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# Experimental and analytical studies of the parameters influencing the action of TBM disc tools in tunnelling

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## Abstract

The use of tunnel boring machines (TBMs) is increasingly popular in tunnelling. One of the most important aspects in the use of these machines is to assess with certain accuracy the effectiveness of the action of the discs on the cutter-head in the different rock types to be excavated.

A specific machine, called an intermediate linear cutting machine (ILCM) has been developed at the Politecnico di Torino in order to study, on a reduced scale in detail in the laboratory, the interaction between the discs of the TBM and the rock: this machine allows a series of grooves to be cut on a rock sample of 0.5 x 0.3 x 0.2 m, through the rolling of a 6.5” disc, and evaluation, during testing, of the parameters associated with the action of the cutting tool.

The parameters measured during the tests were compared with the results obtained employing two analytical methods widely used for predicting the performance of TBMs: the *Colorado School of Mines* (CSM) model and the *Norwegian University of Science and Technology* (NTNU) model. The latter showed a greater ability to reproduce tests conducted using the ILCM. However, as with the CSM model, it does not allow the optimal excavation condition (the ratio, which minimizes the specific energy of excavation, between the groove spacing and the penetration of the disc), necessary for the correct design of the TBM cutter-head, to be identified.

An example, based on a real case of a tunnel in Northern Italy, allowed a demonstration of how the NTNU model provides results in line with the measurements taken during the excavation and represents, therefore, a model that is able to reliably simulate both laboratory tests and the action of a TBM on site. The NTNU model, together with the results of the tests with ILCM targeted on the identification of the optimal conditions of excavation, may allow the correct dimensioning of the TBM cutter-head to be attained in order to effectively implement the excavation.

**Keywords:** Tunnel Boring Machine TBM, linear cutting machine LCM, ILCM, cutting forces, NTNU model, CSM model

## 1. Introduction

Mechanized excavation by means of tunnel boring machines (TBMs) today represents the most common solution for hard-rock tunnelling.

The correct design of the TBM cutter-head involves careful study of the knowledge of the parameters that affect the rock-breaking mechanism under the action of disc tools (e.g., Innaurato and Oreste, 2011a, 2011b).

As quoted by Rostami and Ozdemir (1993), after the penetration of a disc into the rock, a crushed zone develops immediately under the tool, which is subject to high stress concentrations; starting from this zone, tensile cracks develop radially and intersect the fractures produced by the adjacent grooves, allowing the formation and the detachment of chips.

The parameters influencing the above mentioned complex mechanism are: 1) the geo-mechanical characteristics of the rock; 2) the geometry, diameter and shape of the disc; 3) forces acting on the tool; 4) disc penetration; and 5) spacing between the grooves produced by the discs.

While the first two parameters are usually known, forces acting on the disc through the cutter-head - normal force, perpendicular to the direction of rolling; rolling force, in the direction of cutting, and side force, orthogonal to both - depend on spacing and penetration: in particular, by increasing the penetration and/or the spacing, equally in the rock to be excavated and the disc to be employed, an increase in the normal and rolling forces acting on the disc is required.

The layout of the cutter-head is arranged by determining the spacing among the discs, so that the maximum efficiency of the interaction among the grooves can be obtained: this is possible when the minimum excavation specific energy (SE) value is reached, which means that the amount of energy required to excavate a unit volume of rock is minimum.

Figure 1, according to Tuncdemir et al. (2008), qualitatively shows the dependence of SE on the spacing/penetration ratio (s/p) and highlights the advisability of setting up spacing and penetration in accordance with a ratio close to the optimum: when the s/p ratio is too small, pulverization of the rock occurs, with high SE consumption; in contrast, if the s/p ratio is too high, chip detachment cannot be achieved until after several tool paths have been cut, greatly reducing the efficiency of the excavation. The results of extensive laboratory tests for the optimized s/p ratio show that the ratio is close to 20 for brittle rock types, while for ductile rocks it is close to 10. Roxborough and Phillips (1975) suggested the optimized s/p ratio is correlated with the ratio of compressive to shear strength of the rock.

