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# The "penalty factors" method for the prediction of TBM performances in changing grounds

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ABSTRACT

Tunnel construction by TBMs through hard rock is significantly affected by the geological and geotechnical conditions at tunnel level. Ground parameters such as uniaxial compressive strength, fracturing degree and abrasiveness, and factors such as water inflows and stress level may deeply affect the way a TBM will perform. In addition, different types of TBMs will behave differently in a given condition.

This paper presents a method for TBM performance prediction in changing grounds, which has been developed in the framework of the European project "New Technologies for Tunnelling and Underground Works" (NeTTUN). The model starts from an optimum TBM performance in best conditions, i.e. when all ground parameters are in their "best state". A stepwise reduction of the optimum advance rate is then performed, according to "reduction factors" that quantify the effect of degrading ground conditions on the TBM advance rate. By doing so, the "penalty factors" model is able to take into account a very wide range of ground conditions, from very good to very poor. Two types of TBMs commonly employed in rock tunnelling have been considered, i.e. Gripper and Shielded machines, each of them characterized by its own set of reduction factors.

In order to consolidate the factor values and to validate the model, a TBM performance database, also developed in the framework of the project NeTTUN, has been used. The database includes a large number of tunnels excavated in different ground conditions with all standard TBM types. The comparison between the values given by the "penalty factors" model and the actual TBM performances observed during construction shows that the developed tool may provide a reliable estimation of the TBM performance based on simple ground parameters.

The "penalty factors" model has also been interfaced with the DAT ("Decision Aids for Tunnelling"). The DAT software, co-developed by MIT and LMR-EPFL, is able to compute the probabilistic distributions of the tunnel construction time and – cost in function of the geology – and construction related uncertainties.

The model is conceived to be used in its present form. However, the methodology can be easily adapted to match the expertize of the user, who is free to update the optimal performances, the ground parameters and/or the values of the reduction factors according to his/her own experience. The model can also be extended to other TBM types and to conventional excavation methods.



## 1. Introduction

During the planning phase of a tunnel project, it is important to predict as accurately as possible the advance rate of the excavation, in order to assess correctly the construction time and thus also the cost. In hard rock tunnels, the advance rate depends mainly on the geology along the tunnel alignment, the selected excavation method, the tunnel characteristics and the crew efficiency. Project engineers generally use several methods to predict the advance rate:

- Their own experience on past projects in similar conditions.
- Data from the literature.
- Data from Databases, if available.

In the literature, numerous are the models available for the TBM performance prediction in a variety of ground conditions. Among them, the Colorado School of Mines or CSM (Rostami, 1997; Rostami and Ozdemir, 1993; Rostami et al., 1996) and the Norwegian University of Science and Technology or NTNU (Bruland, 1998) models are the most widely recognized and used around the world. The CSM model can be defined as a semi-theoretical model which starts from the calculation of individual cutter forces

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to determine the overall thrust, torque and power requirement of the entire cutterhead. On the contrary, the NTNU model is primarily based on empirical correlations between the geological/geotechnical parameters and the actual TBM performance.

The time and cost curves for various tunnelling operations have been developed by collecting and analyzing a large amount of data. Other prediction models have been developed in recent years to account for a wide range of rock properties and rock mass conditions. The $Q_{TBM}$ (Barton, 2000) is based on an expanded $Q$-system which can be used for TBM performance estimation. Hassanpour et al. (2009a, 2009b, 2011) analyzed the TBM performance in relation to the Field Penetration Index previously introduced by Klein et al. (1995). Gong and Zhao (2009) introduced the Boreability Index. Sapigni et al. (2002) and Ribacchi and Fazio (2005) analyzed the relationship between TBM performance and RMR. Yagiz (2002) and Ramezanzadeh et al. (2008) modified the CSM model to account for the influence of the rock mass parameters. Finally, Delisio et al. (2013) and Delisio and Zhao (2014) developed a model for TBM performance estimation in blocky and jointed rocks based on a modified version of the Field Penetration Index.

In the present study, a new approach has been followed. Instead of developing equations based on regression analyses of past tunnelling data, the TBM performance is estimated by taking into account the effect of selected ground parameters, and their states, on the TBM advance rate. This effect is quantified via "penalty factors" which aim at reducing an optimum tunnelling performance in good grounds to account for degrading rock mass conditions.

