Performance evaluation and monitoring of the tunnel excavation with a Mobile Tunnel Borer

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Abstract. The use of Tunnel Boring Machines (TBM) for tunnel excavation is widespread around the world for its capabilities and great advantages against the traditional tunnel excavation method, but sometimes this technology can be difficult to manage, requiring huge spaces for the assembly on the job site and involving complex installations at the tail of the machine.

Aiming at creating a versatile and compact tunnel borer, TunnelPro and Master Drilling designed the MTB (Mobile Tunnel Borer) that is built on crawlers, easy and fast to assembly with no need of special equipment. This prototype MTB is currently excavating a Platinum mine in South Africa, being tested in very hard rocks.

The study here presented, carried out by GEEG srl, startup of Sapienza University of Rome, compares the actual values of thrust, torque, penetration and cutter wear recorded during the trial excavation monitoring with those estimated with models commonly used in TBM performance prediction. The aims of this study, still ongoing, are a better comprehension of the MTB operation in terms of efficiency, work of the excavation tools, load distribution, and the evaluation of the adequacy of the most known methods when applied to this prototype machine.

1. Introduction
The Tunnel Borer Machine is nowadays the preferred method for the excavation of underground works as subways, railways or hydraulic tunnels in urban as well as non-urban areas, thanks to its many advantages in terms of production, surface displacements control and safety, even if the drill and blast tunneling method can still be more effective depending on the rock conditions, tunnel cross section and length. The drill and blast can be in fact more feasible when the excavation affects a complex geology, when the tunnel has a variable cross section, a high slope or when its length may not justify the initial cost of a TBM, which happens for a length less than about 3 km, as discussed by Zare, Bruland and Rostami [1], Girmscheid and Schexnayder [2].

Due to the above reasons, a field of application so far dominated by the drill and blast tunneling method is mining, despite all the disadvantages that the use of explosives entails for the health and safety department, especially when the ore is deep and the temperatures inside the tunnel are consequently very high. To implement a solution for mining with mechanized tunneling, TunnelPro s.r.l and Masterdrilling Group Ltd designed a Mobile Tunnel Borer (MTB), built on tracked wagons, which assembly takes a few days and does not require a special equipment; an open machine to be applied in rocks that doesn’t need segmental lining but only spot bolting. The prototype MTB was tested in a Platinum mine in South Africa to prove if it could achieve an equal or better advance rate than the mine daily rate of about 1.5-3 m, simultaneously improving safety and logistic.
This paper presents an overview of the MTB performance by means of a comparison between the preliminary estimation made according to the rock mass conditions on site and the monitoring data recorded by the Programmable Logic Controller of the MTB for few months during trial excavation. The predictive models adopted were the analytical CSM model developed by the Colorado School of Mines [4] and the empirical NTNU model developed by Norwegian University of Science and Technology at Trondheim [3], while monitoring data were processed producing daily average values from the 10 s logs.

2. The Mobile Tunnel Borer

The MTB system, whose shield is shown in Figure 1, is versatile and can be utilised to excavate a variety of tunnels such as declines, portals and ramps, even though it was specifically designed for the mining sector. It requires a small area for assembly due to its length of 31 m including the back-up system and a side wall to grip to initiate cutting.

Table 1 summarizes the most important features of the MTB, some of which are the input data for the performance analysis. Initial disc cutters of 17” diameter and tip width ¾” were replaced with disk cutters of 17” diameter and tip width ½”, maintaining the loading capacity of 250 kN/cutter.

