Looking inside TBM parameters: feedback from the Tunnel 4 case study, Angat Water Transmission Improvement Project (Philippines)

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Abstract. The use of TBMs in the tunnel industry has undergone a continuous growth over the last years, with application in ever expanding ranges of geotechnical conditions. Nevertheless, the feedback from completed projects with respect to the use of machine data for assessing geotechnical conditions are not common: there are only a few attempts to correlate machine data with geotechnical conditions during excavation and in most cases the use of machine data is related to assessment of TBM performance for prediction of advance rate. The analysis of TBM parameters may represent an interesting tool for monitoring of geotechnical conditions at the tunnel face and early detection of adverse face conditions. This work presents the feedback from the Tunnel 4, a 6.4 km long water transfer tunnel excavated by double shield TBM in the Philippines. The machine data have been analysed for identification of most sensitive parameters to geomechanical properties of the rock mass. In this respect, the use of specific-excavation parameters provides best results for assessing geotechnical conditions during excavation. Specific energy and Field Penetration Index displayed a good correlation with RMR values. The combined use of Net Advance Rate and Drillability Index allows to highlight how unstable face conditions and / or tough rock can influence the TBM advance.

1. Introduction
The use of Tunnel Boring Machines (TBMs) in the tunnel industry has undergone a continuous growth over the last years and improvements in technical features (e.g. cutter-head size, value of machine torque and thrust) allowed the use of TBMs in always wider range of geological and geotechnical context. Despite of such increase in the application of TBM, there is a poor feedback from completed projects with respect to the use of machine data for assessing geological and geotechnical conditions at the tunnel face, namely in the frame of hard rock excavation. In most of cases, the analysis of machine data is related to assessment of TBM performance, i.e. as a tool for prediction of advance rate. As a matter of fact, TBM is not a flexible method of excavation and a reliable assessment of geotechnical conditions along the tunnel alignment is a key-aspect for successful application of mechanized excavation. The choice whether using a TBM or not is therefore crucial in terms of project planning and cost estimation and this choice is often based on the expected TBM’s rate of advance. In this respect, the most recognized TBM performance prediction models correspond to the CSM (Colorado School of Mines) model (e.g. [1-2]) and to the NTNU (Norwegian University of Science and Technology) model (e.g. [3-4]) and adjustments factors for these two models are continuously suggested (see e.g. review in [5]). On the other hand, there are only a few feedbacks from completed TBM projects about correlation between
machine data and encountered geotechnical conditions. Bieniawski et al. [6] suggested the use of specific energy of excavation for detecting changes in tunnelling ground conditions, based on the good correlation between this parameter and the Rock Mass Rating (RMR). Alber [7] indicates a good relationship between specific penetration and rock mass conditions such as uniaxial compressive strength (UCS) and spacing of discontinuities. Hassanpour et al. [5] highlight the correlation between some rock mass parameters (RQD, UCS) and the Field Penetration Index.

The present work aims to provide the feedback from the Tunnel 4 (Angat Water Transmission Improvement Project – AWTIP), a 6.4 km long water transfer tunnel excavated by double shield TBM. Two steps of analysis have been carried out: in the first step the TBM performance parameters are correlated to geomechanical conditions at the tunnel face in order to identify which parameters are most sensitive to ground conditions; in the second step, specific performance parameters are used in order to highlight how unstable face conditions and / or poor chipping due to tough rock influenced the TBM advance.

2. Project setting

The Tunnel 4 is a water transfer tunnel located in the Norzagaray region, about 50 km north-east of Manila. It is part of the Angat Water Transmission Improvement Project, aimed to improve the water supply systems to Metro Manila. The tunnel is 6.4 km long with an excavation diameter of 4.94 m and a precast segmental lining of 25 cm in thickness and 1.3 m in length.

2.1. Geological setting

The project area is characterized by occurrence of a sequence of volcanic and sedimentary rocks ranging in age from Mesozoic to Cenozoic. Two main formations are identified along the tunnel alignment: the Madlum Formation and the Bayabas Formation.

The Madlum Formation, of Middle Miocene age, consists of two members:

- the Alagao Volcanics which corresponds to a sequence of volcanic breccia, tuff and andesite flows with local layers of claystone, mudstone and minor limestone;
- the Buenacop Limestone, made of rather homogeneous, grey to light brown, massive and unweathered rocks. The basal layer of this member is a conglomerate made of pebbles and blocks of limestone and volcanic rocks in a well cemented matrix of tuff and sand.

