Prediction of penetration per revolution in TBM tunneling as a function of intact rock and rock mass characteristics

Penetration per revolution prediction in TBM tunneling as a function of intact rock and rock mass characteristics

A. Benato[1] and P. Oreste[2]

1: DIATI (Dept. of Environmental, Land and Infrastructural Eng., Politecnico di Torino, Italy). Tel. number: +39 3408387418, e-mail address: benato.andrea89@gmail.com

2: DIATI (Dept. of Environmental, Land and Infrastructural Eng., Politecnico di Torino, Italy). Tel. number: +39 0110907608, e-mail address: pierpaolo.oreste@polito.it

1. Abstract

The estimation of the penetration per revolution of the cutterhead is one of the most interesting aspects of the design of a tunnel excavated with TBM. Thanks to the contribution of several authors, nowadays it is not only possible to study the complex tensional state of the rock in the vicinity of the tools, but also to estimate the penetration per revolution through empirical correlations that take into account the most important parameters of rock and tools. Such empirical formulations generally prefer the contribution of intact rock or of natural discontinuities and in some cases have proved to be valid for some applications only.

In this paper a new empirical formulation is presented in order to estimate the penetration per revolution derived from the TBM behavior monitoring data in alpine tunnels in the North-West of Italy. This formulation proved to be easy to use and allows to take into account both the contribution of intact rock characteristics and of the natural discontinuities in the rock mass.

2. Introduction

One of the most important aspects in the design of a tunnel excavated with a Tunnel Boring Machine (TBM) (Innaurato N. and Oreste P., 2011) is the evaluation of its speed of advancement and, therefore, the time estimate to build the tunnel. These times not only affect the organisation of the construction site, but also the total costs.

The net advancement rate of a TBM depends on the penetration of its disc tools per revolution of the cutterhead (Oggeri C. and Oreste P., 2012), that is the depth of the part of rock detached from the tunnel face at each revolution of the cutterhead.

Several authors have studied the mechanism of destruction of the rock (Innaurato et al., 2007; Cook et al., 1984; Innaurato and Oreste, 2001; Lindqvist and Hai-Hui, 1983; Nishimatsu, 1972; Oreste and Innaurato, 2011, Cardu et al., 2013), but today is not yet possible to have an analytical model capable of assessing with precision the failure conditions of the rock under the application of forces on the TBM disc tools.

Through tridimensional numerical modeling it is possible to study, even if with some difficulty, the development of tensions near the single disc. However, the mechanism of breakage of the rock that leads to the formation of chips is not completely understood yet for the following reasons:

- evolution of the processes of rupture of the rock at a very small scale, where resistance criteria and rock parameters involved are very different from those that may be used on the laboratory scale;
- considerable variation in space of rock characteristics on a small scale;
- application of the thrust at the rock over short periods, with dynamic effects that influence the evolution of rupture;
- interaction between contiguous grooves produced by the previous passage of the discs;
- influence of the stress state at the face of the tunnel and fractures and micro fractures present on the rock during the evolution of the rupture.

As often happens when physical mechanisms are complex and not completely known, empirical formulations were developed over time on the basis of experience, capable of estimating the penetration per revolution as a function of the most critical parameters, including: contact force applied to each disc, disc size, spacing between grooves produced on the tunnel face from the passage of discs, parameters of rock strength evaluated on the lab tests scale, and fracturing degree of the rock mass.

Some empirical formulations which consider all the parameters controlling the penetration per revolution – some even requiring the execution of special tests which are not always easy to execute - are complex to use. Others are easier, but can be used in a limited range of applications. In general, some of them put more emphasis on the characteristics of the intact rock (for example Rostami, 2008), other on the characteristics of the natural fractures of the rock mass (for example Blindheim, 1998). Often the results obtained by applying various formulations are very different from each other.

For this reason, a new empirical formulation is presented in this paper to estimate the penetration per revolution. This formulation has been obtained from data from the excavation of a tunnel (alpine tunnel in the North-West of Italy). The proposed formulation has the advantage of being very simple to use because it requires a small number of parameters (only the most influential ones) which are always known during the design phase of a tunnel; at the same time it is efficient, while taking into account both the characteristics of intact rock, and the natural fracturing degree of the rock mass.

First we briefly introduce the characterictics of the TBM and of the mechanism of action of the discs on the cutterhead and we illustrate the parameters - generally measured during the construction of tunnels - which represent the database from which the empirical formulations are obtained to estimate the penetration per revolution. We then present today's most commonly used empirical formulations when estimating the penetration per revolution (Norwegian School and Barton methods) and the one proposed here. Finally, the results obtained with the existing empirical formulations and with the one proposed will be analyzed for comparison.

