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

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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.

23 The net advancement rate of a TBM depends on the penetration of its disc tools per revolution of the cutterhead

24 (Oggeri C. and Oreste P., 2012), that is the depth of the part of rock detached from the tunnel face at each revolution

25 of the cutterhead.

26 Several authors have studied the mechanism of destruction of the rock (Innaurato et al., 2007; Cook et al., 1984;

27 Innaurato and Oreste, 2001; Lindqvist and Hai-Hui, 1983; Nishimatsu, 1972; Oreste and Innaurato, 2011, Cardu et al.,

28 2013), but today is not yet possible to have an analytical model capable of assessing with precision the failure

29 conditions of the rock under the application of forces on the TBM disc tools.

30 Through tridimensional numerical modeling it is possible to study, even if with some difficulty, the development of

31 tensions near the single disc. However, the mechanism of breakage of the rock that leads to the formation of chips is

32 not completely understood yet for the following reasons:

33 • evolution of the processes of rupture of the rock at a very small scale, where resistance criteria and rock

34   parameters involved are very different from those that may be used on the laboratory scale;

35 • considerable variation in space of rock characteristics on a small scale;

36 • application of the thrust at the rock over short periods, with dynamic effects that influence the evolution of

37   rupture;

38 • interaction between contiguous grooves produced by the previous passage of the discs;

39 • influence of the stress state at the face of the tunnel and fractures and micro fractures present on the rock

40   during the evolution of the rupture.

41 As often happens when physical mechanisms are complex and not completely known, empirical formulations were

42 developed over time on the basis of experience, capable of estimating the penetration per revolution as a function

43 of the most critical parameters, including: contact force applied to each disc, disc size, spacing between grooves

44 produced on the tunnel face from the passage of discs, parameters of rock strength evaluated on the lab tests scale,

45 and fracturing degree of the rock mass.

46 Some empirical formulations which consider all the parameters controlling the penetration per revolution – some

47 even requiring the execution of special tests which are not always easy to execute - are complex to use. Others are

48 easier, but can be used in a limited range of applications. In general, some of them put more emphasis on the

49 characteristics of the intact rock (for example Rostami, 2008), other on the characteristics of the natural fractures of

50 the rock mass (for example Blindheim, 1998). Often the results obtained by applying various formulations are very

51 different from each other.

52 For this reason, a new empirical formulation is presented in this paper to estimate the penetration per revolution.

53 This formulation has been obtained from data from the excavation of a tunnel (alpine tunnel in the North-West of

54 Italy). The proposed formulation has the advantage of being very simple to use because it requires a small number of

55 parameters (only the most influential ones) which are always known during the design phase of a tunnel; at the

56 same time it is efficient, while taking into account both the characteristics of intact rock, and the natural fracturing

57 degree of the rock mass.

58 First we briefly introduce the characterictics of the TBM and of the mechanism of action of the discs on the

59 cutterhead and we illustrate the parameters - generally measured during the construction of tunnels - which

60 represent the database from which the empirical formulations are obtained to estimate the penetration per

61 revolution. We then present today's most commonly used empirical formulations when estimating the penetration

62 per revolution (Norwegian School and Barton methods) and the one proposed here. Finally, the results obtained

63 with the existing empirical formulations and with the one proposed will be analyzed for comparison.

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

65 The excavation of tunnels with full section machines (TBM) has experienced a large development in the last years.

66 Nowadays, the safety of this kind of machine is comparable to traditional methods of excavation, and productivities

67 are generally higher. Still, knowing the geological conditions at any stage in tunnel development is critical in order to

68 predict the performances of the Tunnel Boring Machines.

69 The rock TBMs may have different configurations: open, shield or double shield. The main difference is in the

70 modality of the thrust with which they can advance in the tunnel excavation. The choice of machine is generally

71 influenced by the degree of fracturing of the rock mass and by the mechanical strength of the intact rock. Open

72 TBMs are used on less fractured rock masses characterized by a high resistance of the intact rock; these machines

73 are able to exert high thrust values on the tunnel face thanks to the lateral contrast forces on the tunnel's walls.