For the outlined reasons, in order to effectively configure the cutter-head, it is evident that it is necessary to provide forecasting methods able to estimate the parameters that affect the phenomenon being examined and the performance of the TBM on site.

Widely used analytical methods, such as those proposed by the *Colorado School of Mines* (CSM) (Rostami and Ozdemir, 1993) and the *Norwegian University of Science and Technology* (NTNU) (Bruland, 1998), are simple and immediate forecasting methods, but often show significant uncertainties about the results and do not allow all the parameters necessary for the proper design of the cutter-head to be determined; in particular, they do not allow the conditions for efficient excavation to be estimated effectively (the optimum s/p ratio cannot be evaluated by these methods).

Currently, the most reliable and complete method for the determination of the parameters related to the cutting action of a TBM is a laboratory test called the "full-scale linear cutting test" (e.g., Roxborough and Phillips, 1975; Snowdon et al., 1982; Sanio, 1985; Copur et al., 2001; Chang et al., 2006; Gertsch et al., 2007; Cho et al., 2013) undertaken using a linear cutting machine (LCM).

This machine, employed for the execution of full-scale tests since the 1970s, allows the use of typical TBM cutter-head discs, using rock samples big enough to avoid the scale-effects and allowing several repetitions of the test. The sample sizes used are considerable: Gertsch et al. (2007) used samples 1.1 x 0.8 x 0.6 m. The test consisted of realizing a set of disc paths on the rock specimen, setting penetration of the cutting edge and spacing of the grooves in advance, and measuring the forces acting on the tool.

The full-scale linear cutting test has thus the advantage of simulating the actual conditions of the site and, therefore, is able to apply the results in predicting the performance of a real TBM; however, the retrieval of samples to conduct the test is often difficult and quite expensive, due to the large size of the blocks required.

Among the methods based on laboratory tests, reported in the literature, are also the so-called "small-scale" tests (e.g., Ozdemir and Nilsen, 1999; Balci and Bilgin, 2007; Innaurato et al., 2007), which represent a more practical and economical alternative than full-scale tests: being employed on substantially smaller samples, they allow considerable advantages to be obtained in terms of preparation, transport and positioning of the specimens.

However, these methods are less reliable than the tests conducted with LCM, as often they do not allow assessment of all the necessary parameters, together with the need to determine an appropriate scale factor for the results (Entacher et al., 2014).

In the past few years at the *Istanbul Technical University*, a machine has been developed that allows reliable results to be obtained with good correspondences comparable with those obtained using a full-scale test; this machine, called the "Portable Linear Cutting Machine" (PLCM)$^{TM}$ (Bilgin et al., 2010), using a 5.1-inch disc diameter and having a V-section, is used on rock samples of 0.2 x 0.2 x 0.1 m. In order to develop a methodology that would combine the reliability of a test performed by LCM with the convenience of a small-scale method, the Environment, Land and Infrastructures Department (DIATI) of the *Politecnico di Torino*, in collaboration with the Institute of Environmental Geology and Geoengineering of the *National Research Council* (CNR-IGAG), has developed a machine called the intermediate linear cutting machine (ILCM). In this study, the ILCM and the results of the first tests carried out on two types of rock are presented; the ability of the models proposed by the CSM and the NTNU to describe the tests conducted by ILCM is also assessed, together with the aptitude to effectively configure the cutter-head of a TBM.

## 2. The Intermediate Linear Cutting Machine

### 2.1 General

The ILCM (Figure 2) is designed with the same principles as the LCM, but with the main objective of allowing the testing of samples that are easily transportable and available (e.g., 0.5 x 0.3 x 0.2 m); this solution, to cut a series of adjacent grooves on the same surface of the specimen without incurring edge effects, requires the use of a mini-disc, smaller than that commonly mounted on the LCM, to effectively carry out the tests with lower penetrations (e.g., 2 to 4 mm) and, consequently, with lower spacing. Moreover, being able also to support larger size tools, it is possible to directly determine, through the same machine, the correction factor to be applied to the results obtained using a mini-disc, to adapt them to the actual conditions of the site.

