Water jet tunneling: a theoretical advanced rate evaluation

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Abstract

Tunnel Boring Machines play an important role in the underground infrastructure execution of modern cities. They weigh thousands of tons and measure hundreds of meters besides utilizing high powered energy in the excavation process. Although being well established, they are based on a last century design approach and they are not compatible anymore with the sustainable concept that characterizes current society. An alternative is looking for news technologies capable of replacing the traditional cutter disc in the excavation process. This is the approach of Tunnels Laboratory – LabTun – of Santa Catarina University. In this context, one of the lastest developments is a water jet tunnel boring machine (WJTBM). It utilizes a high power water jet (hydrodemolition) combined with diamond wire to execute the excavation process in a lighter, smart and less powerfull way. Therefore, it is just as important to compare the proposed new concept with the alternatives. This study deals with this necessity by analysing its technological performance. The advanced rate index was chosen for this task. It was calculated by the NTNU prediction model for traditional TBMs and by a proposed method for LabTun's concept. This method envolves experimental results of volumetric removal rate for high power water jet and geometrical characteristics of water jet TBM. The analysis utilized four types of rocks (sandstone, slate, meta-sandstone and granite) as geologic scenarium. The results show a better performance of WJTBM for soft and porous rock and an inexpressive performance for hard rock.

Keywords: tunnel boring machine, hydrodemotion, prediction model.

1. Introduction

For thousands of years, humanity has been trapped in two dimensions of the earth's surface. However, the uneasiness inherent in human nature has pushed us to seek new frontiers. This challenge has never been so important as when the early decades of this century faced the demand increase for natural resources, urban space and climates changes. These facts increased the need to explore the underground space in a more efficient way. Tunnels play an important role in this scenario. They are considered a high performance solution to overcome urban and natural obstacles with low social and environmental impact.

They are underground infrastructure elements that can be executed by several methods. One of the most important is the "Tunnel Boring Machine – TBM" method. It makes use of equipment especially designed and manufactured for excavation purposes. This equipment usually weighs thousands of tons and measures hundreds of meters. Other characterists are the high power utilized and the constant necessity of expensive replacement parts. However, the actual TBM cannot be competitive with other excavation methods for short tunnels with a big diameter. While the high price does not justify the acquisition of an especially designed and manufactured equipment for a short tunnel, the operational cost has an exponential increase with TBM diameter (Zare, Bruland *et al.* 2016). As an alternative to reduce these values as well as improving the advanced rate, there is the combination of water jet cutting technology and mechanical methods in the TBM cutter head.

Since the 70's, the main researches have been focused, in the first moment, on analyzing the feasiability of water jet assistance for the excavating tool task and afterwards (1) on the optimization of hydro-mechanical system geometry (number amd position of nozzle, stand-off distance, point and angle of impact of the jet on the rock) and (2) on the study of the influence of the jet parameters (generation pressure and nozzle diameters).

One example of feasiability investigation was the work describedin (Hood 1977). It investigated the performance of drag bits with and without water jet combined. The work concluded that it is possible to cut hard rock deeper and faster with a water jet at 400 bar. Later, (Pritchard and Reimer 1980) confirmed that drag bit assisted with water jet could reduce the excavation force and disc cutter wear, improving, in this way, the advanced rate and cutter disc life time. These results were confirmed by (Ciccu and Grosso 2010) whose results of experimental analysis of drag bit excavation assisted, suggested that water jet assitence is effective in improving the performances of the mechanical tool. According to (Wilson, Summers *et al.* 1997) the application in Roadheaders was almost immediate. The benefits achieved by the use of WJ could be simplified by stating that without water jet assisted cutting (WJAC), a 100 tons machine was necessary to cut rock with a strength over 1.200 bar. The addition of WJAC reduced this value to only 35 tons.

