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# The Wear of Tunnel Boring Machine Excavation Tools in Rock

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**Abstract:** Some of the most important aspects in the study of the fragmentation of rock due to the action of TBM disks concern the abrasiveness of the rock and the wear of the tools. The wear of the disks in fact means that they have to be substituted, with consequent effects on the efficiency of the excavation, on the speed of advancement and therefore, on the times and costs of constructing the tunnel. After having conducted a detailed examination of the methods that have become established in scientific literature to assess the degree of abrasiveness of rock and the potential speed of tools wear, the formulas that allow an estimation to be made of the mean advancement velocity of the excavation machine are presented, considering the effect of wear on the tools and the necessity of substituting them. By applying the Barton method to four different types of rock, for three types of tunnel diameter, it has been possible to obtain the trend of the global advancement velocity of a TBM with variations of the GSI index. It has been possible to note how the CLI parameter, which describes the potentiality of the rock to wear the disks, can influence the global advancement velocity of the TBM to a great extent. Data obtained during the recent construction of a tunnel in North Italy have made it possible to compare the currently available calculation methods and obtain the CLI parameter through back-analysis. A good agreement has been found, above all between the Barton calculation method and that of the Norwegian School, both of which have shown to be reliable systems for the forecasting of the wear of disks on a TBM and for the estimation of the advancement speed of the excavation machine.

**Keywords:** Tunneling, Tunnel Boring Machine (TBM), rock abrasiveness, tool wear, construction time, excavation rate, Cutter Life Index (CLI), barton $Q_{TBM}$, Geological Strength Index (GSI)

## INTRODUCTION

The technological, mechanical and geometrical characteristics of excavation tools, together with the physical, mechanical and geostructural characteristics of the rock, influence the effectiveness and the productivity of excavation machines (Cardu *et al*., 2009; Bellopede *et al*., 2011; Oreste and Castellano, 2012).

From both the technical and economic point of view, abrasivity is one of the rock properties that are most involved in tunnelling. Even if a rock is not too strong for mechanised excavation, tool wear can infact render the operation costly due to the fact that a change in tools influences the time spent on stops and the cost of the tools themselves.

No standard test is universally used for the measurement of the abrasivity of a rock and alarge number of different tests are in fact today inuse. The difficulty of making standard tests is relatedto the different modes of the study of the tools in theinteraction with the rock: drilling, excavation by TBM discs and so on. The wear mechanism is in fact different according to the type of tool (drilling bit, disc) and how it works i.e., through impact or through rotation and so on. This fact probably depends on the elusive nature of the properties that cause the wear of the tools in rock machining.

Some aspects pertaining to the wear of disks during the excavation of tunnels in rock using TBMs are analyzed in this study. After having presented the most common rock characterization tests, with reference to the wear of disks and illustrated the methods used to forecast wear of the tools currently available in literature, some data relative to the wear of TBM disks, recorded during the excavation of tunnels in rock, are reported and commented.

## MATERIALS AND METHODS

**Forecasting the productivity of TBM disks:** There are different ways of inducing fragmentation, or permanent deformation on rock material using a tool. According to a hypothesis by Hartman (1959) and Maurer and Rinchart (1960) and later summarised by other authors (i.e., Nishimatsu, 1972) and which is still

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able to explain such complex phenomena, rock destruction under a tool includes phases such as: rock deformation, surface crushing, formation of a destruction nucleus, squashing and spalling of the rock bordered by the destruction nucleus and the free crack surface towards a free surface. In other words, the nucleus (which may be cylindrical or spherical, Fig. 1) acts like a fluid that is subjected to hydrostatic pressure which pushes in every direction (Wittke, 2007). If a free surface is sufficiently close to the tool, the formation of chips takes place under a determined load (interactive tool). At small spacing/penetration (s/p) ratios, cracks propagating from one groove interact with the cracks produced by indentation of the cutter situated in the neighbouring groove and chip formation occurs at lower forces than would be required for chip release from grooves spread further apart. At s/p ratios that are larger than the critical value $(s/p)_{crit}$, grooves are too far apart for the interaction to occur and chips form at applied force levels which are independent of any further increase in the groove spacing.

However, fracture propagation occurs more easily because of some inter-granular defects, (micro-cracks, micro-fissures, micro-fractures), the presence of schistosity, inter-strata planes, diaclases and fissures. The actual start of one or other failure mechanism therefore depends on the scale of the phenomena that is involved.

The disk action on the tunnel face is initially a phenomenon that occurs at a millimetric scale, because the rock portion involved has the same dimension as the tip of the disk. As long as the disk penetrates the rock, the scale of the phenomenon reaches centrimetric values.

Different authors have set up methods that can be used to forecast the penetration per revolution (p) in function of the force $F_N$ applied by the tool in the direction perpendicular to the excavation face.

One of the best known formulas is that by Rostami *et al*. (2002), according to which:

$$F_N = T.R.\phi.P*\cos\left(\frac{\phi}{2}\right)$$

Where:

- T = The width of the tip of the disk (in mm)
- R = The radius of the disk (in mm)
- $\Phi$ = The angle of contact between the disk and the rock: $\phi = \arccos\left(\frac{R-p}{R}\right)$
- p = The penetration of the disk per revolution of the TBM head (in mm)
- $P^*$ = The mean pressure in the rock-disk contact arc (in MPa) when rock rupture occurs with the formation of chips

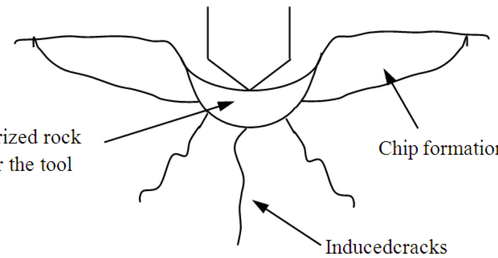



Fig. 1: Chip formation due to TBM disk action (Wittke, 2007)

Rostami *et al*. (2002) obtained this value of $P^*$, which is necessary for the rupture of rock and the formation of chips, in an experimental manner:

$$P^* \cong 2.12.\sqrt[s]{\frac{\sigma_c^2.\sigma_t.s}{\sqrt{R.T}}}$$

Where:

- $\sigma_c$ = The uniaxial compression strength of the intact rock (in MPa)
- $\sigma_t$ = The traction strength of the intact rock (in MPa)
- S = The spacing between the grooves produced by the disks on the excavation face (in mm)

The same authors derived $F_T$ (dragging force of the disk):

$$F_T = F_N.\tan\left(\frac{\phi}{2}\right)$$

According to Rostami *et al*. (2002), the penetration per revolution depends on the hauling force, $F_N$, the geometrical parameters of the disk and excavation head and on the mechanical characteristics of the intact rock (compression strength and traction strength).