The ILCM tests have developed in a more practical and economical way than the LCM tests: a standard size rock sample weighs only about 80 kg with considerable advantages both in terms of its handling and positioning; moreover, rock blocks of limited thickness can be easily found in quarries, sometimes even from waste material, and can be shaped with a small to medium sized disc saw.

### 2.2 Structure

The bearing structure of the ILCM, which must ensure sufficient strength and stiffness of the frame during the execution of the tests, comprises a solid steel frame composed of two coupled HEB beams (arranged vertically) (Figure 2); a transverse beam is housed inside the portal, on which is placed the tool holder, and a longitudinal beam intended to support this structure. The structure in which the tool is placed is formed by a cylinder containing the piston that maintains the support for the disc and adjusts its vertical movement for setting the spacing through a 1.5 kW electric motor, which acts on an endless screw (stroke 300 mm); between the base of the piston and the tool holder is mounted a triaxial load cell for the evaluation of the three components of the force acting on the disc. It has a capacity of 100 kN along the X and Y (horizontal) directions, 200 kN in the Z (vertical) direction. Currently a 6.5-inch V-shaped disc, produced by Robbins Ltd, with a 12-mm thick cutting edge is inserted (Figure 2 right); it is composed of steel reinforced with tungsten carbide. The sample-holding structure comprises a 960 x 495 mm sample steel box, and is movable horizontally in the longitudinal direction (along which the cut is performed) by means of a mechanical jack driven by a 15 kW electric motor; it can be translated in the transverse direction, for setting the spacing, through a threaded screw manually operated.

In order to facilitate the installation of the wide range of discs currently available on the market, from mini-discs up to 19-inch discs, and consequently to be able to accommodate rock samples of different thicknesses, the frame has been designed to provide three levels of housing of the transverse beam, at a distance of about 300 mm to each other (which corresponds with the piston stroke).

The machine is able to acquire the following parameters:

– the three components of the force acting on the disc, by means of the triaxial load cell;

– the horizontal displacement of the sample box along the cutting direction, by means of a position transducer (wire type);

– the vertical displacement of the piston, to adjust the depth (penetration), by means of a position transducer (wire type).

### 2.3 Main assessable parameters

The tests performed by the ILCM primarily allow evaluation of the forces acting on the disc: the normal force ($F_N$) can first be used to calculate the actual thrust that the machine must ensure so that the tools can effectively penetrate the rock, while the rolling force ($F_R$) is directly related to the torque to be supplied to the cutter-head to allow the rotation of the discs and, consequently, the creation of the grooves which determine the detachment of the chips.

The evaluation of the $F_N$ when the set penetration varies also allows estimation of the production obtained from the TBM as a function of the thrust provided on each disc (e.g. Yin et al., 2014; Ates et al., 2014; Benato and Oreste, 2015). The evaluation of the $F_R$, together with the assessment of the debris produced by the interaction between the grooves, allows the SE to be determined (SE is the ratio between $F_R \cdot l$ and the volume V of the detached rock, being l the length of the groove) and, consequently, more efficient excavation conditions: by cutting various grooves at different distances, in fact, it is possible to assess the SE trend as a function of the ratio between the spacing and penetration (s/p). Determining the optimal value of this ratio in correspondence with the minimum SE value, the optimal spacing among the tools on the cutter-head can be defined.

## 3. ILCM tests

### 3.1 Testing conditions

The results provided in this study refer to the first tests carried out by ILCM: the forces acting on a 6.5-inch disc for different values of the ratio s/p were investigated; this phase did not involve the determination of the SE, because it is still necessary to develop an appropriate method of containment and collection of debris during the test for its volume estimation.

The analysed samples come from two rock types from the Piedmont area: Luserna stone, a schistose metamorphic rock belonging to the group of gneisses, and the Prali white marble, a medium-grained metamorphic rock; the geo-mechanical characteristics of both rocks are shown in Table 1. It can be seen that both rocks have comparable values of compressive and tensile strengths, while the elastic modulus and the Knoop hardness are significantly lower in the marble (the elastic modulus in the marble is almost one half that of the Luserna stone); Luserna stone, also, shows a pronounced anisotropy, while the Prali white marble is, on average, homogeneous; the values of the Drilling Rate Index (DRI) (Blindheim and Bruland, 1998) shows the different characteristics of the two rock types: Luserna stone, whose DRI is 33, has thus a low aptitude to drilling, whereas Prali white marble, with a DRI of 90, is easier to excavate.