In (Kouzmich and Merzlyakov 1983, Fenn, Protheroe *et al.* 1985), and (Ciccu and Grosso 2014) the experimental analyses were focused on disc cutter performance assisted by water jet. While (Fenn, Protheroe *et al.* 1985) utilized four low-pressure jets of water (two on each side of the disc) to remove the crushed material after its formation and report a 40% reduction of thrust and rolling force over disc cutter, (Kouzmich and Merzlyakov 1983) and (Ciccu and Grosso 2014) investigated the feasiability of water jet assistance in disc cutter assistance.

While (Kouzmich and Merzlyakov 1983) only analysed the feasiability of technology in coal excavation, (Ciccu and Grosso 2014) went futher. They experimentally investigated the deep groove and volume removed per unit length of the tool's path in two situations for sandstone and limestone: one with and another without water jet assistance. The main operational variables measured were the thrust and cutting forces, the tangential velocity of the tool and the energy involved, both mechanical and hydraulic. The pressure and flow rate were kept constant and all tests were repeated at least three times. The result concluded that both variables (depth of grooves and volume removed) are higher for water jet assistance situation. The authors suggested that the rock-tool interaction forces were reduced (or, conversely, the penetration was increased under fixed normal force applied to the tool). As a consequence, the stress level in the tool's material as well as the wear rate became lower, thus, increasing the working life of the tool. These facts concluded that water jet-assisted tools are regarded as a solution for not only extending mechanical excavation to hard and abrasive materials, but also to improve the excavation performance.

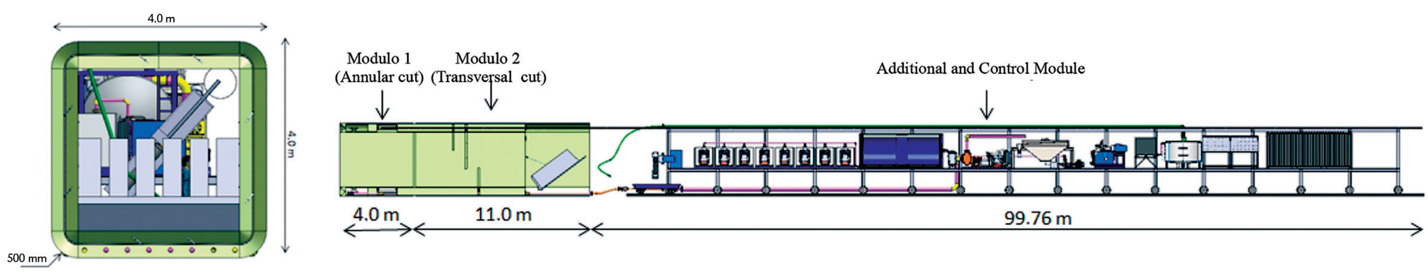
The use of WJ in other excavation equipment had parallelal development. The development of a petroleum drill concept described in (Maurer, Heilhecker *et al.* 1973) was an important step too. An oil drilling rig which utilizes WJ as the main technology in order to cut rock was proposed. Low power capacity and leak problems stopped the works. The water jet technology has also been utilized for methane drainage in coal mines, especially in China since the nineties. A self-propelled nozzle that increased the drainage area in coal mine was proposed by (Lu, Zhou *et al.* 2015). A different approach has been followed by (Lu, Tang *et al.* 2013). A drilling equipment for coaling mining has been proposed that digs the rock in two stages, one with water jet and another with mechanical enlargement.

An important point is that in all aproaches described, the water jet serves in a secondary role, an assistance technology of traditional excavation tools. Only in (Jeng, Huang *et al.* 2004), was there discussed the possibility of water jet to be used as main excavation technology in modern tunnel equipment. In this works there was reported a set of experiments that investigated the water jet performance in soft, medium and hard rock. As expected, the WJ performance in hard rock was entirely insignificant, but for soft rock the results were interesting. Discussion about the results found in (Jeng, Huang *et al.* 2004) and the realistic application of water jet in tunneling can be found in (Nygårdsvoll 2014).