3. The Tunnel Boring Machines (TBM) and monitoring of the excavation parameters

The excavation of tunnels with full section machines (TBM) has experienced a large development in the last years. Nowadays, the safety of this kind of machine is comparable to traditional methods of excavation, and productivities are generally higher. Still, knowing the geological conditions at any stage in tunnel development is critical in order to predict the performances of the Tunnel Boring Machines.

The rock TBMs may have different configurations: open, shield or double shield. The main difference is in the modality of the thrust with which they can advance in the tunnel excavation. The choice of machine is generally influenced by the degree of fracturing of the rock mass and by the mechanical strength of the intact rock. Open TBMs are used on less fractured rock masses characterized by a high resistance of the intact rock; these machines are able to exert high thrust values on the tunnel face thanks to the lateral contrast forces on the tunnel's walls. Shield machines are generally used for highly fractured rocks as they are able to guarantee the stability of the tunnel by means of a metallic shield placed behind the head of the TBM. With this configuration the precast lining concrete segments are assembled inside the shield itself, and the thrust needed to advance with the excavation is applied on the last ring of segments through hydraulic jacks. Double shield TBMs are characterized by a high versatility and they can be used in mixed conditions, operating either as open TBMs (with similar productivities), either as shield TBMs. Depending on the excavating configuration chosen, the thrust can be exerted by applying contrast forces on the tunnel's walls or on the last ring of segments through hydraulic jacks.

TBMs operate through the application of a thrust on the cutter head which allows its disc tools to penetrate the rock. Disc tools can have different diameters (generally 15", 17" or 19"): the greater the diameter, the larger the maximum usable thrust, up to maximum values higher than 250 kN per cutter.

The contact force together with the rotational motion of the cutterhead, allow the penetration of discs in the rock, and consequently the detachment of rock chips. The movement of disc cutters causes the formation of grooves on the excavation face (fig. 2).

According to a hypothesis by Hartman (1959) and Maurer (1960), and later summarized by other authors (i.e. Nishimatsu, 1972), which still applies to such complex phenomena, rock breaking from using 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. 3) acts like a fluid that is subjected to hydrostatic pressure which pushes in every direction. 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 cracks produced by indentation of the cutter situated in the neighboring 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.

During the excavation of a tunnel with a TBM, it is of great importance to control the operating parameters of the machine, generally performed by an automatic system of data acquisition and recording. The monitoring is carried out continuously throughout the excavation so that it is linkable to the chainage of the tunnel. The most important parameters are: the thrust applied on each disc cutter, the net advancement rate, the torque, and the speed of rotation applied to the cutterhead (fig.4). Through analysis of these parameters it is possible to assess the specific energy of excavation used to break down the rock, generally expressed in kWh/m^3 (Cardu et al., 2013). The specific energy can be linked to the geomechanical quality of the rock mass along the tunnel's layout.

The TBM's excavation parameters can be used to verify the rock mass conditions throughout the tunnel and can be compared with the original project, in order to modify the geomechanical model of the tunnel if needed.

4. Prediction methods to estimate the net advancement rate (Barton method and Norwegian School)

Estimating the TBM's performance is a crucial phase in tunnel design and for the selection of the appropriate excavation machine. To this purpose, forecasting methods of the net advancement rate based on the analysis of rock mass characteristics along the tunnel, geometrical characteristics of disc cutters, and the characteristics of the cutterhead, are generally employed.

The most interesting analysis techniques - Norwegian School (NTH/NTNU) (Bruland, 1998; Blindheim and Bruland, 1998) and Barton (2000) - allow for disc penetration per revolution to be predicted, while taking into account the presence of natural discontinuities in the rock mass.

The Norwegian School Method allows for a DRI (Drilling Rate Index) estimate as a function of the S_{20} and SJ indices (Bruland, 1998). S_{20} is an index of fragility and it is based on impact strength tests which involve dropping a weight of 14 kg for a total of 20 times onto crushed rock of a predefined size. 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 by an 8.5 mm miniature drill bit after 200 revolutions.

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}).

The first parameter (k_{ekv}) depends on the fracture density of the rock mass and on the discontinuity orientation with respect to the tunnel axis. This parameter is subsequently modified as a function of the DRI index estimated for the intact rock.

The second parameter (M_{ekv}) depends on the contact force applied to each disc (F_N), modified by the geometrical characteristics of disc cutters (diameter, distance between grooves produced by their use on the excavation face).