The specimens used in the tests have dimensions of 0.5 x 0.3 x 0.2 m (Figure 3); the test type chosen provides that the trajectory of the tool is in a direction parallel to the short side (30 cm) of the sample, so as to cut multiple paths with different spacing along the same surface without being affected by the edge effects: a suitable distance from the sides of the sample was left, whereas edge effects are present in the proximity of the sides that intersect the cutting direction; during the data processing, such portions have not been considered as not representative of the breaking mechanism analyzed. Considering the strong schistosity presented by Luserna stone, the samples belonging to this rock type were all placed along the same orientation, allowing the disc to act perpendicularly to the planes of discontinuity.

Furthermore, the surface of the sample was not conditioned in advance and the cut was made on a smooth surface: in this way, considering the values of the limited depth of penetration characterizing the ILCM tests, the variation in the effective penetration was further contained during the test.

Figure 4 (on the right) shows the upper surface of the sample obtained after the detachment of the chips.

### 3.2 Experimental results

Table 2 shows the normal forces and the rolling forces obtained by varying the s/p ratio; the penetrations have been set to about 3 mm (*Prali* marble) and about 4 mm (*Luserna* stone); for the latter rock type a penetration greater than that of the marble was chosen due to experimental evidence found in the first test with the ILCM: during the trajectory of the disc, a variation in the penetration in the order of a few tenths of mm was observed in the *Luserna* stone (the variability of the penetration during the test is much more pronounced as the material is hard and anisotropic). As a result, by increasing the values of the penetration for the *Luserna* stone, the effect of the variation has less influence on the total value. Moreover, *Luserna* stone, which is harder than *Prali* marble, reaches an optimal interaction between the fractures for s/p ratios lower than marble; consequently, to keep the spacing within applicable ranges to both samples (depending on their size) it was necessary to use a greater penetration in Luserna stone samples.

The values of $F_N$ and $F_R$ are obtained as averages of the peak zones assessed during the test; they can be considered representative of the forces which cause the detachment of the chips. For the sake of simplicity, the following references were used: letter M refers to the tests performed on *Prali* marble samples, whereas letter P to those relating to *Luserna* stone.

## 4. Analytical methods

Currently, the most widely used analytical methods for predicting the performance of a TBM are those proposed by the CSM (Rostami and Ozdemir, 1993; Rostami et al., 2002) and by the NTNU (Bruland, 1998).

The CSM is a theoretical-experimental model that allows the estimation of the forces to be applied to the disc for a given penetration and spacing as a function of the mechanical characteristics of the rock and the geometry of the discs. The NTNU is an empirical model based on data from different tunnels in different geological and geo-technical conditions and allows estimating, in addition to other parameters not examined in this study, the penetration of the disc, obtainable according to the characteristics of the rock mass, disc diameter, spacing and normal forces acting on the disc.

In the following, the attitudes of the two methods to represent the tests carried out by ILCM are compared.

### 4.1 CSM model

As illustrated by Rostami et al. (2002), the CSM model can be summarized by the analytical formulations given in Table 3; it can be seen how this method, using easily definable input parameters, is simple and immediate. However, it is also known that it does not take into account the conditions of the rock mass, along with some important mechanical properties of the rock; in particular, it can be seen that the formulations provided by the method are conditioned by only two characteristic parameters of the intact rock: compressive strength ($\sigma_c$) and tensile strength ($\sigma_t$). Referring to the rock types tested, and considering that both have comparable values of $\sigma_c$ to that of $\sigma_t$, it is guessed that such a method, not taking into account, for example, the difference in elastic modulus, provides values of normal force to be applied to the disc rather similar for both types of rock considered in this study.

This condition is in contrast with the experimentation carried out through the ILCM: referring, for example, to tests P1 and M6 (Table 4), it can be seen that a considerable difference in the normal force between the two tests (about 40 kN) was obtained, while the CSM model estimates an $F_N$ value that is similar for both cases.