74 Shield machines are generally used for highly fractured rocks as they are able to guarantee the stability of the tunnel

75 by means of a metallic shield placed behind the head of the TBM. With this configuration the precast lining concrete

76 segments are assembled inside the shield itself, and the thrust needed to advance with the excavation is applied on

77 the last ring of segments through hydraulic jacks. Double shield TBMs are characterized by a high versatility and they

78 can be used in mixed conditions, operating either as open TBMs (with similar productivities), either as shield TBMs.

79 Depending on the excavating configuration chosen, the thrust can be exerted by applying contrast forces on the

80 tunnel's walls or on the last ring of segments through hydraulic jacks.

81 TBMs operate through the application of a thrust on the cutter head which allows its disc tools to penetrate the

82 rock. Disc tools can have different diameters (generally 15", 17" or 19"): the greater the diameter, the larger the

83 maximum usable thrust, up to maximum values higher than 250 kN per cutter.

84 The contact force together with the rotational motion of the cutterhead, allow the penetration of discs in the rock,

85 and consequently the detachment of rock chips. The movement of disc cutters causes the formation of grooves on

86 the excavation face (fig. 2).

87 According to a hypothesis by Hartman (1959) and Maurer (1960), and later summarized by other authors (i.e.

88 Nishimatsu, 1972), which still applies to such complex phenomena, rock breaking from using a tool includes phases

89 such as: rock deformation, surface crushing, formation of a destruction nucleus, squashing and spalling of the rock

90 bordered by the destruction nucleus and the free crack surface towards a free surface. In other words, the nucleus

91 (which may be cylindrical or spherical, fig. 3) acts like a fluid that is subjected to hydrostatic pressure which pushes in

92 every direction. If a free surface is sufficiently close to the tool, the formation of chips takes place under a

93 determined load (interactive tool). At small spacing/penetration (s/p) ratios, cracks propagating from one groove

94 interact with cracks produced by indentation of the cutter situated in the neighboring groove and chip formation

95 occurs at lower forces than would be required for chip release from grooves spread further apart. At s/p ratios that

96 are larger than the critical value $(s/p)_{crit}$, grooves are too far apart for the interaction to occur, and chips form at

97 applied force levels which are independent of any further increase in the groove spacing.

98 During the excavation of a tunnel with a TBM, it is of great importance to control the operating parameters of the

99 machine, generally performed by an automatic system of data acquisition and recording. The monitoring is carried

100 out continuously throughout the excavation so that it is linkable to the chainage of the tunnel. The most important

101 parameters are: the thrust applied on each disc cutter, the net advancement rate, the torque, and the speed of

102 rotation applied to the cutterhead (fig.4). Through analysis of these parameters it is possible to assess the specific

103 energy of excavation used to break down the rock, generally expressed in kWh/m³ (Cardu et al., 2013). The specific

104 energy can be linked to the geomechanical quality of the rock mass along the tunnel's layout.

105 The TBM's excavation parameters can be used to verify the rock mass conditions throughout the tunnel and can be

106 compared with the original project, in order to modify the geomechanical model of the tunnel if needed.

107 **4. Prediction methods to estimate the net advancement rate (Barton method and Norwegian**

108 **School)**

109 Estimating the TBM's performance is a crucial phase in tunnel design and for the selection of the appropriate

110 excavation machine. To this purpose, forecasting methods of the net advancement rate based on the analysis of rock

111 mass characteristics along the tunnel, geometrical characteristics of disc cutters, and the characteristics of the

112 cutterhead, are generally employed.

113 The most interesting analysis techniques - Norwegian School (NTH/NTNU) (Bruland, 1998; Blindheim and Bruland,

114 1998) and Barton (2000) - allow for disc penetration per revolution to be predicted, while taking into account the

115 presence of natural discontinuities in the rock mass.

116 **The Norwegian School Method** allows for a DRI (Drilling Rate Index) estimate as a function of the S_{20} and SJ indices

117 (Bruland, 1998). S_{20} is an index of fragility and it is based on impact strength tests which involve dropping a weight of

118 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

119 mini drill bit to perforate a rock sample (surface hardness). The Siever J-value (SJ) is defined as the mean value of the

120 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.