Two more complex analysis techniques, that of the Norwegian School (NTH/NTNU) (Bruland 1998); Blindheim and Bruland 1998) and that of Barton (2000), allow the penetration per revolution of the disks to be forecast, while taking into consideration the presence of the natural discontinuities of the rock mass.

The Norwegian School, in particular, allows the Drilling Rate Index (DRI) to be determined in function of the $S_{20}$ and SJ indices (Bruland 1998). It is possible to obtain the following estimations of DRI from the graph prepared by the author:

$$\text{when } S_J > 50: DRI \cong (0.13 \cdot S_J + 2.33) + S_{20}$$
$$\text{when } S_J > 50: DRI \cong (5.84 \cdot \text{In } S_J - 14) + S_{20}$$

Table 1: Rock classification in relation to surface hardness (perforation strength) on the basis of an analysis of 3200 rock samples (Dahl *et al*., 2012)

| | SJ value (tenths of mm) | Cumulative (%) |
|---|---|---|
| Extremely high | ≤2.0 | 0÷5 |
| Very high | 2.1÷3.9 | 5÷15 |
| High | 4.0÷6.9 | 15÷35 |
| Medium | 7.0÷18.9 | 35÷65 |
| Low | 19.0÷55.9 | 65÷85 |
| Very low | 56.0÷85.9 | 85÷95 |
| Extremely low | ≥86.0 | 95÷100 |

Table 2: Determination of the fracture class for the joints and fissures in function of the mean spacing between the discontinuities (Bruland 1998)

| Fracture class (joints or fissures) | Distance between planes of weakness (mm) |
|---|---|
| 0 | - |
| 0-I | 1600 |
| I- | 800 |
| I | 400 |
| II | 200 |
| III | 100 |
| IV | 50 |

$S_{20}$ is an index of fragility and it is based on impact strength tests which involve dropping a weight of 14 kg onto crushed rock of a predefined size 20 times. The other index is connected to the capacity of a mini drill bit to perforate a rock sample (surface hardness). The Siever J-value (SJ) is defined as the mean value of the depth of the measured drill hole (in 1/10 mm) of 4-8 drill holes after 200 revolutions of a 8.5 mm miniature drill bit.

The SJ parameter is also very important to evaluate the wear of the TBM disks, which is obtained through the determination of the CLI parameter (see beyond). Dahl *et al*. (2012) determined the SJ parameter on 3200 rock samples and defined a rock classification on the basis of this parameter (Table 1).

According to Bruland (1998), the penetration per revolution p (mm/rev) should be estimated considering the equivalent fracturing factor ($k_{ekv}$) of the rock mass for different values of the equivalent thrust parameter ($M_{ekv}$):

$$M_{ekv} = 100 KN / disc$$

$$\text{when } k_{ekv} < 1: p \cong -0.5208 \cdot k_{ekv}^2 + 3.0521 \cdot k_{ekv} - 0.8313$$

$$\text{when } k_{ekv} \leq 1: p \cong -0.36 \cdot k_{ekv}^2 + 2.38 \cdot k_{ekv} + 0.32$$

$$M_{ekv} = 150 \ {}^{kN}\!/_{disc}$$

$$\text{when } K_{ekv} < 1: p \cong -1.1489.k_{ekv}^2 + 4.9531.k_{ekv} - 1.2042$$

$$\text{when } K_{ekv} \geq 1: p \cong -0.4533.k_{ekv}^2 + 2.96.K_{ekv} + 0.0933$$

$$M_{ekv} = 200 \ {}^{kN}\!/_{disc}$$

$$\text{when } K_{ekv} < 1: p \cong -2.2825.k_{ekv}^2 + 7.7135.k_{ekv} - 1.4811$$

$$\text{when } K_{ekv} \geq 1: p \cong -0.3888.k_{ekv}^2 + 2.814.k_{ekv} + 1.524$$

$$M_{ekv} = 250 \ {}^{kN}\!/_{disc}$$

$$\text{when } k_{ekv} < 1: p \cong -5.5423 \cdot k_{ekv}^2 + 13.522 \cdot k_{ekv} - 2.3496$$

$$\text{when } k_{ekv} \leq 1: p \cong -0.3733 \cdot k_{ekv}^2 + 2.92 \cdot k_{ekv} + 3.0533$$

$$M_{ekv} = 300 \ {}^{kN}\!/_{disc}$$

$$\text{when } k_{ekv} < 1: p \cong -8.2721.k_{ekv}^2 + 19.063.k_{ekv} - 2.7904$$

$$\text{when } k_{ekv} \geq 1: p \cong -0.38.k_{ekv}^2 + 2.91.k_{ekv} + 5.47$$

Where:

$$k_{ekv} = k_{s-tot}.k_{DRI}$$

$$M_{ekv} \cong M_B.\left(1 + \frac{484 - d_{disc}}{176} 0.05\right).\left(1 - \frac{S - 69}{11} 0.05\right)$$

S = The spacing between the grooves produced by the disks on the excavation face (in mm)
$d_{disc}$ = The diameter of the disc (in mm);
$k_{DRI}$ = A corrective coefficient that depends on DRI and $k_{s\text{-}tot}$ (Bruland 1998):

$$\text{when } k_{s-tot} \cong 0.36: K_{DRI} \cong -0.0001.DRI^2 + 0.0247.DRI + 0.0293$$

$$\text{when } k_{s-tot} \geq 2: k_{DRI} \cong -0.00007.DRI^2 + 0.0134.DRI + 0.51$$