Some researches have been executed by workgroups at the Laboratory of Tunnels – LabTun – of Santa Catarina Federal University, since 2008. In (Noronha, Gomes *et al.* 2012) there was discussed the opportunity of manufacturing non-circular TBM with water jet technology and, in (Noronha, Gomes *et al.* 2012), there was proposed a circular tunnel boring machine that makes use of water jet and hydraulic cylinder for rock excavation. The last development of the workgroup was a concept of a rectangular tunnel boring machine (Figure 1) that uses water jet to execute an annular cut and diamond wire to slice across the remaining rock. It is expected that the smart configuration and the low power requeriments produce a cheaper, less powefull and faster machine.

This machine has a square transversal section with 4 meters. Rounding radius of 500 millimeters that can be found in every corner. The length, by the way, is around 114 meters divided in three modules: Axial Cutting Module, Transversal Cutting Module and Additional System Module. The first one, responsible for annular cut and drainage of the excavation front, is formed by a double metallic shield which accommodates the water jet drive system and drainage tube system. The second one has the task of rock cutting but utilizing different technology and for different purposes. The idea now is to make a sharp cut in a transversal direction of axial axis of TBM. This cut is done in three steps (there can be more if necessary) by the diamond wire system. The Additional System Module (or backup module) is formed basically by a hydrodemolition pump, hydraulic unit power, separation plant, water tank, cement unit, tooling area, storage area and control unit.

Figure 1
LabTun's concept.



This article focuses in the theoretical performance analyses of water jet tunnel boring machine (WJTBM) concept proposed by LabTun workgroup and traditional TBMs. The NTNU prediction model performance by TBM has been utilized to calculate the advanced rate in four geological conditionsfor traditional TBMs, while performance and geometrical data allowed the advanced rate for LabTun's concept as described in the followed sections.

2. Prediction performance

As important as the generation of concepts which make use of highly potential innovative technologies, is the performance analysis itself. This has become more robust when the result was compared with the performance of similar equipment under the same conditions.

This can be done with the calculation of performance index. One of the most important is the advanced rate which represents how fast the excavation process occurs and is measurable in meters per day, [m/day].

For traditional TBMs, there are several methods to elaborate this calculus. A detail study about can be found in (Hassanpour, Vanani *et al.* 2016), which concluded that the accuracy of the main performance prediction method is reasonable. According to (Zare, Bruland *et al.* 2016), one of the most accepted and widely used is the performance method prediction proposed by the Norwegian University of Science and Technology – NTNU. It makes use of empirical and laboratorial data together with TBM that characterizes the prediction of four performance indexes, among them, the advanced rates.

The NTNU method and all others are designed to predict performance of traditional TMB which makes use of a cutter disc. As LabTun's concept has a radical innovative approach and makes use of water jet for cutting rock, a different prediction performance method is utilized.

It takes into account mechanical design characteristics, mainly the geometrical characteristic of a cutter head, and the experimental hydrodemolition result for performance prediction. As it is possible to increase a transversal cutting station that makes use of the diamond wire technology, it is expected that this process is not a bottleneck for the TBM operation.

2.1 Prediction performance for traditional TBMs: NTNU method.

The basic approach is to calculate the Basic Penetration index (I_o) from geological and TBM parameters. The method suggests that the influence of geological parameters, mainly rock fracture level, can be combined in only one factor denominated "Equivalent Fractures Factor", k_{ev}. In a similar way the influences of TBM's parameters can be combined with another factor too. This new factor is called "Equivalent Thrust", M_{ev}. According to (Bruland 2000), while k_{ev} depends on "fracturing index" (k_s), the "drilling correction index" (k_{DRI}) and "porosity correction index" (k_{por}), Mev are dependent on cutter thrust (M_B), cutter disc diameter correction index (k_d) and space between cutter disc correction index (k_a).

$$k_{ev} = k_s . k_{DRI} . K_{por} \qquad (1)$$

$$M_{ev} = M_B . k_d . k_a \qquad (2)$$

The calculation of k_s is made of a few steps. First of all, it is necessary to find the "fracturing index" for each discontinuity family, k_{si}. This task can be done with a discontinuos family angle, Q-barton familiy classification and in Figure 2. The equation, $k_s = (\sum k_{si}) - (n - 1).0{,}36$, permits the final definition of the fracturing index. The k_{por}, however, can be directly identified on a porosity correction index abacus, in Figure 3, from porosity value, as input information.