121 According to Bruland (1998), the penetration per revolution p (mm/rev) should be estimated considering the

122 equivalent fracturing factor (k_{ekv}) of the rock mass for different values of the equivalent thrust parameter (M_{ekv}).

123 The first parameter (k_{ekv}) depends on the fracture density of the rock mass and on the discontinuity orientation with

124 respect to the tunnel axis. This parameter is subsequently modified as a function of the DRI index estimated for the

125 intact rock.

126 The second parameter (M_{ekv}) depends on the contact force applied to each disc (F_N), modified by the geometrical

127 characteristics of disc cutters (diameter, distance between grooves produced by their use on the excavation face).

128 The penetration per revolution p (mm/rev) allows one to obtain an estimate of the net advancement velocity PR of

129 the excavation machine (m/hr), if the rotational speed of the cutterhead in RPM (rounds per minute) is known:

130 $$PR = p \cdot \frac{60 \cdot RPM}{1000}$$ (eq. 1)

5

131 The limit of the forecasting method developed by the Norwegian School is its own complexity. In fact, for the

132 determination of the net advancement rate, the elaboration of several, often unavailable parameters is needed.

133 **According to the Barton method (Barton, 2000)**, it is possible to define an index, Q_{TBM}, on the basis of the

134 geomechanical quality index of the rock mass Q (Barton, 1974) (with the RQD parameter estimated in the direction

135 of the tunnel axis):

136
$$Q_{TBM} = Q \cdot \frac{5 \cdot \gamma \cdot \sqrt[3]{Q \cdot \frac{\sigma_C}{100}}}{F_N}$$
(eq. 2)

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

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

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

140 Once the value of Q_{TBM} is known, it is possible to directly estimate the net advancement velocity of the TBM PR

141 (m/hr), on the basis of the following equation:

142
$$PR \cong \frac{5}{\sqrt[5]{Q_{TBM}}}$$
(eq. 3)

143 The forecasting method developed by Barton allows to obtain an evaluation of the net advancement rate in a non-

144 complex way, considering each of the most influential parameters. Furthermore, this method gives greater

145 importance to the discontinuities in the rock mass rather than to the characteristics of the intact rock.

146 **5. Experiences in mechanized tunneling in the Western Alps.**

147 From the analysis of several TBM operating parameters used for the excavation of tunnels of various sizes in

148 metamorphic rocks in the Western Alps, it has been possible to divide the penetration per revolution p into classes,

149 depending on the intact rock strength values σ_c and on the GSI index (Hoek, 2007). For each class, it has been

150 possible to determine a relationship between the penetration per revolution and the contact force F_N. These

151 relations have later been extended to consider the effect of the σ_c and the GSI. The result of the analysis has allowed

152 to derive an equation yielding the estimate of a TBM's penetration per revolution as a function of: contact force,

153 strength of intact rock, and GSI:

154 $$p \cong \frac{5}{8} \cdot [(F_N - 14) + (0,0132 - 0,00009 \cdot \sigma_c) \cdot (100 - GSI)^2] \qquad \text{(eq. 4)}$$

155 where:

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

157 F_N is the contact force on the disc (in tons$_f$);

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

159 GSI is the Geological Strength Index.

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

161 parameter ranges:

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

163 Figure 5 shows five diagrams for predicting the penetration per revolution, each referring to a different σ_c (40-100

164 MPa range) as a function of GSI and contact force F_N. These graphics allow a quick evaluation of p. For intermediate

165 values of the σ_c and the GSI it is possible to proceed with a linear interpolation between the values obtained from

166 the diagrams.

167 From the diagrams below, it is possible to observe that for high GSI values, the intact rock strength has little

168 influence on penetration per revolution prediction; on the other hand, with high intact rock strength values, the GSI

169 also appears to have a reduced influence on the penetration per revolution. At the same time, the opposite is also

170 true: with low intact rock strength values, the GSI plays an important role and with low GSI values, the penetration

171 per revolution varies considerably depending on the intact rock strength.