![Figure 1. Mobile Tunnel Borer.](image)

| Table 1. MTB features. |
|-----------------------|
| **Cutting diameter**  | 5.5 m |
| **Cutting tools**     | n° 36 discs |
|                      | diameter 17” (430 mm) |
|                      | tip width ¾” (19 mm) |
| **Maximum disc cutter load** | 245 kN (Nominal) |
| **Face cutter spacing** | 90 mm |
| **Recommended maximum thrust** | 7486 kN |
| **Total installed power** | 1000 kW |
| **Rotation speed**    | 0 – 9.2 RPM |
| **Torque @ 0-2.6 RPM** | 1750 kN·m |
| **Torque @ 8 RPM**    | 825 kN·m |
| **Maximum total thrust** | 11460 kN |
3. Geotechnical characterization of the site

The trial excavation with MTB was performed in a platinum mine located in South Africa on the western limb of the Bushveld Complex (BC), a geological formation made by igneous mafic rocks that hosts the world’s most important reserve of PGE (platinum-group elements, which are ruthenium, rhodium, palladium, osmium, iridium, and platinum). Its peculiar features as well as its economical worth made this portion of the earth crust the object of many geological researches, according to which the formation can be divided stratigraphically into five zones known as the Marginal, Lower, Critical, Main and Upper Zones from the base upwards.

The lithology of the mine consists of a layered sequence of anorthosite, norite, chromite and pyroxenite belonging to the Upper Critical Zone and the overlying gabbronorites of the younger Main Zone in the north. The Critical Zone is characterized by a regular alternation, often in thin layers, of cumulus chromite within pyroxenites and olivine-rich rocks and hosts the most significant seams of economic PGE mineralization, occurring within two regionally continuous horizons known as the UG2 Reef and Merensky Reef. The Main Zone consists of norites grading upwards into gabbronorites and includes mottled anorthosite and a distinctive pyroxenite layer named the Pyroxenite Marker. Both Merensky and UG2 reefs are continuous across the mine area, the latter reaching a maximum depth below surface of approximately 1300 m, dipping at 16° - 20° to the north.

The geo-structural layout of the MTB application mining area consists mainly of two subvertical sets of discontinuities, one striking NNW to SSE and one striking NE to SW, associated with two major structures of this area, namely the Brits graben at approximately 5km east of the site and the Kareespruit fault crossing the north western region, and a third system striking NW to SE. Preliminary geotechnical mapping pointed out also the presence of some flat dipping joints.

The rock mass in the surrounding of the tunnel was investigated by means of three sub-horizontal boreholes (figure 2) providing useful information about the lithotypes to be encountered and the rock degree of fracturing.

![Figure 2. Section of the boreholes along the tunnel alignment. Bars width indicates the RQD values estimated every 5 m stretch.](image)

Here the rock mass is constituted mainly by an alternance of norite, anorthosite, pyroxenite and chromitite, in layers with thickness that may range from centimeters to dozens of meters. The boreholes logs show that the tunnel should be excavated in norite and anorthosite (represented by green and yellow stretches in the figures) for most of its length but the stratigraphic layout available does not allow to exclude the presence along the front face of thin layers of other lithotypes as chromitite, pyroxenite and pegmatite, that may not have been intercepted by the horizontal holes. As can be noted from figure 2, the RQD estimated from the boreholes logs (for 5 m stretches) fairly grasps the occurrence of few fault zones at the beginning of the tunnel, corresponding to a moderate spacing of the fractures, especially along the hole K008A that is closer to the ground surface. At the tunnel elevation, except for the sections where the borehole K005A crosses the fault zone, the average spacing of the discontinuities is greater.
than 60 cm, going from wide to very wide according the ISRM classification, with RQD values never lower than 90%.

The geological mapping carried out on exposed fronts leads to the geo-structural scheme shown in figure 3, which is consistent with the overall geological characterization. Due to the boreholes orientation that introduces a bias in the fractures sampling, little can be said about the flat dipping discontinuities, if any. According to the geotechnical assessment for this case study it can be safely assumed that for most of the tunnel length a low degree of fracturing is to be expected.