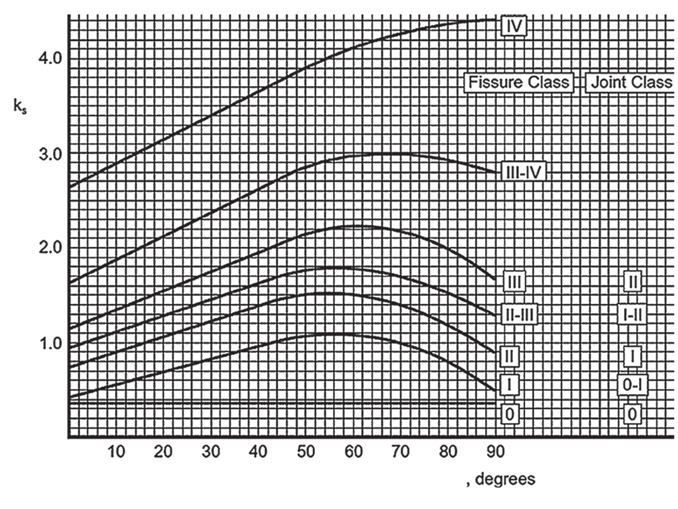


Figure 2
Fracture correction index abacus for each discontinuity family.
Source: (Bruland 2000)

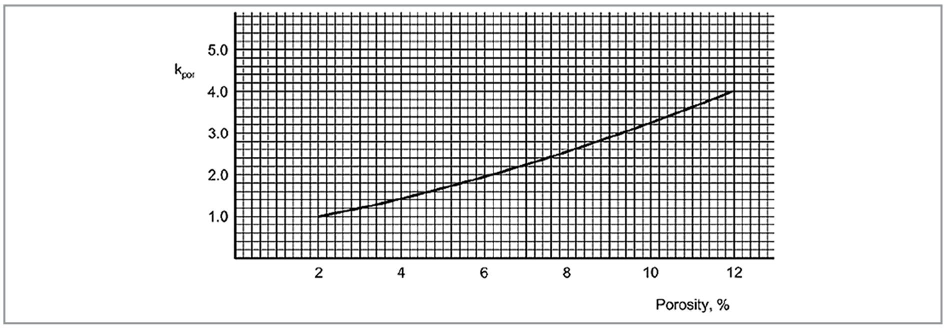


Figure 3
Porosity correction index abacus.
Source: (Bruland 2000)

Before the calculation of the last index, necessary for defining k_{ev}, it is necessary to define the "drilling rate index", DRI. It expresses the drilliability of an intact rock. The DRI should be well suited for the purpose, since it is composed of the measured rock surface hardness and the rock brittleness value (Bruland 2000). Once dependent of experimental result and similiary of porosity, this parameter usually is available for a wide range of rock in reports published by NTNU. Typical values of this index are shown in Figure 4 for different types of rocks.