172 **6. Comparison between new and existing prediction methods**

173 Using the existing correlation between the index of geomechanical qualities RMR and Q (Bieniawski, 1976; Barton,

174 1974; Bieniawski, 1974), and considering GSI=RMR–5 and a unit weight of the rock equal to 27 kN/m³, it has been

175 possible to compare the evaluation of the penetration per revolution determined with Barton's method (Barton,

176 2000) with the evaluation of the penetration per revolution determined by the equation proposed in paragraph 4.

177 The penetrations per revolution have been evaluated based on varying RMR indexes using three values of the

178   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

179   intact rock (σ_c=50 MPa; σ_c=70 MPa; σ_c=90 MPa). The comparison, shown in figure 6, illustrates that Barton's

180   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

181   determined by Barton's method is in between the values estimated by eq. 4 in the variability interval considered for

182   σ_c and RMR. With increasing contact force (F_N=20 tons$_f$; F_N=25 tons$_f$), Barton's method provides penetration per

183   revolution estimates which are lower than those from eq. 4; nevertheless, the trend of p as a function of the RMR

184   quality index is similar.

185   The evaluation of the penetration per revolution with the Norwegian School Method appears to be quite complex,

186   especially concerning the definition of the influence of natural discontinuities in the rock mass: both the orientation

187   of each set of discontinuities with respect to the tunnel axis, and the average spacing between discontinuities for

188   each set, are needed. On the contrary, the penetration per revolution in intact rock estimated through the DRI

189   (Drilling Rate Index) parameter (Blindheim, 1979), which quantifies how easily the rock is excavated with cutting

190   tools, can be obtained quickly. This index ranges from 20 to 80: the higher its value, the easier the excavation of the

191   rock. Figure 7 shows the comparison between the penetration per revolution values determined by the Norwegian

192   School Method for intact rock, and by eq. 4 for rock mass. The first case refers to three different DRI values (40, 55,

193   70), representing three different categories of rock to be excavated, respectively: hard, intermediate, and easy. In

194   the first case the values of the penetration per revolution do not change as a function of the RMR index. In the

195   second case, the usual three values of the uniaxial compressive strength of intact rock σ_c (50 MPa, 70 MPa, 90 MPa)

196   are considered, representing three categories of resistance, respectively: not very resistant rock, rock with average

197   resistance, very resistant rock. A comparison between easily excavated and low uniaxial compressive strength rock,

198   as well as between hardly excavated and high uniaxial compressive strength rock, is considered.

199   The difference between the values of the penetration per revolution determined using both methods is then related

200   to the influence of natural discontinuities in the rock mass.

201   It is possible to use the Norwegian School Method for an initial estimate of the intact rock contribution.

202   Subsequently, the effect of natural discontinuities can be determined by eq. 5. The latter is derived from the

203   functional analysis of the differences between the penetration per revolution from both methods, considering the

204   effect of the geomechanical quality of the rock mass, the contact force F_N and the uniaxial compressive strength of

205   intact rock:

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

207    $(0,2852 \cdot F_N + 84,765)$

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

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

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

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

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

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

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

215   Adding up the two contributions illustrated above (intact rock and natural discontinuities) it is possible to obtain an

216   evaluation of the effective penetration per revolution for the considered rock mass.

217   As an example, in a tunnel excavated with a TBM in a rock mass which presents an RMR index value equal to 65, and

218   a uniaxial compressive strength of the intact rock of 70 MPa (moderate rock from a geomechnical point of view), the

219   estimated penetration per revolution, corresponding to a contact force F_N of 20 tons$_f$, is approximately equal to:

220   1.7 mm/rev (rate of the intact rock) +

221   7.5 mm/rev (natural discontinuity contribution calculated by eq.5) = 9.2 mm/rev

222   **7. Conclusions**

223   One of the most important elements in the design of a tunnel excavated with TBM is the evaluation of its speed of

224   advancement and, therefore, the estimation of the penetration per revolution of the cutterhead. Given the

225   complexity of the process of chip formation under the disc tools of the cutterhead, empirical formulations have been

226   developed over time in order to estimate the penetration per revolution as a function of some of the most critical

227   parameters of rock and of tools. Some empirical formulations have proved to be complex to use or valid for a limited

228   range of applications only.