## 2. Principle of the "penalty factors model

This paper presents a new method for assessing tunnelling advance rates in hard rock, the "Penalty factors" model developed in the framework of the European project "New Technologies for Tunnelling and Underground Works" (NeTTUN). The model assumes following hypotheses:

– For a given excavation method (any type of TBM, drill & blast, roadheader, or other), tunnel characteristics (geometry, etc.), and a given crew, the tunnelling advance rate depends mainly on the geological conditions.
– The geological conditions can be described with a finite number of independent geo-parameters.
– Each geo-parameter can be subdivided into a finite number of states which are more or less favorable for tunneling. Each Parameter "$i$" has an "optimal state", noted $S_{i,opt}$, which produces the greatest advance rate. The other states can be seen as "penalizing states".
– If all the parameters are in their "optimal state", the TBM advance rate is also optimal (i.e. maximal) and is noted $V_{opt}$.
– If all the parameters, except parameter "$i$", are in their "optimal state", then for each state "$j$" of the parameter "$i$", there exists a reduction factor $f_{ij}$ so that

$$V_{ij} = V_{opt} \cdot f_{ij} \tag{1}$$

where
$V_{ij}$ = advance rate in state "$j$" of parameter "$i$";
$V_{opt}$ = optimal advance rate;
$f_{ij}$ = advance rate *reduction factor* for state "$j$" of parameter "$i$";
note: $f_{ij}$ = 1.0 for the optimal state $S_{i,opt}$, and $f_{ij}$ < 1.0 for the penalizing states

– In presence of "$n$" independent geo-parameters $P_i$ ($i = 1,\ldots,n$), each in a given state $j(i)$, it is assumed that the reduction factors $f_{i,j(i)}$ are also independent from each other. Thus, the advance rate $V$ will be given by:

$$V = V_{opt} \cdot f_{1,j(1)} \cdot f_{2,j(2)} \cdot f_{i,j(i)} \cdots f_{n,j(n)} = V_{opt} \cdot \prod_{i=1}^{i=n} f_{i,j(i)} \tag{2}$$

– The efficiency of the crew can also be taken into account with a reduction factor $f_{crew}$. But as the crew efficiency is in principle improving from the beginning of the excavation on, this reduction factor should be applied to the final efficiency, and not during the "learning phase".

This very straight forward model needs following input:

– An overall optimal value of the advance rate $V_{opt}$.
– The list of all relevant independent geological parameters governing the TBM advance rate.
– For each parameter, the list of its relevant parameter states.
– For each state "$j$" of parameter "$i$", the numerical value of the corresponding "reduction factor" $f_{ij}$ for the selected tunnelling method and tunnel characteristics.
– Eventually a "crew reduction factor".

## 3. A proposed "penalty factors model for gripper and shield TBM in hard-rock

As an example, a "Penalty factors" model is presented for the two common TBM types used in rock-tunnelling, Gripper and Shield TBMs, and for tunnel diameters between 7 and 12 m.

Table 1 shows the selected optimal advance rates, which are reasonable values resulting from a number of case studies.

The five following geological parameters governing the TBM advance rate in rock-tunnelling have been selected:

– Degree of fracturing.
– Uniaxial compressive strength UCS.
– Water inflow.
– Stress level,
– Abrasivity.

### *3.1. Geo-parameter "FRACTURING"*

The degree of fracturing of the rock mass governs both the penetration rate and the required support measures, i.e. the associated delays. Following relevant states have been selected:

- "<u>*normally jointed*</u>" (joint spacing = 0.4–1.0 m; GSI = 50–70; $J_v$ = 5–10 joints/m$^3$): This is the optimal state, because of the good penetration rate (due to the pre-existing fractures) and the relatively small amount of support needed. Thus a reduction factor of 1.0 (i.e. no reduction of the advance rate) is assigned to this state.
- "<u>*massive to slightly jointed*</u>" (joint spacing > 1.0 m; GSI > 70–80; volumetric joint count $J_v$ < 5 joints/m$^3$): Here, the fractures produced by the cutters propagate less easily in the rock, and thus the advance rate is reduced. The reduction factor has been estimated to be 0.7 for both TBM types.
- "<u>*heavily jointed*</u>" (joint spacing = 0.1–0.4 m; GSI = 30–50; $J_v$ = 10–30 joints/m$^3$): The cutter penetration is good, but the needed support measures and the bad gripping conditions slow down the advancement of Gripper TBMs. A heavily jointed rock mass may also induce some squeezing on the TBM shield, but this may rather motivate the crew to accelerate the advance. Thus the reduction factors have been estimated to be 0.6 for Gripper TBMs and 0.95 (i.e. almost 1.0) for Shield TBMs.
- "<u>*very heavily jointed*</u>" (joint spacing < 0.1 m; GSI < 30; $J_v$ > 30 joints/m$^3$): Here the conditions are even worse, and the reduction factors have been decreased to 0.4 for Gripper TBMs and to 0.7 for Shield TBMs.