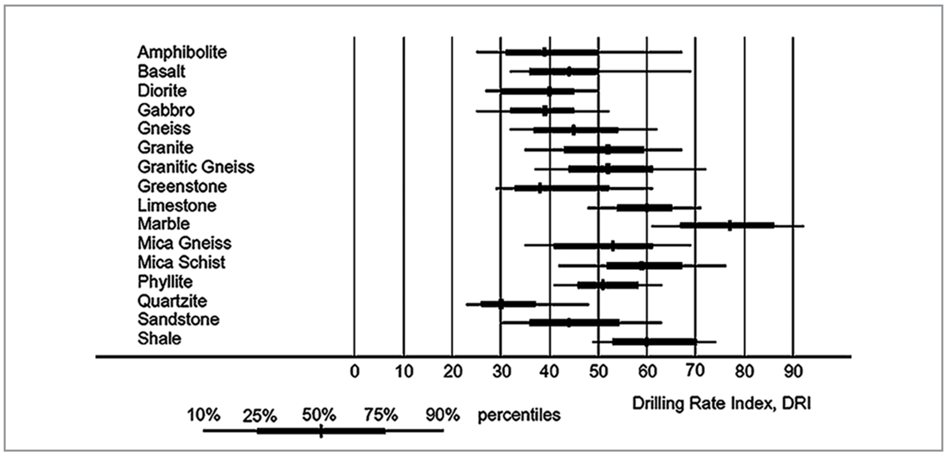


Figure 4
Tipical values of drilling
rate index for several types of rock.
Source: (Bruland 2000)

Only if DRI is different of 50, will it be necessary to correct the DRI value with the use of drilling correction index abacus shown in Figure 5. In this case, the value of fracture correction index is also necessary.

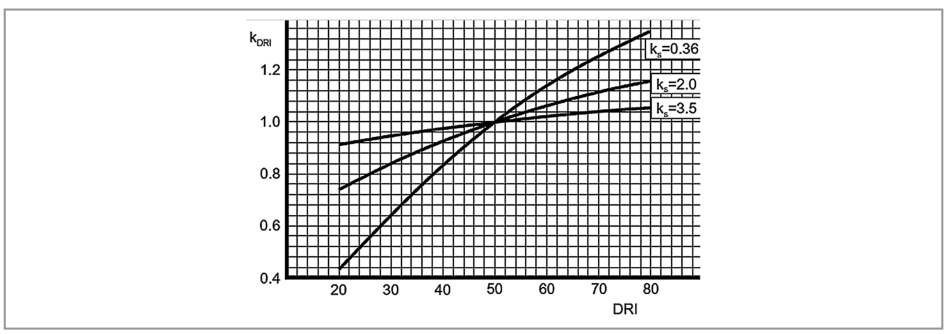


Figure 5
Drilling correction index abacus.
Source: (Bruland 2000)

While the cutter thrust can be found from the cutter head and cutter disc diameters (as shown in Figure 6), the cutter disc correction index and the space between the cutter disc correction index can be easely determinated by the use of Figures 7a and 7b.

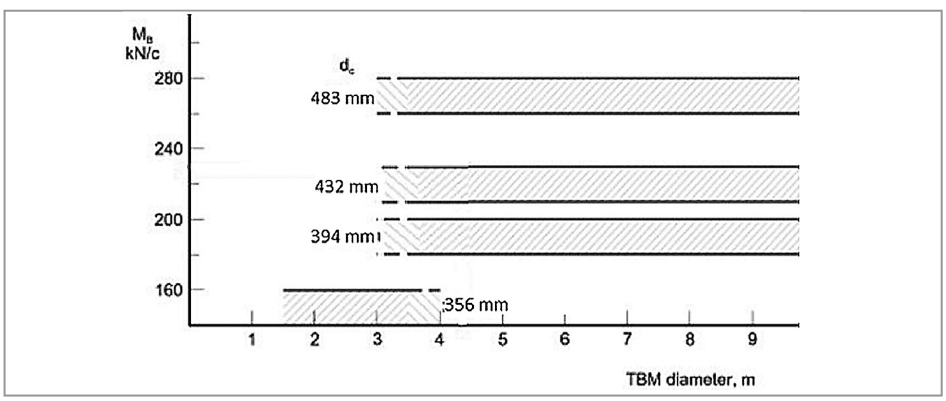


Figure 6
Maximum and mininum thrust by cutter disc from TBM and cutter disc diameters.
Source: (Bruland 2000)