The Bayabas Formation is dated to be Late Eocene to Early Oligocene. This formation is composed of dark green massive basalt, tuff and volcanic breccia, with pebbles and blocks of massive basalt in a tuff-like matrix.

From the structural point of view, three main sets of faults have been identified, based on analysis of aerial images and field survey. The fault zones have been subdivided into local and regional faults according to the thickness of the core zone, to the total thickness and to the fault length: regional faults are characterized by a thickness of the core zone greater than 5 m, a total thickness greater than 10 m and a total length at the hectometer – kilometer scale; local faults show a core zone of 1 to 3 m, a total thickness of 2 to 5 m and a total length at the decameter – hectometer scale.

2.2. Geomechanical characterization

Based on intact rock parameters and on GSI and RMR values assessed during field survey and borehole analysis, the rock types along the tunnel alignment have been grouped into five geomechanical units (GU):

- Geomechanical Unit 1 (GU1) corresponds to the basalts, pyroclastites, andesite and tuff of the Bayabas Formation. This unit is characterized by hard and rather low fractured rock masses with fair to very good conditions of discontinuities. The measured parameters point to good geomechanical features in terms of rock strength and resistance parameters;
- Geomechanical Unit 2 (GU2) is represented by the volcanic rock of the Alagao Volcanics (Madlum Formation), corresponding to a hard rock with various degree of jointing; conditions of joint surfaces range between poor and very good. Despite of similar values of intact rock
strength with respect to the Bayabas Formation, the volcanics of the Alagao Volcanics have been considered as a different unit due to the wider range of jointing and of joint conditions which may imply local different behaviour during TBM excavation with respect to GU1;

- Geomechanical Unit 3 (GU3) corresponds to interlayering of volcanic rocks and claystones, mudstones and limestones within Alagao Volcanics formation. Although the thickness of these bands may be limited to about 20-30 m, their occurrence may lead to a different behaviour of the rock mass and therefore these rocks have been classified in a different unit;

- Geomechanical Unit 4 (GU4) corresponds to the limestones and to the conglomerates of the Buenaocp Limestones (Madlum Formation). Measured parameters and GSI values are consistent with a hard and poorly fractured rock.

- Geomechanical Unit 5 (GU5) is represented by fractured and weathered rocks occurring along fault zones and includes both core and damage zones of the faults. This unit is characterized by poor geomechanical properties with low to very values of rock strength and of GSI.

A summary of the main features of the geomechanical units and of intact rock and rock mass parameters is illustrated in table 1.

**Table 1.** Intact rock and rock mass parameters assumed for the identified geomechanical units.

| Geomechanical Unit | Rock type                      | $\gamma$ (kg/m$^3$) | UCS (mean, MPa) | GSI  | RMR  | $\sigma$cm (mean, MPa) |
|--------------------|--------------------------------|----------------------|-----------------|------|------|------------------------|
| GU1                | Basalt, andesite, tuff         | 2680                 | 43.0            | 45-80| 38-66| 3.5                    |
| GU2                | Tuff, andesite                 | 2640                 | 47.1            | 40-80| 35-71| 3.8                    |
| GU3                | Claystone, limestone           | 2520                 | -               | 35-75| 32-63| -                      |
| GU4                | Limestone, conglomerate         | 2650                 | 42.4            | 55-80| 47-75| 10.7                   |
| GU5                | Faulted, fractured rock        | 2400                 | 9.8             | 20-40| 20-40| 0.2                    |

Apart from fault zones, the data pointed to a rather homogeneous rock mass from the geomechanical point of view, with fair to good conditions expected along most of the tunnel alignment. Foreseen geological and geotechnical conditions along the axis of Tunnel 4 are illustrated in figure 1.

**Figure 1.** Longitudinal geotechnical profile along the axis of Tunnel 4.
The excavation of Tunnel 4 began in March 2018 and was completed in February 2019. The average production rate corresponds to 490 m/month, with peak production of 890 m/month in September and October 2018. Encountered geological and geomechanical conditions were in good agreement with foreseen ones, as shown in the following figure.