The penetration per revolution p (mm/rev) allows one to obtain an estimate of the net advancement velocity PR of the excavation machine (m/hr), if the rotational speed of the cutterhead in RPM (rounds per minute) is known:

$$PR = p \cdot \frac{60 \cdot RPM}{1000} \qquad \textit{(eq. 1)}$$

The limit of the forecasting method developed by the Norwegian School is its own complexity. In fact, for the determination of the net advancement rate, the elaboration of several, often unavailable parameters is needed.

According to the Barton method (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, 1974) (with the RQD parameter estimated in the direction of the tunnel axis):

$$Q_{TBM} = Q \cdot \frac{5 \cdot \gamma \cdot \sqrt[3]{Q \cdot \frac{\sigma_c}{100}}}{F_N} \qquad \textit{(eq. 2)}$$

where: γ is the specific weight of the rock (in $tons_f/m^3$);

σ_c is the uniaxial compression strength of the intact rock (in MPa);

F_N is the force applied by the disc in the direction perpendicular to the excavation face (in $tons_f$).

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

$$PR \cong \frac{5}{\sqrt[5]{Q_{TBM}}} \qquad \textit{(eq. 3)}$$

The forecasting method developed by Barton allows to obtain an evaluation of the net advancement rate in a non-complex way, considering each of the most influential parameters. Furthermore, this method gives greater importance to the discontinuities in the rock mass rather than to the characteristics of the intact rock.

5. Experiences in mechanized tunneling in the Western Alps.

From the analysis of several TBM operating parameters used for the excavation of tunnels of various sizes in metamorphic rocks in the Western Alps, it has been possible to divide the penetration per revolution p into classes, depending on the intact rock strength values σ_c and on the GSI index (Hoek, 2007). For each class, it has been possible to determine a relationship between the penetration per revolution and the contact force F_N. These relations have later been extended to consider the effect of the σ_c and the GSI. The result of the analysis has allowed to derive an equation yielding the estimate of a TBM's penetration per revolution as a function of: contact force, strength of intact rock, and GSI:

$$p \cong \frac{5}{8} \cdot [(F_N - 14) + (0{,}0132 - 0{,}00009 \cdot \sigma_c) \cdot (100 - GSI)^2] \quad \textit{(eq. 4)}$$

where:

p is the penetration per revolution (in mm/rev);

F_N is the contact force on the disc (in $tons_f$);

σ_c is the uniaxial compression strength of the intact rock (in MPa);

GSI is the Geological Strength Index.

Depending on the variability of the data used for the functional analysis, this equation can be used for the following parameter ranges:

GSI = 40÷80 ; $\sigma_c = 20 \div 100$ MPa ; F_N = 15 ÷ 25 $tons_f$.

Figure 5 shows five diagrams for predicting the penetration per revolution, each referring to a different σ_c (40-100 MPa range) as a function of GSI and contact force F_N. These graphics allow a quick evaluation of p. For intermediate values of the σ_c and the GSI it is possible to proceed with a linear interpolation between the values obtained from the diagrams.

From the diagrams below, it is possible to observe that for high GSI values, the intact rock strength has little influence on penetration per revolution prediction; on the other hand, with high intact rock strength values, the GSI also appears to have a reduced influence on the penetration per revolution. At the same time, the opposite is also true: with low intact rock strength values, the GSI plays an important role and with low GSI values, the penetration per revolution varies considerably depending on the intact rock strength.

6. Comparison between new and existing prediction methods

Using the existing correlation between the index of geomechanical qualities RMR and Q (Bieniawski, 1976; Barton, 1974; Bieniawski, 1974), and considering GSI=RMR–5 and a unit weight of the rock equal to 27 kN/m^3, it has been possible to compare the evaluation of the penetration per revolution determined with Barton's method (Barton, 2000) with the evaluation of the penetration per revolution determined by the equation proposed in paragraph 4. The penetrations per revolution have been evaluated based on varying RMR indexes using three values of the contact force (F_N=15 $tons_f$; F_N=20 $tons_f$; F_N=25 $tons_f$) and three values of the uniaxial compressive strength of the intact rock (σ_c=50 MPa; σ_c=70 MPa; σ_c=90 MPa). The comparison, shown in figure 6, illustrates that Barton's method considers the influence of σ_c to be negligible. Furthermore, for values of F_N equal to 15 $tons_f$, the trend of p determined by Barton's method is in between the values estimated by eq. 4 in the variability interval considered for σ_c and RMR. With increasing contact force (F_N=20 $tons_f$; F_N=25 $tons_f$), Barton's method provides penetration per revolution estimates which are lower than those from eq. 4; nevertheless, the trend of p as a function of the RMR quality index is similar.