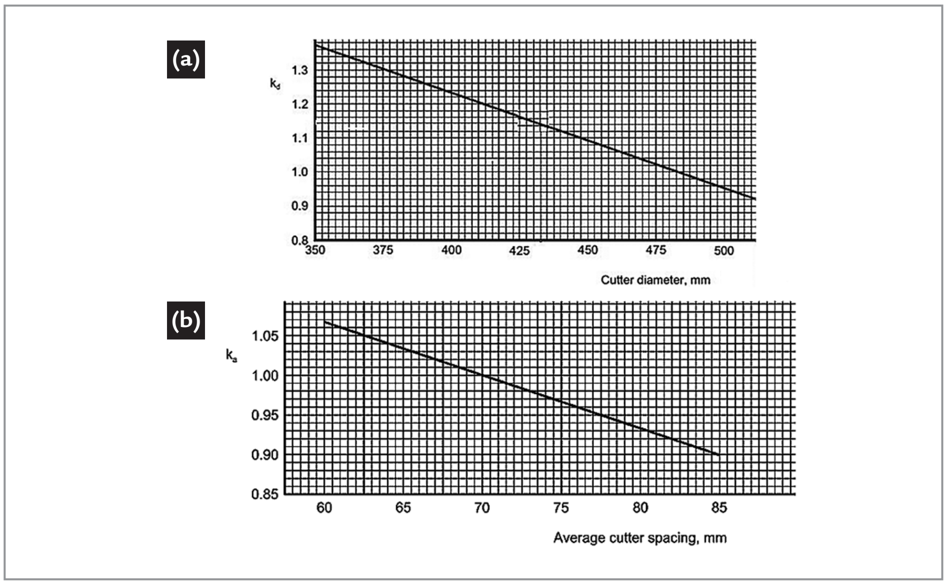


Figure 7
a.Cutter disc diameter correction index abacus; b.Space between cutter disc correction index abacus
Source: (Bruland 2000)

The definition of k_{ev} and M_{ev} allows defining the basic penetration net using the abacus provided by NTNU. One exemple is shown in Figure 8. The specific abacus is the design for TBMs with cutter disc diameter of 483 mm and spacing of 700 mm.

The net penetration (I_n) can be evaluated by multiplying the basic net penetration (I_o) by the angular velocity of cutter head, in RPM. Finally the advanced rate is calculated multiplying (I_n), TBM productivity (Pr) and working hours, (Hr_{work}).