![Comparison between foreseen and as-built geotechnical profile. The dashed area highlights the main differences between the two profiles.](image)

**Figure 2.** Comparison between foreseen and as-built geotechnical profile. The dashed area highlights the main differences between the two profiles.

In general, the encountered rock mass was characterized by good to very good conditions for most of the tunnel section, with RMR values mainly ranging between 40 and 70 and peak values between 55 and 65. Nevertheless, local worsening of geotechnical conditions was encountered along fault zones, where an increase of the jointing degree was observed. Despite of this, fault rocks (e.g. fault gauge or breccia, cataclasite) were only occasionally encountered and no significant water inflow has been recorded; the measured RMR values along fault zones are between 30 and 40 (RMR Class IV).

### 2.3. The adopted tunnel boring machine

The adopted TBM is a hard rock, double shield machine. Main specifications of the TBM are reported in table 2.

| Table 2. Main technical features of the TBM |
|--------------------------------------------------|
| **Type of TBM** | Hard Rock – Double Shield |
| **Diameter of the cutter head (m)** | 4.94 |
| **Cutters (N°)** | 31 – 17 inches |
| **Total length of the shield (m)** | 10 |
| **Normal thrust (kN)** | 22500 |
| **Unlocking thrust (kN)** | 40000 |
| **Torque (at 7 rpm) (kNm)** | 2300 |
| **Unlocking torque (kNm)** | 4200 |
3. Analysis of TBM parameters

TBM parameters recorded during proceeding of excavation have been analyzed for evaluating possible correlation with actual geotechnical conditions along the tunnel axis.

As to the excavation parameters, two main sets of data were considered:

- Machine raw-data
- Performance parameters which may provide indications of rock mass conditions as stated by the Authors mentioned above.

For assessment of ground conditions along the tunnel alignment, the RMR classification system was adopted as indicator of geomechanical properties of the rock mass.

3.1. TBM Parameters

The TBM parameters adopted in the study comprehends operational parameters (machine raw data) and performance parameters.

The operational parameters include thrust force (kN), torque (kNm) and rotation speed (rpm). The performance parameters adopted in the present study correspond to the penetration (mm/rev) and the advance rate (mm/min).

These machine raw-data were used for calculating further performance parameters:

- Specific Energy of Excavation
- Field Penetration Index
- Net Advance Rate
- Drilling Index

The Specific energy of excavation (Es) is defined as [8]:

\[ Es (kJ/m^3) = \frac{F}{A} + 2\pi N T A ARA \]  

where \( F \) = total cutterhead thrust (kN); \( A \) = excavated area (m\(^2\)); \( N \) = cutterhead rotation speed (rps); \( T \) = applied torque (kNm); and \( ARA \) = average rate of advance (m/s).

Specific energy is therefore composed of two terms: the first one corresponding to thrust energy and the second corresponds to rotation energy. This parameter indicates the energy which is necessary to excavate one unit of weight of material.

The Field Penetration Index (FPI; [9]) allows to proportionate the thrust per cutter to penetrate 1 mm per revolution and is defined as:

\[ FPI (kN/mm/rev) = \frac{F_c}{penraw} \]  

where \( F_c \) = value of thrust per cutter (kN); and \( Penraw \) = penetration raw data (mm/rev).

The Net Advance rate (NET) represents the distance travelled by the TBM in a single stroke divided by the amount of time the TBM was actively driving, and is expressed as mm/min. In the present analysis the data for the single strokes were not available; the NET has been therefore calculated on a daily basis rather than on a one-stroke basis.

The Drillability Index (DI) is also referred as specific penetration (e.g. [10]) and is defined as:

\[ DI (mm/rev/kN) = \frac{penraw}{F} \]

The Drillability Index is therefore the inverse of FPI.

4. Performed analyses

A first step of the analysis was aimed to evaluate possible correlations between TBM parameters and geomechanical conditions at the tunnel face; all the operational and performance parameters listed above were therefore correlated to geomechanical indicators of rock mass conditions, i.e. the measured RMR values. As result, good relationships were identified between Specific Energy and Field Penetration Index on one side and RMR values on the other, as illustrated in the following. It shall be noted that the
correlation is defined between two different type of data, i.e. machine data which are continuously recorded and values of a geomechanical index which cannot be provided with the same frequency.