$k_{s\text{-}tot}$ is the coefficient that takes into consideration the presence of the rock mass discontinuities:

$$k_{s-tot} = \left[\sum_{i=1}^{n} k_{si} - (n-1).0.36\right]$$

Where:
N = The number of discontinuity sets present in the rock mass
$M_B$ = The force acting on the disk (also known as $F_N$)
$k_{si}$ = A parameter that describes the presence of each single discontinuity set in function of the angle $a_i$ (angle between the tunnel axis and the $n^{th}$ discontinuity plain) and of the fracture class (Table 2) (Fissure: non-continuous discontinuity; Joint: continuous discontinuity)

Fissure class 0 or Joint class 0:

$$K_{si} = 0.36$$

Fissure class I or Joint class 0-I:

$$\text{when } a_i < 40: k_{is} \cong 0.0133.a_i + 0.45$$

$$\text{when } 40 \le a_i \le 90: k_{is} \cong -0.0005.a_i^2 + 0.0564.a_i - 0.4901$$

Fissure class II or Joint class I:

$$\text{when } a_i < 40: k_{is} \cong 0.0158.a_i + 0.75$$
$$\text{when } 40 \le a_i \le 90: k_{is} \cong -0.0005.a_i^2 + 0.0586.a_i - 0.1196$$

Fissure class II-III or Joint class I-II:

$$\text{when } a_i < 40 k_{is} \cong 0.017.a_i + 0.93$$
$$\text{when } 40 \le a_i \le 90: k_{is} \cong -0.0005.a_i^2 + 0.0576.a_i + 0.1291$$

Fissure class III or Joint class II:

$$\text{when } a_i < 40: k_{is} \cong 0.02.a_i + 1.16$$
$$\text{when } 40 \le a_i \le 90: k_{is} \cong -0.0007.a_i^2 + 0.0835.a_i = 0.2894$$

Fissure class III-IV or Joint class II-III:

$$\text{when } a_i < 40: k_{is} \cong 0.0248.a_i + 1.63$$
$$\text{when } 40 \le a_i \le 90: k_{si} \cong -0.0005.a_i^2 + 0.0622.a_i + 0.8789$$

Fissure class IV:

$$\text{when } a_i < 40: k_{si} \cong 0.0243.a_i + 2.67$$
$$\text{when } 40 \le a_i \le 90: k_{si} \cong -0.0003.a_i^2 + 0.0483.a_i + 2.1246$$

The penetration per revolution p (mm/rev) allows one to obtain an estimation of the net advancement velocity PR of the excavation machine (m/hr):

$$PR = p.\frac{60.RPM}{1000}$$

where, RPM is the rotation velocity of the TBM head in revolutions per minute.

According to Barton (2000), it is possible to define an index, $Q_{TBM}$, on the basis of the geomechanical quality index of the rock mass Q (Barton, 2000) (with the RQD parameter estimated in the direction of the tunnel axis):

$$Q_{TBM} = Q.\frac{5.\gamma.\sqrt[s]{Q.\frac{\sigma c}{100}}}{F_N}$$

Where:

$\gamma_c$ = The specific weight of the rock (in $tons_f/m^3$)

$\sigma_c$ = The uniaxial compression strength of the intact rock (in MPa)

$F_N$ = The force applied by the tool in the direction perpendicular to the excavation face (in $tons_f$)

Once the value of $Q_{TBM}$ is known, it is possible to determine the net advancement velocity of the TBM, PR (m/hr), on the basis of the following formula:

$$PR = \frac{5}{\sqrt[5]{Q_{TBM}}}$$

From this formula, it is possible to derive p (mm/rev), if the rotation velocity of the TBM head is known:

$$p = PR.\frac{1000}{60.RPM}$$

In addition, the Politecnico di Torino School (Innaurato *et al*., 1990) has prepared a relation that allows the penetration per revolution p (mm/rev) to be estimated in function of the uniaxial compression strength of the intact rock $\sigma_c$(in MPa), of the geomechanical quality index of the rock mass RSR (Wickham *et al*., 1972) and of the diameter of the tunnel D (m):

$$p \cong 40.41.\sigma_c^{-0.437} - 0.047.RSR.[0.11.(9-D)^{0.35} + 1] + 3.15$$

Another interesting rock excavation estimation method was introduced in 2006 (Preinl *et al*., 2006; Bieniawski *et al*., 2007; 2009; Bieniawski and Benjamin, 2007). This method is once again based on an examination of homogeneous sections, in terms of the geomechanical characteristics. The RME is calculated using five input parameters with the following ratings:

- Uniaxial compressive strength of the intact rock material: 0-15 points
- Drilling rate index, DRI 0-15 points
- Number of discontinuities present at the tunnel face, their orientation with respect to the tunnel axis and homogeneity at the tunnel face: 0-40 points
- Stand up time of the tunnel face: 0-25 points
- Water inflow at the tunnel face: 0-5 points

The sum of the ratings of the above parameters (RME value) varies from 0-100 rating points: the higher the RME value, the easier and more productive the mechanical excavation of the tunnel by TBM.

The mean advance rate in a tunnel section (ARA in m/day) is then obtained on the basisof the RME value. ARA can eventually be corrected, considering the tunnel diameter, crew efficiency and adaptation to the rock.

Each considered characteristic section of the tunnel should be longer than 30 m, should not have significant variations in the RME and rock mass quality (RMR value) and should have the TBM utilization within 30-60%.

**Microscale rock abrasivity characterization tests:** The first step towards the knowledge of thewear attitude of a rock on a tool consists of a petrographic analysis in order to determine the mineralogical composition of the rockwith particular attention being paid to the contents of quartz and other abrasive minerals such as feldspar and laminated silicates. Other minerals, which are sometimes present in small quantities, can also confer important wear properties to the rock.

The second step consists in conducting mechanicaltests on the rock (Table 3) (Innaurato *et al*., 1990).