The evaluation of the penetration per revolution with the Norwegian School Method appears to be quite complex, especially concerning the definition of the influence of natural discontinuities in the rock mass: both the orientation of each set of discontinuities with respect to the tunnel axis, and the average spacing between discontinuities for each set, are needed. On the contrary, the penetration per revolution in intact rock estimated through the DRI (Drilling Rate Index) parameter (Blindheim, 1979), which quantifies how easily the rock is excavated with cutting tools, can be obtained quickly. This index ranges from 20 to 80: the higher its value, the easier the excavation of the rock. Figure 7 shows the comparison between the penetration per revolution values determined by the Norwegian School Method for intact rock, and by eq. 4 for rock mass. The first case refers to three different DRI values (40, 55, 70), representing three different categories of rock to be excavated, respectively: hard, intermediate, and easy. In the first case the values of the penetration per revolution do not change as a function of the RMR index. In the second case, the usual three values of the uniaxial compressive strength of intact rock σ_c (50 MPa, 70 MPa, 90 MPa) are considered, representing three categories of resistance, respectively: not very resistant rock, rock with average resistance, very resistant rock. A comparison between easily excavated and low uniaxial compressive strength rock, as well as between hardly excavated and high uniaxial compressive strength rock, is considered.

The difference between the values of the penetration per revolution determined using both methods is then related to the influence of natural discontinuities in the rock mass.

It is possible to use the Norwegian School Method for an initial estimate of the intact rock contribution. Subsequently, the effect of natural discontinuities can be determined by eq. 5. The latter is derived from the functional analysis of the differences between the penetration per revolution from both methods, considering the effect of the geomechanical quality of the rock mass, the contact force F_N and the uniaxial compressive strength of intact rock:

$$\Delta \cong (-6 \cdot 10^{-5} \cdot \sigma_c + 0{,}0082) \cdot RMR^2 + (0{,}0118 \cdot \sigma_c - 1{,}7325) \cdot RMR + (0{,}0025 \cdot F_N - 0{,}6343) \cdot \sigma_c + (0{,}2852 \cdot F_N + 84{,}765) \quad \textit{(eq. 5)}$$

To estimate the contribution of intact rock on the penetration per revolution, it is possible to proceed as follows:

poor intact rock from a geomechanical point of view (low resistance and/or high DRI value):

p=1.0-3.8 mm/rev with contact force F_N ranging between 15 and 25 $tons_f$;

moderate intact rock from a geomechanical point of view (average resistance and/or average DRI value):

p=0.7-2.7 mm/rev with contact force F_N ranging between 15 and 25 $tons_f$;

good intact rock from a geomechanical point of view (high resistance and/or low DRI value):

p=0.3-1.8 mm/rev with contact force F_N ranging between 15 and 25 $tons_f$;

Adding up the two contributions illustrated above (intact rock and natural discontinuities) it is possible to obtain an evaluation of the effective penetration per revolution for the considered rock mass.

As an example, in a tunnel excavated with a TBM in a rock mass which presents an RMR index value equal to 65, and a uniaxial compressive strength of the intact rock of 70 MPa (moderate rock from a geomechnical point of view), the estimated penetration per revolution, corresponding to a contact force F_N of 20 $tons_f$, is approximately equal to:

1.7 mm/rev (rate of the intact rock) +

7.5 mm/rev (natural discontinuity contribution calculated by eq.5) = 9.2 mm/rev

7. Conclusions

One of the most important elements in the design of a tunnel excavated with TBM is the evaluation of its speed of advancement and, therefore, the estimation of the penetration per revolution of the cutterhead. Given the complexity of the process of chip formation under the disc tools of the cutterhead, empirical formulations have been developed over time in order to estimate the penetration per revolution as a function of some of the most critical parameters of rock and of tools. Some empirical formulations have proved to be complex to use or valid for a limited range of applications only.

In this paper, a new empirical formulation is presented in order to estimate the penetration per revolution derived from the TBM behavior monitoring data in alpine tunnels in the North-West of Italy. This formulation is capable of taking into account the most critical parameters only, considering both the contribution of intact rock, and natural discontinuities in the rock mass.

The comparison of results produced by the proposed formulation with those obtained using the well known Barton method, shows an equivalence of values for the penetration per revolution as a function of typical contact forces (F_N=15÷20 $tons_f$), even if the resistance of intact rock appears to have a greater influence in the proposed equation. From the comparison with the Norwegian School method, it was possible to isolate both intact rock and natural discontinuity contributions on the estimate of the penetration per revolution of the TBM.

8. References

Barton, N., Lien, R. and Lunde, J. (1974). Engineering classification of rock masses for the design of tunnel support. Rock Mechanics, 10, 1-54.

Barton, N.R. (2000). TBM Tunnelling in Jointed and Faulted Rock. Taylor & Francis. p. 184. ISBN 978-9058093417.