![Figure 3](image)

**Figure 3.** Stereographic plot of the main joints set observed crossing the tunnel axis.

### 3.1. Laboratory test

Laboratory tests were executed on a limited number of Norite and Anorthosite rock samples cored from a niche excavated alongside the tunnel, near the chainage A1257 (figure 1), with the aim of estimating the rock properties on which the most common predictive models of TBM performance are based. The main parameters involved in these analyses are the uniaxial compressive strength (UCS), the Brazilian indirect tensile strength (BTS) and the drillability indexes derived from NTNU/SINTEF tests as follows [8]:

- the brittleness ($S_{20}$) and the Sievers’ drill test (SJ) together provide the Drilling Rate Index (DRI);
- the Abrasion Value Steel (AVS) together with SJ are input parameters for the estimation of the Cutter Life Index (CLI);
- the Abrasion Value Test (AV) and the DRI are used for the calculation of the Bit Wear Index (BWI).

The abrasiveness of the rock expressed also by the Cerchar Abrasiveness Index (CAI) was estimated through the relevant test. All tests were performed by a local laboratory according to ISRM standards and NTNU specifications, applying standard procedures reported in the references [7,8], proving the results shown in Table 2 and Table 3.

The amount of available data and their little dispersion, except for the specimen 4A that is clearly an outlier, justified the adoption of a single strength criterion regardless of the lithological variation between the “pink” and “green” facies of the cores mentioned in the laboratory report but not further underlined in the sample descriptions. Average values of UCS and BTS calculated excluding sample 4 are 182 MPa and 13 MPa respectively. The records of uniaxial strength and tangent Young modulus place this rock in the rank of high/very high strength and high modulus ratio according to the Deere – Miller classification [6] and are in agreement with the studies carried out on the Bushveld complex [9, 10] for Norite and Anorthosite samples, that indeed report a very wide interval of UCS values, from lower than 100 MPa up to 230 MPa.
Table 2. Summary of the UCS and BTS tests.

| Specimen ID | Specimen | Density $\text{Mg/m}^3$ | UCS $\text{MPa}$ | $E_{\text{tan}}$ $\text{GPa}$ | $E_{\text{sec}}$ $\text{GPa}$ | Poisson's Ratio | BTS $\text{MPa}$ |
|-------------|----------|--------------------------|------------------|---------------------|---------------------|----------------|----------------|
| 1 A         | A        | 2.94                     | 187.2            | 99.3                | 100.0               | 0.29           | 15.9          |
| 1 B         | B        | 2.92                     | 192.5            | 99.9                | 99.9                | 0.28           | 14.8          |
| 1 C         | C        | 2.91                     | 167.0            | 99.7                | 100.0               | 0.30           | 15.0          |
| 2 A         | A        | 2.92                     | 202.5            | 102.0               | 102.0               | 0.30           | 14.9          |
| 2 B         | B        | 2.91                     | 183.9            | 101.0               | 101.0               | 0.30           | 10.9          |
| 2 C         | C        | 2.93                     | 189.3            | 99.6                | 102.0               | 0.28           | 13.2          |
| 3 A         | A        | 2.96                     | 178.4            | 100.0               | 102.0               | 0.29           | 12.6          |
| 3 B         | B        | 2.93                     | 187.6            | 106.0               | 118.0               | 0.26           | 13.2          |
| 3 C         | C        | 2.91                     | 195.5            | 99.8                | 102.0               | 0.31           | 11.7          |
| 4 A         | A        | 2.91                     | 39.7             | 63.2                | 61.9                | 0.20           | 12.5          |
| 4 B         | B        | 2.95                     | 162.9            | 89.7                | 91.4                | 0.28           | 12.0          |
| 4 C         | C        | 2.98                     | 162.0            | 103.0               | 105.0               | 0.29           | 14.4          |

Table 3. Summary of the Cerchar and NTNU/SINTEF tests.

| ID | CAI | S20 | SJ | AV | AVS |
|----|-----|-----|----|----|-----|
|    | -   | %   | $\text{1/10 mm}$ | mg | mg  |
| 1  | 4.6 | 41  | 9.6          | 2.3 | 11.1 |
| 2  | 4.5 | 42  | 6.5          | 2.0 | 14.8 |
| 3  | 4.2 | 51  | 7.0          | 2.4 | 20.1 |
| 4  | 3.8 | 42  | 15.7         | 1.1 | 7.3  |