$$I_n = I_0.w_{RPM}.(60/1000) \quad (3)$$

$$A = I_n.Pr.Hr_{work} \quad (4)$$

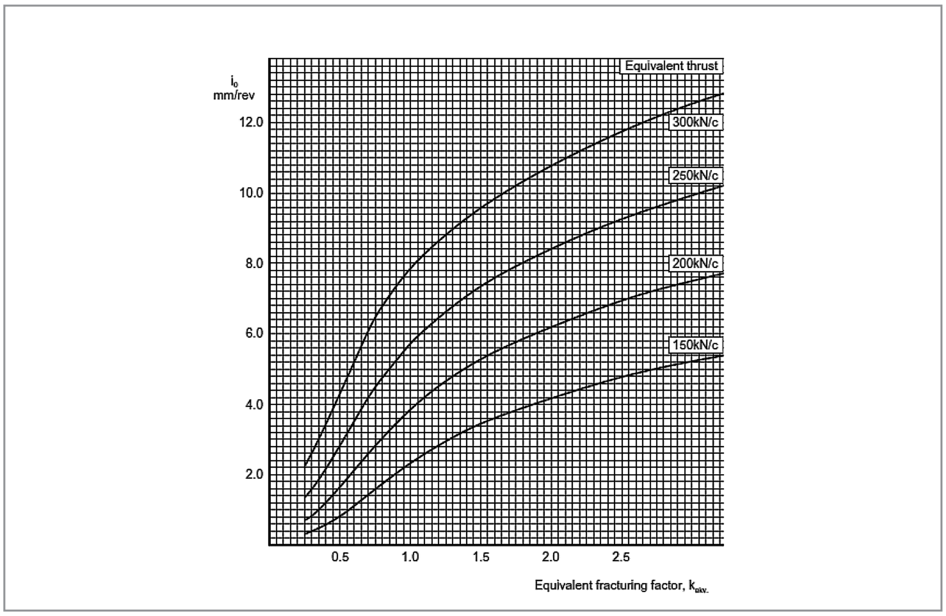


Figure 8
Basic net penetration abacus.
Source: (Bruland 2000)

2.2 Prediction performance for LabTun's concept

Since the LabTun's concept has not been prototyped yet, the predictive performance only uses geometrical and performance data of the technology involved. The main inputs are the external width ($W_{external}$), internal width ($W_{internal}$), rounding radius (R), volumetrical removal rate (V), number of nozzles (N_{nozzle}), productivity (Pr) and working hours (HR).

The volumetrical removal rate is the main input from the performance data of the involved technologies. There are a great number of experiments executed that have investigated Hydrodemolition (HD). One very interesting and specially focused on investigating the tunneling application of HD can be found in (Jeng, Huang *et al.* 2004).

In this work, the authors investigated the penetration rate and volumetrical removal rate of four types of rocks with a 450 HP hydrodemolition pump. The maximum flow rate and working pressure were 193 l/min and 1.000 MPa, respectivaly. The nozzle utilized has 3.2 mm diameter. The influence of abrasive injection rate over penetration and volumetric removal rates were investigated. The main information necessary to evaluate the performance of the LabTun's concept are summarized in Table 1.

Parameters	Sandstone	Slate	Meta-Sandstone	Granite
Penetration rate, [cm/s]	5.0	4.5	0.01	0.01
Volumetric removal rate, [m^3/h]	10.92	7.8	0.08	0.04
Transversal speed, [cm/s]	1.5	1.4	0.3	0.3

Table 1
Hydrodemolitionperfomance data utilized.
Source: (Jeng, Huang *et al.* 2004)

From the volume of the removal rate, it is possible to determine the advanced rate (A). This relationship takes into account the annular area, number of nozzles, productivity and working hours per week, as described the Equation 5.

$$A = (N.V/S_{annular}).Pr.HR, \text{ with } S_{annular} = W^2_{external} - W^2_{internal} - R^2.(4-\pi) \quad (5)$$

3. Perfomance analysis

The performance analysis took into account four rock types that are widely found in tunnel construction sites. They are sandstone, slate, meta-sandstone, granite and their characteristics are summarized in Table 2.

Parameters	Sandstone	Slate	Meta-Sandstone	Granite
UCS, [MPa]	35	45	148	165
S_{20}, []	53	50	40	39
Drilling rate index, []	56	52	40	39
Porosity, [%]	13	1.0	10	1.0
Angle, [degree]	0.0	0.0	0.0	0.0
Fracture class, []	Zero	Zero	Zero	Zero

Table 2
Rock types and some proprieties.

As important as the geological proprietie are, they are the traditional TBM and LabTun characteristics. They are several and are shown in Table 3.

Traditional TBMs parameters		LabTun's Concept parameters	
TBM diameter, [m]	4.50	External width, [m]	4.00
Cutterdiscdiameter, [mm]	483.00	Internal width, [m]	3.00
Numberofcutterdisc, []	32	Rounding radius, [m]	0.50
Distancecutterdisc, [mm]	700.00	Nozzle number, [mm]	8
Cutter head rotation speed, rpm]	11.20	Working hours, [h]	14.30
Working hours per day, [h]	14.30	Produtivity, []	0.59
Productivity, []	0.59		

Table 3
TBMs parameters.