The plot in figure 3 illustrates the comparison between Es and RMR and highlights a rather good relationship between the pattern of these two parameters.

Figure 3. Comparison between measured values of specific energy of excavation (Es) and RMR along the Tunnel 4.

More in detail it can be observed that:

- For tunnel sections characterized by RMR class II, the specific energy requested for excavation is greater than 55 MJ/m$^3$;
- Tunnel sections with RMR class III are characterized by a specific energy between 20 and 55 MJ/m$^3$;
- A strong decrease of Es values below 15 MJ/m$^3$ is observed along tunnel sections characterized by RMR class IV.

A similar correlation is also observed between the pattern of RMR values and of field penetration index (FPI) as illustrated in figure 4:

- For tunnel sections characterized by RMR class II, the field penetration index is greater than 50 kN/mm/rev;
- Tunnel sections in RMR class III are characterized by values of FPI ranging between about 15 and 50 kN/mm/rev;
- A decrease of FPI below 10 kN/mm/rev is observed when encountering rock mass in RMR class IV.

Figure 4. Comparison between values of field penetration index (FPI) and RMR along the Tunnel 4.
A second step of the analysis was aimed to evaluate the TBM performance during excavation, i.e. to determine how unstable face conditions and / or poor chipping due to tough rock influenced the TBM advance. In this respect, the approach described by Villeneuve [11] has been adopted: low NAR value can be related to poor chipping in though rock or face instability; in order to distinguish between these two conditions, NAR has to be used in combination with another performance indicator such as DI to differentiate between low NAR values arising from tough excavation conditions (correspondingly low DI) and arising from face instability (correspondingly high DI). This distinction can be therefore provided based on the use of the NAR versus DI graph: points with stable face conditions are those with a linear NAR-DI relationship or high NAR, whereas those with unstable face conditions have low NAR values [11]. In the NAR versus DI plot for the Tunnel 4 (figure 5) is can be observed that optimal operation conditions were recorded in most of the cases and NAR often reached maximum values, only limited by material handling capability. Poor chipping due to occurrence of tough rock was only locally recorded, as it was the case of mixed chipping and face instability. According to the NAR versus DI graph, real instable face conditions were not encountered during the excavation of Tunnel 4. The analysis of these parameters confirms therefore the observations performed at the tunnel face: the fault zones along the tunnel alignment were characterized by local increase in degree of jointing, with RMR values between 30 and 40 and did not lead to critical conditions also thanks to the lack of water inflows and of fault rocks such as fault gouge and / or breccia.

![Figure 5. NAR versus DI graph for the rock masses encountered during the excavation of Tunnel 4](image)

### 5. Conclusions

One of the main hazards during TBM excavation in hard rock is related to occurrence of unforeseen adverse conditions such as highly fractured rock masses, often associated with water inflows. Although different methods for geotechnical investigations ahead of the tunnel face are available, their systematic application easily leads to significant delay in the construction schedule. The continuous analyses of TBM excavation parameters may therefore represent an interesting tool for a continuous monitoring of geotechnical conditions at the tunnel face and for early detection of changing ground conditions. It is therefore of great interest to identify the performance parameters which display a higher sensitivity to changing ground and to geomechanical properties of the rock mass. According to previous studies (e.g. [5-6]), specific energy of excavation and Field Penetration Index displayed a good relationship with observed ground conditions. The analysis of machine raw-data and of performance parameters from the Tunnel 4 allowed to confirm specific energy and Field Penetration Index as most sensitive parameters to changing geomechanical conditions at the tunnel face. A continuous monitoring of these two...
parameters during proceeding of excavation may represent therefore a useful tool for assessing ground conditions at the tunnel face, with particular respect to degree of jointing. In this respect, a two-fold approach may be adopted for a continuous monitoring of Es and of FPI: during excavation, monitoring of Es and of FPI shall focus on the trend of these parameters: a rapid decrease of Es or of FPI within a few strokes may reflect the worsening of joint conditions and the approaching of a fracture or of a fault zone; after excavation of a test section, reference values of Es and of FPI can be defined for each RMR-class, and the analysis of Es and of FPI may represent in this case a useful tool for identification of change in rock type at the tunnel face. Finally, the use of the NAR versus DI graph allows to evaluate how unstable face conditions and / or tough rock with consequent poor chipping may influence the TBM advance.

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