Moreover, Figure 5 shows that the CSM model greatly underestimates the normal forces obtained by the ILCM test results; however, it is clear that, by changing the value of the constant C in the formulations proposed by Rostami et al. (2002), it better matches the experimental results.

The parameter C is a constant estimated through various experiments using LCM with discs of different diameters and CCS profiles; entering a C value of 3.4 for the *Prali* marble and equal to 4 for the *Luserna* stone, the $F_N$ values obtained are close to the experimental ones; this condition occurs more frequently for marble which, presenting a greater homogeneity, favours a more efficient estimation by the forecasting method.

Nevertheless, considering that the corrected values of the C parameter are somewhat different for the two rock types tested, it appears that the CSM model cannot be applied universally to estimate effectively the forces applied during the ILCM tests.

## 4.2 NTNU model

Bruland (1998) shows how to estimate the penetration per revolution reached by the discs by means of a number of formulations and abacuses (subjected to an analytical resume by Oggeri and Oreste, 2012) as a function of several factors summarized in Table 5; in this case it is known that such a method, unlike the one proposed by CSM, considers also the presence of discontinuities in the rock mass. In addition, through the DRI, it is possible to consider more effectively the real attitude of the rock to be drilled.

In order to facilitate the comparison of the parameters obtained from the ILCM tests with those of the NTNU model, the following equation was obtained for the intact rock according to the NTNU model:

$$p = [(0.69 \cdot DRI + 29{,}7) \cdot 10^{-6}] \cdot (F_N \cdot k_d \cdot k_a)^2 - [(8.44 \cdot DRI + 701.79) \cdot 10^{-5}] \cdot (F_N \cdot k_d \cdot k_a) + [(11.87 \cdot DRI + 128.53) \cdot 10^{-3}] \qquad [1]$$

where:

- $p$ is the disc penetration per revolution of the head [mm/rev];
- $DRI$ is the Drilling Rate Index;
- $F_N$ is the average normal force applied on the discs during the chip formation [kN];
- $k_d$ is the coefficient that takes into account the diameter of the disc;
- $k_a$ is the coefficient relating to the spacing between the grooves (this parameter was determined by linear interpolation from the Bruland (1998) abacus).

To evaluate the reliability of the NTNU model in reproducing the tests performed, a comparison was carried out between the $k_d$ values obtained by back-analysis (using eq.1) from p and the $F_N$ values during the tests and the $k_d$ value obtained from the same straight line obtained by Bruland (1998) for a wider range of disc diameters ($k_d$ is around 1.9 for a 6.5-inch mini-disc diameter).

The $k_d$ values obtained by back analysis are similar for the two rocks considered, but a slight difference can be noticed by comparison with $k_d$ proposed by the NTNU model: consequently, a new formulation is suggested, to adapt the original abacus (Bruland, 1998) to the values of $\Phi_{disc}$ (expressed in mm) used in the tests:

$$k_d = -2.364 \cdot 10^{-8} \cdot \Phi_{disc}^3 + 2.816719 \cdot 10^{-5} \cdot \Phi_{disc}^2 - 1.38902628 \cdot 10^{-2} \cdot \Phi_{disc} + 3.801 \quad [2]$$

Then, with a disc diameter ($\Phi_{disc}$) of 165.1 mm (which is the one used in the ILCM), eq.2 provides $k_d$=2.17. In Figure 6, the normal forces resulting from the tests are compared with those estimated both by the original NTNU model and by the modified NTNU model; it is clearly noticeable that the original NTNU model overestimates (some tens of kN) the results of the tests, whereas the modified NTNU model ($k_d$=2.17) provides a good alignment with the experimental values (average standard deviation lower than 4 kN).

With the new correction factor, which can be applied to both rock types, the NTNU model proves to be more appropriate than CSM model in simulating the ILCM tests on the intact rock.

## 5. Preliminary cutter-head design

### 5.1 The lack of $(s/p)_{opt}$ estimation in the CSM and NTNU models

Effective evaluation of the $(s/p)_{opt}$ ratio by means of ILCM involves correct determination of the volume of the excavation debris produced during the cutting test and the rolling force acting on the tool.