The results of Table 3 led to estimate a DRI of 43 and a CLI of 13, in the range suggested by Bruland [3] for gabbro and corresponding to the medium class in both drillability and cutter life index. The abrasiveness according to CAI is extremely high, with values pertaining to rocks with equivalent quartz content of about 50% [11]; the abrasive power of these mafic and ultramafic rocks is in fact provided by minerals as garnet and olivine that have Vickers hardness very close to quartz [3] and are abundant in this type of rocks, as per Streckeisen diagram of mafic and ultramafic rocks.

4. Performance prediction and back-analysis

The estimation of the TBM performance usually entails the prediction of advance rate and cutting tools wear to be expected given rock and borer machine features, more detailed the latter more accurate the former. A shortcoming of the mechanized tunneling is that the front face is no longer available for survey as for traditional excavation so that the geotechnical characterization relies more often and mostly on the information acquired during the investigation phase. As can be noted, the characterization previously exposed was based on few laboratory and field data so that the resulting analysis could only account for an average assessment of the performance along the tunnel alignment, that was however useful for design adjustment and cost-benefit analysis of the MTB.

4.1. Advance rate prediction with CSM model

Penetration rates were calculated according to the CSM method [4,5] performing an iterative calculation in order to find the angle of the contact area $\phi$ for a set of rock strength, thrust and cutterhead features, from which the torque and cutter penetration $p$ are derived; further iterations are required if the value of torque obtained is above the maximum allowed. A sensitivity analysis on the rock strength parameters
as well as on the thrust and disc cutters was performed, providing a range of penetration values going from 0.6 mm/rev, obtained for UCS 200 MPa and thrust equal to 5500 kN, to about 2 mm/rev, obtained for UCS 183 MPa and 7000 kN thrust. Table 4 shows the results for input thrust and RPM matching the average MTB monitoring data.

Table 4. Summary of CSM model results for the actual MTB operation and 17” disc cutters.

| Input data     | Results     |
|----------------|-------------|
| Cutter tip width | ¾” p [mm/rev] 1.1 |
| Thrust [kN]      | 5800 Torque [kNm] 480 |
| RPM [rev/min]    | 6 ROP [m/h] 0.4 |
| UCS [MPa]        | 183 AV at 15% utilization [m/day] 1.4 |
| BTS [MPa]        | 14          |

The CSM model allowed to evaluate some cutting tools adjustments. In detail: reducing the tip width from ¾” to ½” with the same disc diameter resulted in about three times the estimated penetration, while rising the disc diameter from 17” to 19” did not substantially modify the penetration achievable for a given thrust but significantly increased the limit thrust applicable from 7.5 MN to 10.5 MN.

4.2. Advance rate and cutter wear prediction with NTNU model
Penetration rates were calculated according to the NTNU model [3], that is less flexible in considering the machine parameters, i.e. torque or cutters spacing and tip width, but is able to take into account the rock mass fracturing, thus including a very important issue that the CSM model doesn’t address. This model provides also an estimation of the cutter ring life in boring hours, that is proportional to the Cutter Life Index and depending on the cutters and TBM diameter, rock porosity and content of quartz and other hard and abrasive minerals.

Regarding geotechnical input data, apart from DRI and CLI indexes that were measured in laboratory, the fracture class was derived from the boreholes log in terms of average spacing of the discontinuities (which is usually more than 60 cm), the equivalent quartz content was inferred by CAI as in the work by Plinninger [11] and the porosity of the rock was assumed equal to 2% in lack of laboratory measurements, considering the average density of the samples equal to 2.93 Mg/m$^3$ and a specific gravity equal to 3 Mg/m$^3$, as can reasonably be assumed due to the presence in these rocks of heavy metallic minerals. Table 5 shows the advance rate and cutter wear estimated for input thrust and RPM matching the average MTB monitoring data.