Bieniawski, Z. T. (1974). Geomechanics classification of rock masses and its application in tunneling. Proc. Third International Congress on Rock Mechanics, ISRM, Denver, 11A, 27-32.

Bieniawski, Z. T. (1976). Rock mass classification in rock engineering. Proc. Symposium on Exploration for Rock Engineering, Johannesburg, 1, 97-106.

Blindheim, O.T. (1979). Boreability predictionsfor tunneling. Dr. ing. Thesis, Department of Geological Engineering. The Norwegian Institute of Technology, Trondheim, (In Norwegian), 406.

Blindheim, O.T. (1979). Failure mechanism under disc cutters. Rock Mechanics Conference, Oslo, (In Norwegian), 12.

Blindheim O. T. and Bruland A. (1998). Boreability testing. In: Norwegian TBM tunneling, Norwegian Tunnelling Soc., Oslo, Norway.

Bruland A. (1998). Prediction model for performance and costs. In: Norwegian TBM tunneling, Norwegian Tunnelling Soc., Oslo, Norway.

Cardu M., Oreste P., Pettinau D., Guidarelli D, 2013. Automatic measurement of drilling parameters to evaluate the mechanical properties of soils. American journal of applied sciences 10(7): 654-663.

Cook N. G. W., Hood M., Tsai F., 1984. Observation of crack growth in hard rock loaded by an indenter. Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 21(2), 97-107.

Hartman, H.L., 1959. Basic studies of percussion drilling. Trans. AIME, 214: 68-75.

Hoek, E., (1994). Strength of rock and rock masses. *ISRM News Journal, 2(2), 4-16.*

Hoek, E., and Brown, E. T. (1997). Pratical Estimates of Rock Mass Strength. Int. J. Rock Mech. Sci. & Geomech. Abstr., 34, No. 8, 1165-1186.

Hoek, E., Marinos, P. and Benissi, M. (1998). Applicability of the geological strength index (GSI) classification for very weak and sheared rock masses. The case of the Athens Schist Formation. Bull. Eng. Geol. Environ., 57, 151-160.

Hoek, E., 2007. Pratical Rock Engineering, http://www.rocscience.com/education/hoeks_corner.

Innaurato N., Oreste P.P., 2001.Theoretical approach for assessment of the mechanics of rock failure in the TBMs tools-rock interaction. In: Proc., AITES – ITA World Tunneling Congress 2001, Progress in Tunneling after 2000, Milan (Italy). Patron, Bologna, 227-236.

Innaurato N., Oggeri C., Oreste P., Vinai R., 2007. Experimental and numerical studies on rock breaking with TBM tools under high stress confinement. Rock Mechanics and Rock Engineering, n.5.

Innaurato N, Oreste P., 2011. Theoretical study on the TBM Tool-Rock interaction. Geotech. Geol Eng 29: 297-305.

Innaurato N., Oreste P., 2011. Deep tunnel excavations using tunnel boring machines. Archives of Mining Sciences 56 (3), pp. 537-549

Lindqvist P. A., Hai-Hui L., 1983. Behaviour of the crushed zone in rock indentation. Rock Mech. Rock Engng. 16, 199-207.

Marinos P. and E. Hoek E., 2000. GSI. A geologically friendly tool for rock mass strength estimation. Proc. International Conference on Geotechnical & Geological Engineering, GeoEng2000, Technomic publ., Melbourne, 1422-1442.

Maurer, W.C. and J.S. Rinchart, 1960. Impact crater formation in rock. J. Applied Phys., 31: 1247.

Nishimatsu, Y., 1972. The mechanics of rock cutting. Int. J. Rock Mec. Mining Sci. Geomechanics Abstract, 9: 261-270. DOI: 10.1016/014

Oggeri C. and Oreste P., 2012. The wear of tunnel boring machine excavation tools in rock. American Journal of Applied Sciences 9 (10), pp. 1606-1617

Figure 1: Cutterhead of a rock TBM (diameter of 3.8 m).

Figure 2: The formation of grooves on the excavation face resulting from disc cutter motion.

Figure 3: Chip formation due to TBM disc motion: scheme of rock destruction mechanism under a disc.

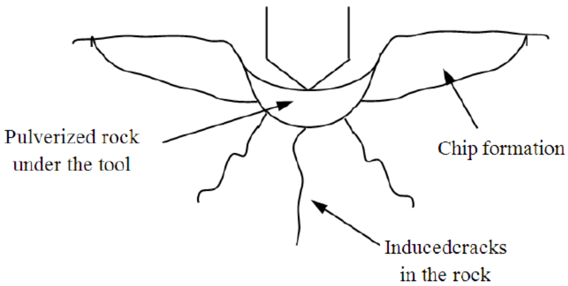


Figure 4: Example of a TBM's principal parameters recorded during the excavation of a tunnel; a): thrust exerted on each disc cutter (tonnf); b): net advancement rate (m/h); c): torque applied to the cutterhead (tonnf x m); d): cutterhead speed of rotation (RPM).