In previous studies (e.g., Snowdon et al., 1982; Sanyo, 1985; Chang et al. 2006; Cho et al., 2013), the volume produced by the disc action was estimated as p·s·l, where p is the penetration, s is the spacing and l is the cutting length; this simple assumption would seem adequate when the production of debris by the disc is entirely concerned with the portion of rock between two adjacent grooves, that is for s/p values not too high compared to the optimal value of the parameter.

Chang et al. (2006), however, show an example in *Hwangdeung* granite in which, for the $(s/p)_{opt}$ ratio, the volume estimated as p·s·l is significantly (about 0.6 times) lower than that actually measured through the LCM tests; this fact is also highlighted by Snowdon et al. (1982), for s/p ratios between 5 and 15.

Another drawback in considering the volume excavated by the disc as p·s·l is that in this way increasing the spacing over $(s/p)_{opt}$ chip formation is always possible, while, in reality, the volume of chips reduces until cancelled. As a consequence, it is impossible to appreciate the typical SE trend with its minimum basin when the volume is evaluated by the p·s·l equation; in Figure 7 the trend of SE is shown, assuming this estimation of the volume, and considering the rolling forces expected by the CSM and NTNU models for the two studied rock types.

It is therefore clear that the CSM and NTNU models do not allow effective estimation of the $(s/p)_{opt}$ and the optimal excavation conditions; however, this can be easily assessed using ILCM, determining the volume of the produced debris during the test.

An example can be then provided of how the preliminary design of a TBM cutter-head can be realized starting from the penetration values estimated by the NTNU model, and showing how the design parameters of the cutter-head vary for different values of the $(s/p)_{opt}$ ratio, depending on the rock to be excavated.

### 5.2 The “Ceppo Morelli” Tunnel case

The by-pass pilot tunnel (*Ceppo Morelli*, Italy), excavated through open TBM, is 876 m long with a radius (R) of 1.8 m; the rock consists of gneiss and mica-schists with the following geo-mechanical characteristics: $\gamma$=2.65 t/m$^3$, average $\sigma_c$=110 MPa and 40% quartz content.

The rotation speed of the cutter-head is 10.6 rpm ($\omega$=1.11 rad/s); 23 disc tools (16 ¼-inch) are mounted on the cutter-head; the applied maximum thrust is 244 kN; the total power of the machine is 700 kW, of which 596.4 kW are necessary for the rock excavation (Tomasini, 2012).

Penetration values were calculated using the NTNU model, for three different disc diameters. The results were then compared with the actual values obtained from the TBM on site and acquired during the excavation.

The input data of the model are summarized in Table 6; reference is made to the DRI value obtained on a rock sample taken from the tunnel during excavation, through the hardness and toughness tests provided by Blindheim and Bruland (1998); the conditions of the rock mass were established on the basis of geo-structural surveys developed along the tunnel (Giunta, 2012).

The number of discs and the net power to be supplied to the cutter-head were subsequently determined through a series of simple formulations: the number of discs by considering the average spacing of the tools obtained from the model; the power by first analytically estimating the rolling force, using the formula introduced by Rostami et al. (2002):

$$F_R = F_N \cdot \tan(\Phi/2) \qquad [3]$$

where $F_N$ is the normal force applied on the disc and $\Phi$ is the angle of the contact area calculated as shown in Table 3.

The required torque was calculated with the following equation:

$$C = F_R \cdot \frac{R}{2} \cdot n \qquad [4]$$

where $R$ is the tunnel radius and $n$ is the number of tools; the average distance of the tools from the centre of the tunnel was in fact considered.

Finally, the net power to be supplied to the cutter-head was determined as:

$$P_{net} = C \cdot \omega \qquad [5]$$

where $\omega$ is the angular speed.

The penetration trends, number of discs and the net power applied to the head are shown in Figures 8–10, depending on the s/p ratio according to the NTNU model. Deriving the ratio $(s/p)_{opt}$ for the excavated rock tested from the ILCM, it would therefore be possible to estimate all the parameters necessary for the design of the cutter-head, and, in particular, the number of discs and the available net power at the cutter-head.