The values of the advanced rate for the traditional and LabTun's concepts can be analyzed in Figure 9. In the sandstone, the high value for the first can be explained especially by the high performance of water jet in soft and porous rock. Besides the erosion effect which causes removal of subtracts, in porous (and permeability) rock the effect of the lifting and peeling process over removal rate is big.

A different phenomenon happens in slate. While the advanced rate for LabTun's concept has a reduction of 55% (from 109.58 to 78.27 meters per day), the traditional concept has a reduction of 85% (from 78.27 to 11.44 meters per day) on an advanced rate. This can be explained by the fact that the porosity reduction (13% to sandstone and 1% to slate) has a bigger effect on the traditional TBM than on the LabTun's concept. The k_{eq} reduction supports this thesis. For sandstone, the k_{eq} is 1.701 while for slate, the value is only 0.254. This fact associated with the high importance of keq in the penetration rate explains the poor performance of the traditional TBM on this scenarium.

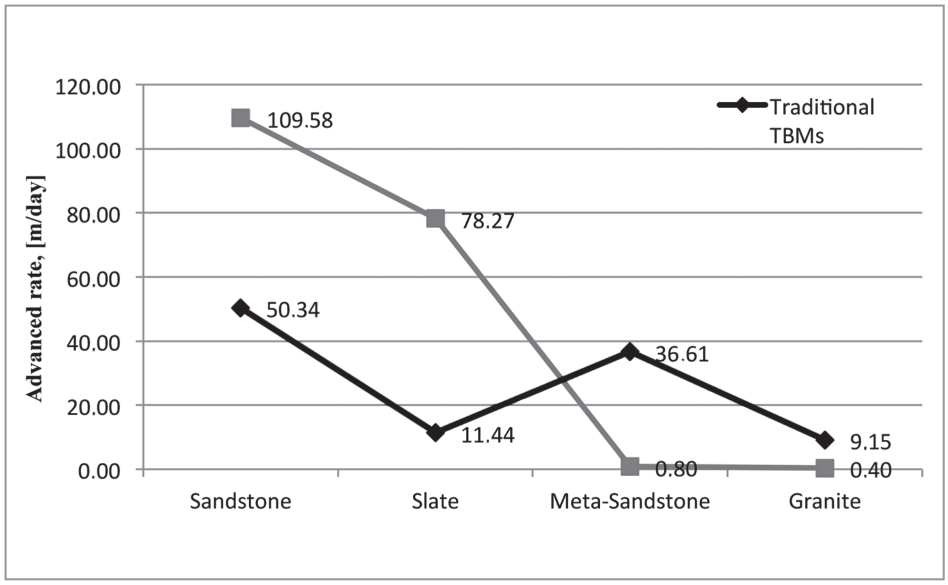


Figure 9
Advanced rate for analised situations.

As Granite and Meta-sandstone are harder, the same magnitude of removal rate (and consequentially advanced rate) cannot be observed in LabTun's concept. For Meta-sandstone the advanced rate reached the value of 0.80 m/day while for Granite, it was 0.40 m/day. Again, the reason for the difference in values is due to the porosity. Meta-sandstone has a 10% porosity and Granite, only 1%. Independently, the advanced rates of LabTun's concept for these rocks are unacceptable and this machine is not an alternative for the traditional Tunnel Boring Machines. However, several works have researched ways to increase the volumetric removal rate for hard rocks. The introduction of high frequency water jet and powerful pumps should be highlighted. Another possibility is to increase the total number of nozzles in the cutter head.

4. Conclusions

The prediction performance models utilized for both technologies proved to be valid. While NTNU model produced acceptable values of traditional TBMs performance for the four rock types, the prediction model proposed for LabTun's concept showed to be rational.

The advanced rates values showed that LabTun's concept is a real alternative for soft rock but not acceptable for hard rock. Futher development is necessary to change this scenario.

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