The Department of Georesourcesand Land (DIGET) at the Politecnico di Torino has performed research on rock hardness at a micrometric scale since the Seventies. Rock hardness is expressed through the frequency distribution of the hardness (Italian Norm UNI 9724, part 6), which measuredwith a Knoop penetrator (pyramidal shapeddiamond) under a load of 1.96 N at 40 points on the specimen.

The micro-hardness value (HK), measured in MPa, can be obtained from the following expression:

$$HK \cong \frac{P}{C_p.L^2}$$

Where:

- $C_p$ = A conversion coefficient, which is equal to 0.070279
- P = The force applied to the penetrator (in $kg_f$)
- L = The maximum length of the sign left on the tested sample (in mm)

The frequency distribution diagram obtained from 40 readings is used to characterize the rock (Fig. 2). The same procedure can also be followed to test the metal the tool is composed. It is important to determine the HK75 parameter, which corresponds to the micro-hardness value with respect to which 75% of the conducted tests supply a lower micro-hardness value.

Innaurato and Mancini (1996) showed, on the basis of in situ investigations and laboratory tests utilizing mini-disks on rock samples, that the wear of tools is closely related to the HK75 parameter of the rock. The relation that connects the wear of the tools to the HK75 parameter is of an exponential type, with a slight initial increase of the wear with an increase in the HK75 parameter and the wear then increases in a remarkable way for high HK75 values.

The same authors showed how an accurate estimation of the degree of wear of the disks of a TBM machine can be obtained by conducting a detailed analysis of the ordinate distribution of the micro-hardness measurements in conjunction for the rock and the excavation tool. By comparing each single micro-hardness value measured on the rock ($HK_{Ri}$) with all the micro-hardness values measured on the excavation tool ($HK_{Tj}$), it is possible to determine the probability of $HK_R$ being greater than $HK_T$. The degree of wear of the tool can be associated to this probability.

**Table 3.** The most widespread tests for abrasivitymeasurements (Innaurato *et al*., 1990)

| Principle of measurement | Test name |
|---|---|
| Impact tests | Protodyakonov test NTI test |
| Attrition tests | Dorry test Taber test |
| Bit wear tests | CHERCHAR test |
| Drillability | NTI test DIGET test<br>Siever s test NTI test<br>CERCHAR test DIGET test |
| Rebound tests | Schmidt impact<br>hammer test shore test |
| Indentation tests | Vickers test knoop<br>test NCB cone indener test |
| Scratch tests | Mohs hardness CERCHAR test |

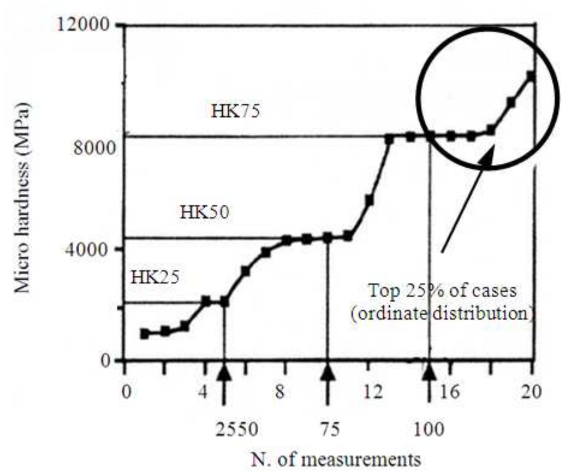



Fig. 2: Determination of the HK75 parameter on the basis of the ordinate distribution of the micro-hardness measurements conducted on a rock sample or on the excavation tool (Innaurato and Mancini, 1996)

Table 4: Rock classification in relation to abrasiveness (the capacity to produce wear of the TBM disks), on the basis of the analysis of 3200 rock samples (Dahl *et al*., 2012)

| | AVS (mg) | Cumulative (%) |
|---|---|---|
| Extremely high | ≤ 2.0 | 95÷100 |
| Very high | 2.1÷3.9 | 85÷95 |
| High | 4.0÷6.9 | 65÷85 |
| Medium | 7.0÷18.9 | 35÷65 |
| Low | 19.0÷55.9 | 15÷35 |
| Very low | 56.0÷85.9 | 5÷15 |
| Extremely low | ≥ 86.0 | 0÷5 |

Another very common mechanical test for the evaluation of rock abrasiveness is the Cerchar test (CERCHAR, 1986), which was developed in France in the eighties (Plinninger and Thuro, 2004). The test involves thrusting a steel punch (with a thrust force of 70 N), with a particular conic shaped tip, against a rock sample.

The measurement of the diameter of the circle produced on the deformed tip during the test allows an index, the Cerchar Abrasivity Index (CAI), to be defined. The CAI parameter is in fact calculated as the mean value of the diameters of the circles observed on the deformed tips, measured in tens of millimeters. The greater the abrasiveness of the rock, the higher the value of CAI.

Maidl *et al*. (2001) were able to show how the wear of the tools is connected to the abrasiveness of the rock (CAI) and to the uniaxial compression strength. The wear of the tools can be extremely variable: very low in some weak rocks, with a CAI value of around 2 and very high in high strength granites, with CAI values of around 6. From the Maidl *et al*. (2001) diagram, it is possible to observe the following expressions for the specific disk cutter wear rate (SDCWR), expressed in $m^3$ excavated from each disk, in function of the uniaxial compression strength (in MPa):

$$\text{when}\,\mathrm{CAI}=2:\mathrm{SDCWR}\cong 10^{(0.000020.\sigma_c^2-0.0088.\sigma_c+3.9944)}$$

$$\text{when}\,\mathrm{CAI}=3:\mathrm{SDCWR}\cong 10^{\left(0.000007.\sigma_c^2-0.0056.\sigma_c+3.1889\right)}$$

$$\text{when}\,\mathrm{CAI}=4:\mathrm{SDCWR}\cong 10^{\left(0.000010.\sigma_c^2-0.0037.\sigma_c+2.8387\right)}$$

$$\text{when}\,\mathrm{CAI}=5:\mathrm{SDCWR}\cong 10^{\left(0.000010.\sigma_c^2-0.0037.\sigma_c+2.4669\right)}$$

$$\text{when}\,\mathrm{CAI}=6:\mathrm{SDCWR}\cong 10^{\left(0.000005.\sigma_c^2-0.0037.\sigma_c+2.2371\right)}$$