Table 7 summarizes the results reported in Figures 8–10, for four different values of the s/p ratio (10, 14, 18 and 22) lying within the typical variation range of the parameter in the optimum condition (condition of minimum SE); considering the results obtained for different sets of parameters, we can see the important influence that the $(s/p)_{opt}$ ratio exerts on the design parameters: assuming, for example, that the rock has an $(s/p)_{opt}$ ratio of 10, using 17-inch discs and applying a constant normal force of 200 kN, penetration values greater than 6 mm, 28 discs and net power to be supplied to the head exceeding 650 kW would be obtained. Conversely, if the $(s/p)_{opt}$ ratio was 22, penetration of less than 5 mm, 17 discs and net power of less than 400 kW would be obtained.

In the first case it is possible to work with a higher p, which involves greater production, but considerably greater power and a greater number of tools are required; it is therefore clear that, working with high $(s/p)_{opt}$ ratios, it is possible to limit the $P_{net}$ value to be supplied to the head, together with the economic advantage of mounting a lower number of tools.

To increase the penetration value, it is rather necessary to provide greater thrust to the tool: increasing the size of the disc and, consequently, the maximum thrust applied on it, being equal to the s/p ratio, an increase in penetration, fewer discs to be mounted and greater power to be supplied to the head is obtained; about this point, referring to Table 7, it is noticeable how, operating with s/p=10, it is necessary to increase $P_{net}$ to about 200 kW to switch from 15-inch discs to 19-inch, whereas, referring to s/p=22, an increase of about 100 kW is required. This result, therefore, shows another advantage presented by excavation with high s/p ratios, i.e. the possibility of applying a greater thrust to each disc containing the increase in net power to be supplied to the cutter-head.

The results obtained from the NTNU model were compared with the mean values acquired during the excavation of the Ceppo Morelli Tunnel. In Table 8 it can be seen that, for an s/p value close to that actually used (s/p=14), the NTNU model overestimates the penetration per revolution by about 0.8 mm (5.97 instead of 5.20 mm) and plans to use 22 discs instead of 23 on the cutter-head and a power of about 60 kW lower.

Considering the values of the parameters involved, it is therefore clear how such a model, in this context, is found to be quite effective in providing a preliminary estimate of the configuration of discs to be used on the cutter-head, and of the power to be employed, whereas it is less reliable on the prediction of the net advancing rate, which is estimated from the penetration per revolution value.

## 6. Conclusions

In this study, the results of early tests conducted using an ILCM were presented; ILCM is a machine designed to perform both full-scale (only in weak rocks and using a maximum disc diameter of 16”) and intermediate-scale tests in a more a practical and economical way than LCM.

The experimental results show that the two widely used analytical methods, proposed by the CSM and by the NTNU, suit this type of test differently; particularly, it was noticed that the first is not able to effectively reproduce the tests carried out, underestimating the values of the forces acting on the disc. The NTNU model, on the contrary, proved to be more suited to simulating the ILCM test results, considering a modified value of the $k_d$ parameter.

Both forecasting methods, however, do not allow effective estimation of the value of the optimal spacing/penetration ratio $(s/p)_{opt}$, which, representing the condition of the most efficient excavation, allows the correct design of a TBM cutter-head. Using ILCM, through further improvements of the instrumentation together with an optimal method for the estimation of debris produced during the disc path, it is possible to estimate, in an appropriate manner, $(s/p)_{opt}$ for the rock types tested.

The importance of determining the optimal s/p ratio for the cutter-head design has been shown for the case study of the Ceppo Morelli Tunnel (Italy): specifically it has been noted that, if the rock presented high $(s/p)_{opt}$ values, significant benefits would be obtained in terms of the reduction in the net power to be provided and of the number of tools to be placed on the cutter-head.

Finally, comparing the results obtained from the model with the data acquired during the excavation of the TBM on site, by analysing ILCM tests it was further understood that the NTNU model proves to be quite effective in the preliminary design of a TBM, when the $(s/p)_{opt}$ ratio is known.

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