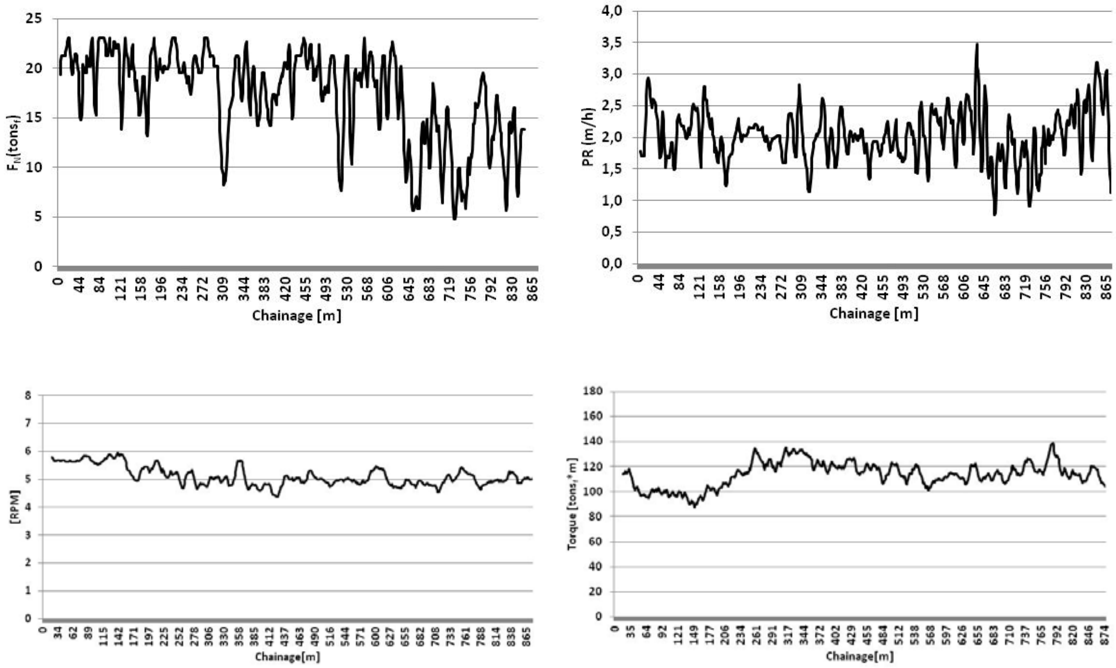
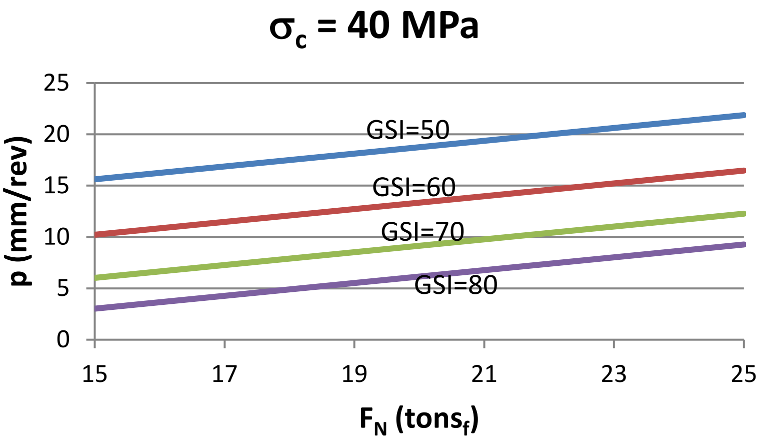
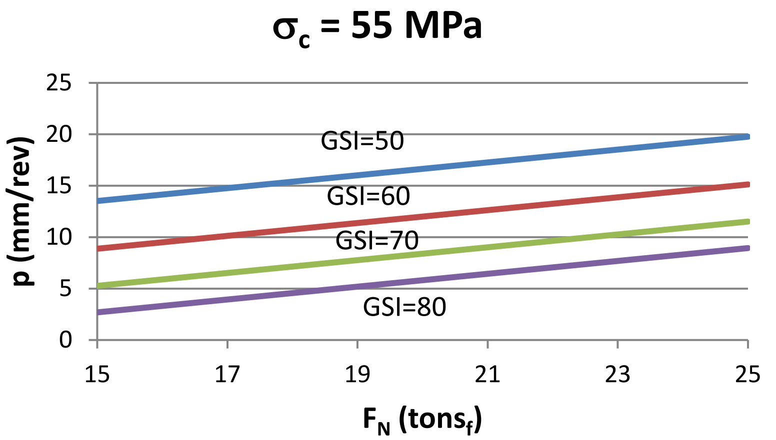
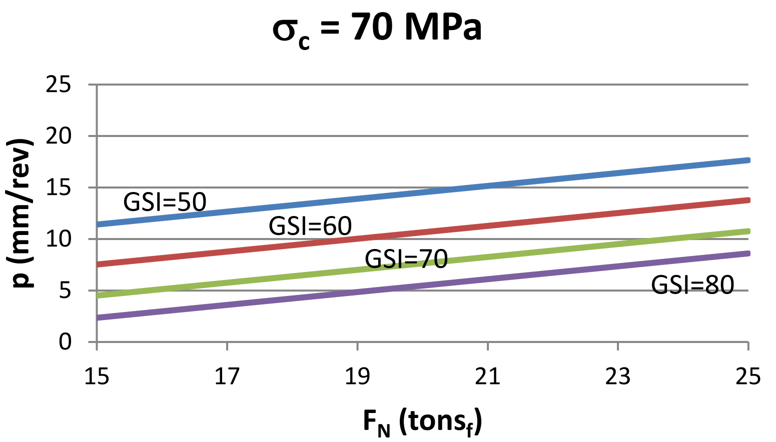
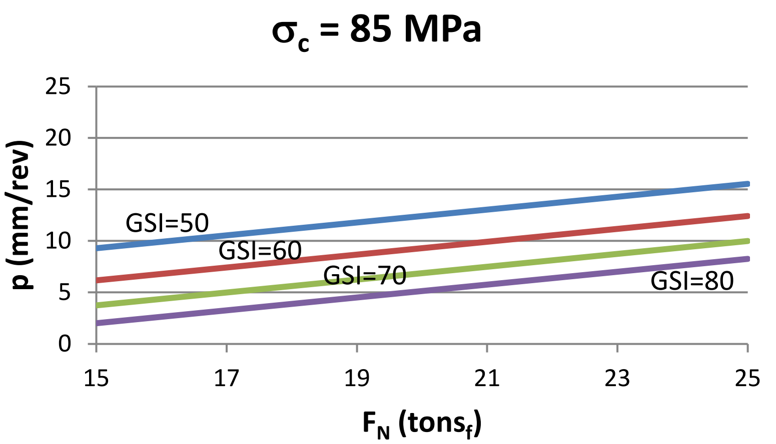