**Tool wear tests in the laboratory:** One well known wear test for tools that can be found in literature and which is used extensively, is the one that was set up by the Norwegian School (NTH/NTNU) (Blindheim and Bruland 1998). This test involves sliding a sample of the TBM disk, on which a 10 kg weight is pressed, along a steel ring on which a powder of the tested rock is deposited continuously. The test lasts 1 minute and involves 20 revolutions of the steel ring. The loss in weight of the TBM disk sample is measured at the end of the test. The AVS parameter is the loss in weight measured in milligrams. Dahl *et al*. (2012) classified rocks with reference to their abrasiveness (or their capacity to induce wear on the steel TBM disks) (Table 4), on the basis of test results on 3200 rock samples.

The Cutter Life Index (CLI) is estimated on the basis of the AVS and SJ:

$$\mathrm{CLI}\cong 14.\left(\frac{\mathrm{SJ}}{\mathrm{AVS}}\right)^{0.4}$$

On the basis of the values obtained for SJ and AVS, it is possible to indicate a variability field for CLI. This field ranges from a minimum of 10-15 for very abrasive rocks and which are very resistant to perforation (granites and gneiss), to a maximum of 80-90 for rocks with very low abrasiveness and very little resistance to perforation (talcs and chlorite schists).

The CLI parameter can be used, together with the quartz contents of the rock, to obtain a modified estimation of the net advancement velocity PR (m/hr) (Barton, 2000), considering the effect of wear on the performance of the disks:

$$\mathrm{PR}=\frac{5}{\sqrt[5]{\mathrm{Q}_{\mathrm{TBM}}\cdot\left(\frac{20}{\mathrm{CLI}}\right)\cdot\left(\frac{\mathrm{qz}}{20}\right)}}$$

where, qz is the percentage of quartz contained in the rock.

Furthermore, it is also possible to obtain an estimation of the mean global velocity of the excavation machine (AR in m/hr), considering all the necessary machine stops, including those necessary to substitute the worn disks:

$$\mathrm{AR}=\mathrm{PR}^{\frac{2.\overline{m}+1}{\overline{m}}}\cdot\mathrm{L}^{\frac{\overline{m}}{\overline{m}+1}}$$

where, L is the length of the tunnel (in m):

$$\overline{m}=\mathrm{m}.\left(\frac{20}{\mathrm{CLI}}\right)^{0.15}.\left(\frac{\mathrm{qz}}{20}\right)^{0.10}$$

m is a negative parameter that can be estimated n function of the geomechanical quality index Q and of the tunnel diameter (Barton, 2000): when

$Q \le 0.1 : m \cong [-0.9 + 0.2.(3 + \log_{10} Q)].\left(\frac{d_{TBM}}{s}\right)^{0.2}$ when

$0.1 < Q \le 1 : m \cong [-0.5 + 0.3.(1 + \log_{10} Q)].\left(\frac{d_{TBM}}{s}\right)^{0.2}$ ;when

$Q > 1 : m \cong -0.2.\left(\frac{d_{TBM}}{s}\right)^{0.2}$ $d_{TBM}$ is the diameter of the TBM (in m).

Bruland (1998), on the basis of the CLI parameter, obtained the following expression, which can be used to estimate the net mean time (in hours) between one substitution of a disk and the next one ($H_h$):

$$H_h = \frac{H_0.k_D k_Q.K_{RPM}.K_N}{N_{TBM}}$$

where, $H_0$is the basic disc life (in hours) (Bruland 1998):

17 inch disk diameter:

$$\text{when } CLI < 30 : H_o \cong -0.0925 \cdot CLI^2 + 6.165 \cdot CLI + 0.65$$
$$\text{when } CLI \ge 30 : H^o \cong -0.0044 \cdot CLI^2 + 1.3333 \cdot CLI + 67.5$$

19 inch disk diameter:

$$\text{when } CLI < 30 : H_o \cong -0.1425 \cdot CLI^2 + 8.305 \cdot CLI + 1.05$$
$$\text{when } CLI \ge 30 : H^o \cong -0.0031 \cdot CLI^2 + 1.2483 \cdot CLI + 88.75$$

$k_D$, $k_Q$, $k_{RPM}$e $k_N$ are the corrective coefficients that take into account the diameter of the TBM, the quartz contents of the rock, the rotation velocity of the excavation head and the number of disks, respectively:

$$K_D \cong -0.0065.d_{TBM}^2 + 0.2061.d_{TBM} + 0.474$$
$$k_Q \cong 0.00009.qz^2 - 0.0196.qz + 1.714 \pm 0.08$$

qz is the percentage of quartz in the rock; for mica-schists, mica-gneiss, gneiss and granites with qz ≤ 27%, the following equation should be used:

$$k_Q \cong -0.00009.qz^3 + 0.004.qz^2 - 0.0192.qz + 0.6 \pm 0.08$$

$$k_{RPM} = \frac{50 / d_{TBM}}{RPM}$$

RPM is the rotation velocity of the head (in rev/min):

$$K_N = \frac{N_{TBM}}{N_o}$$

$N_{TBM}$ = The real number of disks on the TBM head
$N_0$ = Typical number of disks on the TBM head:

$$N_o \cong \frac{\frac{d_{TBM}}{2}}{2.074}$$

Once $H_h$ is known, it is possible to calculate the mean global excavation velocity (AR in m/hr) from the following expression (Bruland 1998):

$$AR = \frac{1000}{T_b + T_t + T_c + T_{tbm} + T_{bak} + T_a}$$

Where:

