. ITA World Tunnel Congress, Seoul, Korea.

Bieniawski Z.T, Celada, B. and Galera, J.M, 2007. *"TBM Excavability and machine-Rock Interaction"* Proc. RETC, Toronto, p. 1118.

Bieniawski Z.T, Celada, B and Galera, J.M, 2007. *"Predicting TBM Excavability".* Tunnel & Tunnelling International, September, p. 25.

Bieniawski Z.T., Celada B., Galera J.M. & Tardaguila I, 2008 – *New applications of the excavability index for selection of TBM types and predicting their performance* - World Tunnel Congress 2008 – Underground Facilities for Better Environment and Safety – India

Padovese P., Berti A., Baldovin E., De Paola A., Morelli G.L., Ascari G., 2017 – *"Innovazioni delle tecnologie di scavo meccanizzato in ammassi rocciosi caratterizzati da roccia dura con distacchi in calotta e alte coperture"* – XXVI Cycle Conference of Mechanical and Engineering of rocks MIR 2017, Turin, Italy