Figure 5: Diagrams of penetration per revolution prediction by application of the new equation: a) σ_c=40MPa; b) σ_c=55MPa; c) σ_c=70MPa; d) σ_c=85MPa; e) σ_c=100MPa.




σc = 55 MPa
25
20
15
10
5
0
p (mm/rev)
GSI=50
GSI=60
GSI=70
GSI=80
15
17
19
21
23
25
FN (tonsf)


σc = 70 MPa
25
20
15
10
5
0
p (mm/rev)
GSI=50
GSI=60
GSI=70
GSI=80
15
17
19
21
23
25
FN (tonsf)


σc = 85 MPa
25
20
15
10
5
0
p (mm/rev)
GSI=50
GSI=60
GSI=70
GSI=80
15
17
19
21
23
25
FN (tonsf)

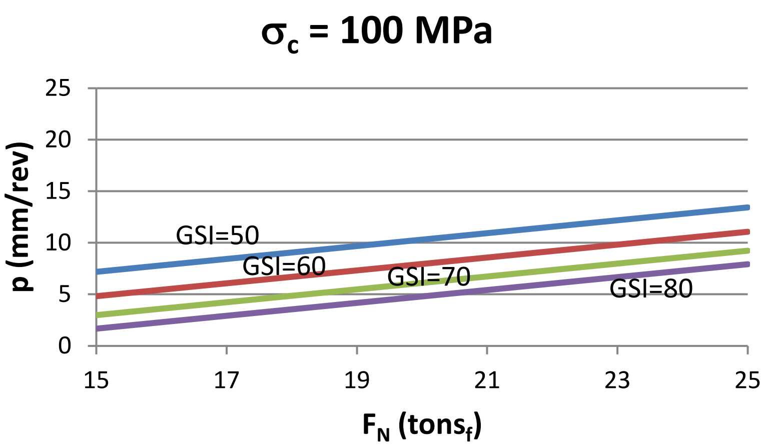

σc = 100 MPa
25
20
15
10
5
0
p (mm/rev)
GSI=50
GSI=60
GSI=70
GSI=80
15
17
19
21
23
25
FN (tonsf)