- $T_b$ = The time (hr) necessary for the excavation for each km of tunnel: $T_b = \frac{1000}{PR}$
- $T_t$ = The time necessary (hr) for the rewrapping of the machine for each km of tunnel: $T_t = \frac{1000.t_{tak}}{60.l_s}$
- $t_{tak}$ = The time necessary for the regripping (in minutes): usually 5÷20
- $l_s$ = The length of the advancement step of the machine (in m): usually 1.2÷2 m
- $T_c$ = The time (hr) necessary to change the disks for each km of tunnel: $T_c = \frac{1000.t_c}{60.H_h.PR}$
- $t_c$ = The time necessary to substitute a disk on the head (in minutes): usually 50÷100 min
- $T_{tbm}$, $T_{bak}$ and $T_a$ = The times (hr) necessary for the maintenance of the machine, for the maintenance of the back-up and for various other activities, for each km of tunnel, per km di galleria:

$T_{tbm} \cong 1.8036.PR^2 - 27.539.PR+125.7$
$T_{bak} \cong 1.6607.PR^2 -21.539.PR+84.7$
$T_a \cong (-5.PR+130) \div(-6.PR+210)$ with the most probable value: $T_a \cong -5.PR+155$

## RESULTS

**The influence of the rock abrasiveness on the performance of a TBM:** The wear of disks on a TBM machine results in a decrease in the efficiency of the excavation and also greater dead times in which the machine has to be stopped in order to substitute excessively worn disks which are no longer able to work in a satisfactory manner.

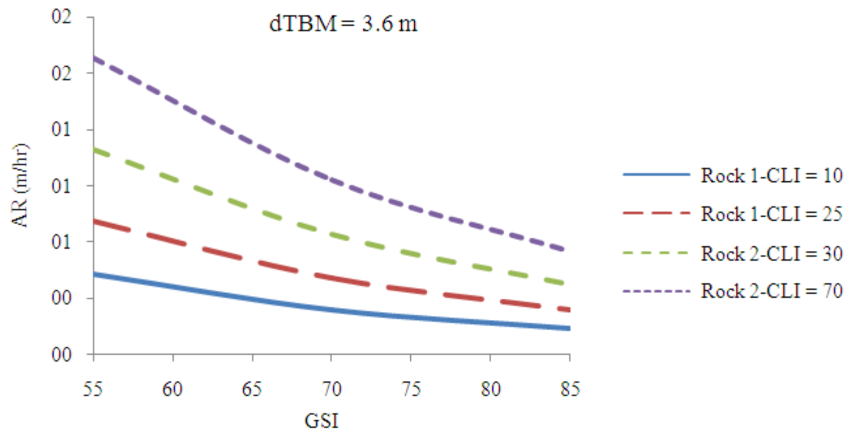
An analysis of the influence of abrasiveness on the construction times of a tunnel excavated with a TBM machine and as a consequence, on the costs, is a very important aspect in the design phase.

In order to have a preliminary evaluation on the effects of abrasiveness of the rock on the construction times of a tunnel with a TBM machine, a calculation of the mean global velocity of the machine has been made for different types of rock and for different tunnel diameters. The method developed by Bartonwas used for this purpose.

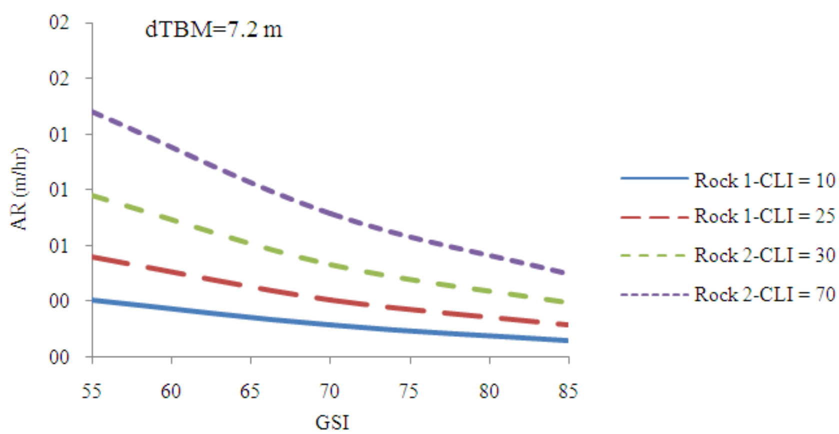
Three different tunnel diameters were considered (small tunnel: 3.6 m; medium tunnel: 7, 2 m; large tunnel: 10 m) and two different types of rock (a highly abrasive granite, a slightly abrasive calce-schist), whose physical and mechanical characteristics, which are necessary for the utilized analysis method, are reported in Table 5. The CLI parameter was considered to vary over a certain interval considered typical of the rocks and three different values of the GSI index (from which the geomechanical quality index Q was obtained) were considered: 55, 70 and 85. The force $F_N$ acting on the individual disks was assumed equal to 140 kN; the length of the tunnel (L) was assumed to be 1000 m.

**Table 5.** Physical and mechanical parameters of the rocks considered in the calculation necessary for the evaluation of the excavation productivity according to the Barton analysis method

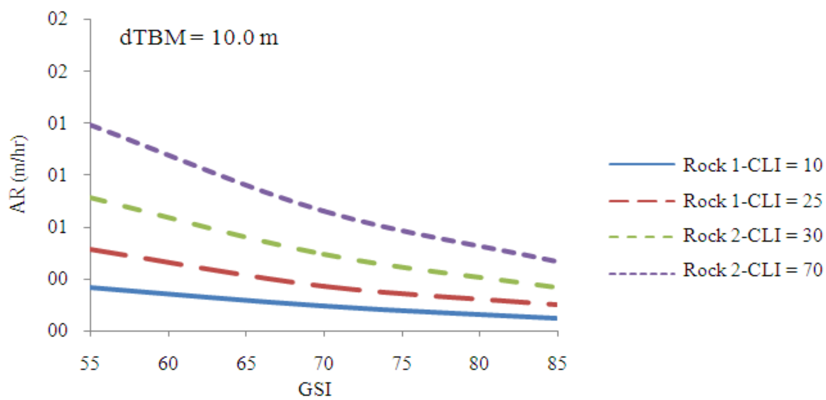
| Rock type | (1) granite | (2) calce-schist |
|---|---|---|
| $\gamma$ (tons$_f$/m$^3$) | 2.7 | 2.7 |
| $\sigma_c$ (MPa) | 80 | 40 |
| CLI | 10-25 | 30-70 |
| qz (%) | 40 | 20 |