Table 5. Summary of NTNU model results for the actual MTB operation.

| Input data     | Results     |
|----------------|-------------|
| Thrust [kN]      | 5800 p [mm/rev] 2.4 |
| RPM [rev/min]    | 6 ROP [m/h] 0.9 |
| DRI             | 43 AV at 15% utilization [m/day] 13 |
| CLI             | 13 H$_6$ [h/disc] 2.3 |
| Porosity [%]     | 2 H$_{m0}$ [m$^3$/disc] 47 |
| Quartz content [%] | 50          |
| Fracture class   | 0-1          |

Penetration values are two times those obtained with CSM model but assuming the lowest fracturing class, which is possible in this rock mass, the penetration would be equal to 0.6 mm/rev and more consistent with the other estimate, as it should reasonably be for intact rock.
Cutter life in m$^3$/disc is about 50 m$^3$, half the value that can be estimated from the correlation between consumption, CAI and UCS (about 100 m$^3$) [11].

4.3. Comparison with monitoring
Monitoring data obtained during the trial excavation consisted in daily records of the significant parameters namely Thrust, Torque, RPM and ROP acquired every 10 seconds. The penetration in mm/rev was calculated as the ratio between the ROP and the RPM. Figure 4 shows the average daily values calculated considering only the boring time.

![Figure 4](image)

**Figure 4.** Average penetration and daily advance rate (above), average daily value of thrust and torque together with the relevant thresholds (below).

The average penetration over the whole period is 1.2 mm/rev, in the lower range preliminary assessed with both models, probably due to a moderate underestimation of the rock strength that, by back-analysis, could actually be approximately 200 MPa. In detail, after a first phase with penetration values less than 1 mm/rev, between October 18th and 21st the discs with cutter tip width ¾” were replaced with ½” ones, slightly improving the performance up to 2 mm/rev but not as much as predicted, as can be noted from the p-time chart in figure 4. The corresponding average rate of penetration during all the excavation is 1.9 m/day, calculated considering the actual utilization, i.e. the ratio between actual boring time and overall time, equal to 16% in this case. A common value of utilization for TBMs is about 25 to 35 % but it can be lower in adverse conditions [5], such as the very hard rock affecting the mine area. It should be also noted that the MTB was in the trial phase, therefore it was in the first stages of the learning curve when operation adjustments are normal.

The below chart of figure 4 shows the average daily thrust and torque, the former often reaching the recommended threshold as can be expected in hard rock where is the cutterhead thrust that limits the machine penetration. A good operation entails an adequate ratio between rolling and normal forces on the cutters, known as cutting coefficient, which is directly proportional to the penetration and for hard rocks assumes values of 10% or less [12]. In this case study the average coefficient is 3% before the cutters replacement and then about 5%, confirming the enhanced performance.

5. Conclusive remarks
The analysis here presented allows to draw few qualitative and quantitative conclusions about the prototype MTB performance.
Regarding preliminary assessment of the advance rate, it can be said that two of the most known prediction models applied for TBMs are adequate also for the Mobile Tunnel Borer and, in the frame of a sensitivity analysis, provided reliable results given the actual operation parameters and a discrete geotechnical characterization. The average ROP recorded during the trial was 0.5 m/hr, a value in line with what expected and very close to the prediction of CSM method, which analytical approach is suitable for modelling the behaviour of rock masses with very low degree of fracturing. The replacement of the disc cutters with thinner ones improved the penetration but only within the limits of the cutter load capacity.

Published works comparing tunneling with drill and blast and TBM [1, 2] underline that even though the advance rates are usually higher for TBMs, these are more affected than drill and blast by the rock condition, i.e. poor boreability, especially for small cross sections. The MTB achieved the daily advance rate that could be foresaw for a traditional TBM with the same utilization of about 16% and proved to be competitive with the drill and blast production of the mine, representing a safe and adaptive solution for the tunnels excavation in the mining sector.

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