Figure 6: Comparison between the penetration per revolution determined by Barton's method with the penetration per revolution calculated by eq. 4, using varying Rock Mass Rating (RMR) indexes for three different values of σ_c: a) contact force of 15 tons$_f$; b) contact force of 20 tons$_f$; c) contact force of 25 tons$_f$;

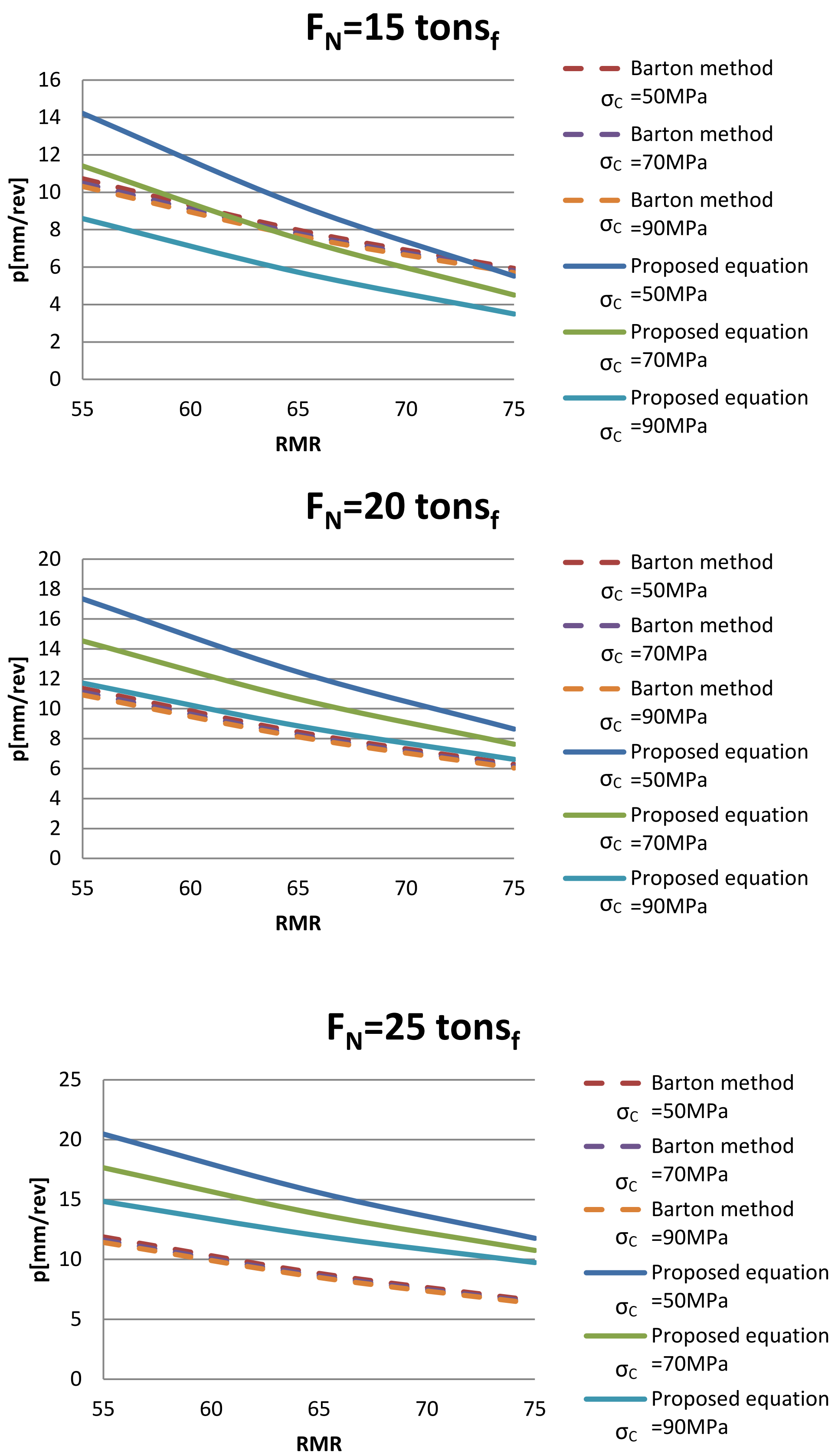


Figure 7: Comparison between the penetration per revolution determined by the Norwegian School Method for intact rock and the penetration per revolution calculated by the eq. 4, using varying uniaxial compressive strength of the intact rock and varying Rock Mass Rating (RMR) indexes: a) contact force of 15 tons$_f$; b) contact force of 20 tons$_f$; c) contact force of 25 tons$_f$;