(a)




(b)




(c)

Fig. 3: Trend of the global velocity (AR) with a variation of the Geological Strength Index (GSI), for the three different diameters of the tunnel and the two types of rock considered. Extreme CLI values of the typical variability interval were assumed for the two types of rock

Table 6: Percentage variations of the global velocity (AR), with respect to the mean value

| Rock type/Diameter | 3.6 m | 7.2 m | 10 m |
|---|---|---|---|
| GSI = 55 | | | |
| 1 | ±24.6% | ±27.1% | ±30.6% |
| 2 | ±18.4% | ±20.5% | ±21.4% |
| GSI = 70 | | | |
| 1 | ±26.2% | ±29.2% | ±30.0% |
| 2 | ±18.5% | ±21.3% | ±22.1% |
| GSI = 85 | | | |
| 1 | ±26.3% | ±30.8% | ±36.4% |
| 2 | ±19.6% | ±21.6% | ±23.1% |

The results of the calculation, in terms of mean global velocity (AR), expressed in m/h and are reported in Fig. 3 for all the considered cases. The percentage variations of the mean global velocity (AR), with respect to the mean value, are given in Table 6.

From Table 6, it is possible to note how the variations in the CLI parameter, in a typical interval for the two considered rocks, lead to remarkable variations in the global advancement velocity of the TBM (AR). In particular, the variation produced by the CLI is always greater than ± 18%, compared to the mean value and can even reach ± 36% in very abrasive rock, with elevated GSI and large tunnel dimensions. Similar values were obtained also through the calculation with the Norwegian School method.

The exact evaluation of the CLI parameter, which characterizes the rock as far as wear of the excavation tools is concerned, is therefore necessary in practically all tunnels excavated by TBMs in order to be able to have a reliable estimation of the construction times and costs. The failure to evaluate the CLI parameter of the rock along the tunnel layout could lead to relevant errors in the estimation of the construction times and costs.

**Field Data from a case history in North Italy:** The examined case concerns a tunnel in Piedmont (Italy) which is under construction close to the Alpine chain, in order to eliminate the risk of a large landslide occurring at the present site of the national road which crosses the bottom of the valley. The tunnel, which has a global length of about 1 km, is being excavated in the rocky substrate below the body of the potential landslide and it will be part of the new national road which will take the place of the present one. The construction of the tunnel has foreseen the excavation of an advance pilot tunnel, with a diameter of 3.6 m and a length of 876 m, using a TBM machine. The rock crossed by the tunnel is made up of minute gneiss and mica-schists: these are ancient pelites that have undergone a polymetamorphic process. The main geomechanical characteristics of the rock are: $\sigma_c$= ≅110 MPa; $\gamma$ = 2.65 $t_f/m^3$; qz≅40%.

The purpose of the pilot tunnel was to optimize and reduce the use of explosives in the subsequent final section enlargement phase and also to provide detailed information on the excavated rock volumes in order to drastically reduce the knowledge uncertainty, due to the lack of investigations (This zone cannot be entered at present).

The TBM utilized for the excavation of the pilot tunnel is of an open type, with 17" diameter disks.

During the excavation, the machine working data were monitored and all the substitutions of worn disks were recorded. The mean force applied to each disk was 16.7 $tons_f$. Moreover, geological surveys along the pilot tunnel have made it possible to establish the GSI of the rock at different chainages. The GSI measured along the entire layout of the pilot tunnel varied between 50 and 60.

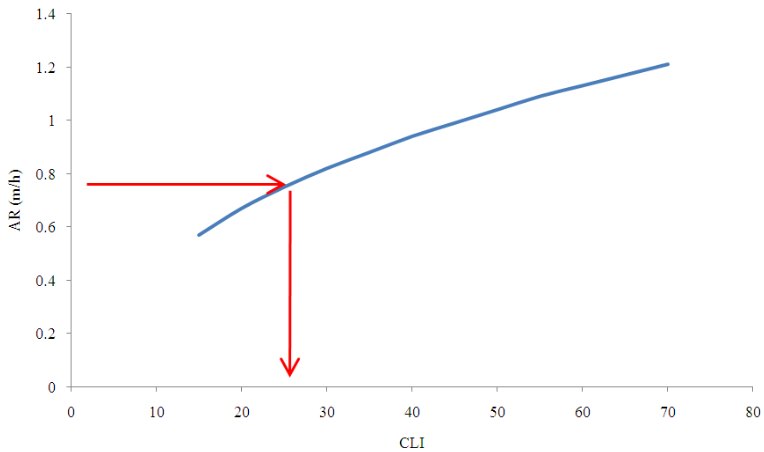



Fig. 4: Andamento della velocità media globale (AR) al variare dell'indice Cutter Life Index (CLI), calcolata secondo il metodo di Barton. Stima del parametro medio CLI a ritroso, a partire dalla determinazione della velocità media globale di avanzamento della macchina registrata in situ

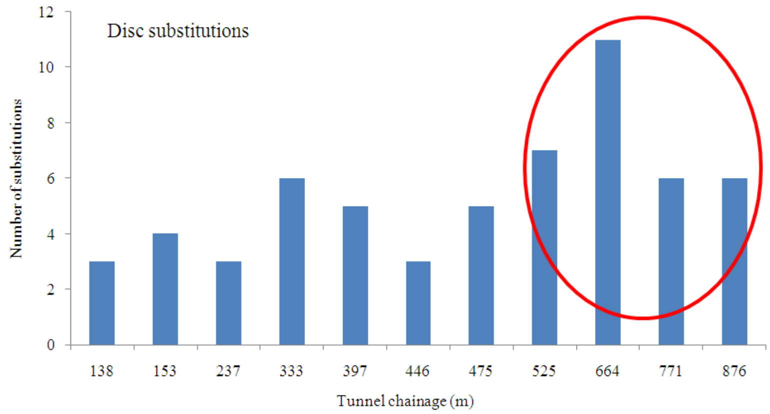



Fig. 5: Number of substitutions of the disks for the various tunnel chainages. The final portion of the tunnel, in which the number of substitutions of the disks was slightly higher than in the first part of the layout, is shown in red circle

The total time necessary to construct the tunnel was 49 working days and the mean global velocity (AR) was about 0.74 m $h^{-1}$. The total excavation time was 26970 min (449.5 h) and the mean value of the net advancement of the machine (PR) was 1.94 m/h.

The evaluation of the CLI parameter for the rock along the layout had not been made before the tunnel was excavated with the TBM. The typical range of variation of the CLI for gneiss is relatively small (15±25), while it is much larger for the mica-schists (15±70).

The values of the global velocity (AR), with a variation of the CLI, calculated according to the Barton method, are reported in Fig. 4.

From an examination of the graph in Fig. 4, it emerges that the CLI parameter has a significant influence on the global advancement velocity of the TBM. If the AR values obtained from the calculation are compared with the value actually measured in situ (0.74 m $h^{-1}$), the mean CLI along the layout can be determined: CLI≅24. If the mean CLI had been 50, it would have been possible to reduce the tunnel construction time to 35 working days; with a CLI = 70, the times would have been reduced to 30 actual working days. Finally, with very elevated CLI values, but which are however within the typical variability interval for the rocks under examination, the pilot tunnel construction times could have been 30-40% lower.

Confirmation of the elevated abrasiveness of the rock and therefore of the low mean CLI values, can be obtained from an analysis of the data on the substitution of the tools on the excavation head. The number of disks substituted at the various chainages can be observed in Fig. 5. From the figure, it is possible to observe a greater wear of the tools in the last section of the tunnel. If the conditions of the disks at the TBM head at the end of the tunnel excavation are considered, it is possible to determine the mean volume of rock excavated by each disk during its useful working life: $V_d \cong 130\ m^3$/disk. This value is much lower than the mean value of 200-210 $m^3$/disk, which represents the mean volume of rock excavated in the medium abrasive rock. The low value of the back-analysed estimation of the mean CLI along the layout can therefore be confirmed by the numerous substitutions of the disks during the excavation of the tunnel and therefore, by the limited duration of the disks in working conditions.

On the basis of the Norwegian School method and the equations reported above and considering CLI = 24, $d_{TBM}$ = 3.6 m, the diameter of the disks 17", $N_{TBM}$ = 25, qz = 40% and RPM = 10.6 rev/min, we obtain $H_h$ = 6.24 hr. From the in situ data we can evaluate $H_h$ = 6.58 hr on the basis of the following equation:

$$H_h = \frac{\left(\frac{L}{PR}\right)}{\left(\frac{L\frac{\pi}{4}d_{TBM}^2}{vd}\right)} = \frac{V_d}{PR.\frac{\pi}{4}.d_{TBM}^2}$$

From a comparison of the previously calculated value (6.24) with that determined through the verification of the substitution of the disks during the construction of the tunnel (6.58), it is possible to obtain further confirmation of the CLI value (≅24) also from the Norwegian School method.

## DISCUSSION

The rock fragmentation mechanism at the excavation face of a tunnel that is produced by the action of the disks of a TBM is complex and is still not completely understood. However, various different methods can be found in the literature for the forecasting of the net advancement velocity and the global velocity of the excavation machine, in function of the physical and mechanical parameters of the rock.

The most well known methods in the scientific community and the procedures adopted to determine the rock parameters that result to influence the advancement velocity and therefore the efficiency of the excavation, have been illustrated in this study.

The preliminary evaluation of the abrasiveness of the rock and the capacity of the rock to wear the tools is of particular interest, both in order to evaluate the reduction in efficiency of the disks because of wear and to determine the frequency of the substitution of the disks and therefore the dead times necessary for this operation. The repercussions of the wear of the disks on the times and costs of construction of a tunnel is an aspect very important.

Among the analysis methods known in literature, the studies developed in this study have shown the validity of the Barton method and that of the Norwegian School (NTH/NTNU). The CLI rock parameter plays an important role in both of these methods and it can be determined through two distinct laboratory tests that measure the surface resistance to perforation of the rock (the former) and the capacity to wear the tools because of friction with previously powdered rock (the latter).

A parametric study that has been conducted for different types of rock and for three tunnel diameters has made it possible to evaluate the important influence of the CLI parameter on the global advancement velocity of the TBM (AR). The extent of the variability of the AR interval can exceed 70% of its mean value, with a variation of CLI in tunnels with large diameters, in very abrasive and slightly fractured rocks. However, it was considerable in all the examined cases.

The two previously mentioned methods were applied to a case history of a tunnel with a small diameter that has recently been excavated in North Italy. From a comparison of the results of the calculation with the Barton method and the data relative to the advancement velocity actually recoded for the machine, it has been possible to back-analyse the mean CLI parameter of the rock along the tunnel; adopting this value in the Norwegian School method, it was then possible to obtain the net mean time $H_h$ (in hours) between one substitution of a disk and another. The calculated value practically coincides with the one that was measured in situ, thus demonstrating the good adherence of the two analysis methods to the real conditions of the excavation.

## CONCLUSION

The studies presented in this study indicate how it is necessary to characterise the rock, as far as abrasiveness and the capacity to wear the disks are concerned, when it is necessary to proceed with the excavation of a tunnel using a TBM. The determination of the CLI parameter in fact results to be of fundamental importance in order to be able to obtain a valid estimation of both the times and costs of the construction of a tunnel. Failing to evaluate the abrasiveness of the rock in the preliminary design phase of a tunnel can lead to considerable delays in the study and much higher costs than those forecasted during the design stage.

The Barton method has proved to be very useful to obtain a correct estimation of the advancement velocities of the excavation machine (both the net and the global velocities). The Norwegian School method has instead been able to offer a precise forecast of the frequency with which it is necessary to change the disks and therefore of the influence of the dead times necessary to allow these operations to be conducted on the construction times of the tunnel.

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