229   In this paper, a new empirical formulation is presented in order to estimate the penetration per revolution derived

230   from the TBM behavior monitoring data in alpine tunnels in the North-West of Italy. This formulation is capable of

231   taking into account the most critical parameters only, considering both the contribution of intact rock, and natural

232   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 ($F_N=15\div20$ 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.

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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.
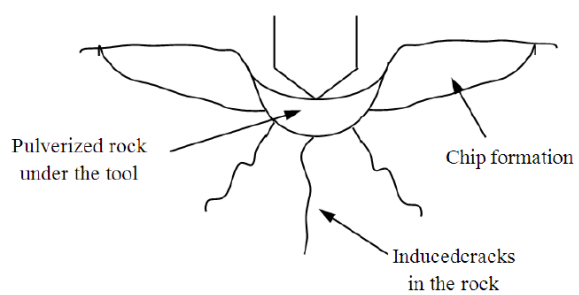
Figure 4: Example of a TBM's principal parameters recorded during the excavation of a tunnel; a): thrust exerted on each disc cutter (tonnf); b): net advancement rate (m/h); c): torque applied to the cutterhead (tonnf x m); d): cutterhead speed of rotation (RPM).
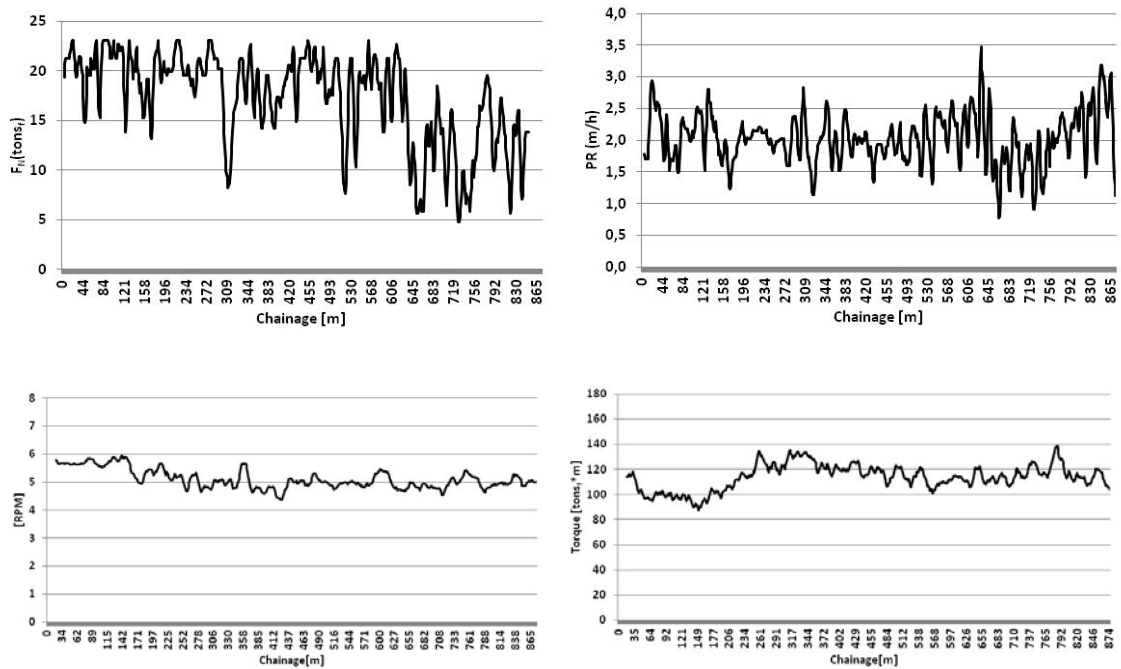
Figure 5: Diagrams of penetration per revolution prediction by application of the new equation: a) σ_c=40MPa; b) σ_c=55MPa; c) σ_c=70MPa; d) σ_c=85MPa; e) σ_c=100MPa.
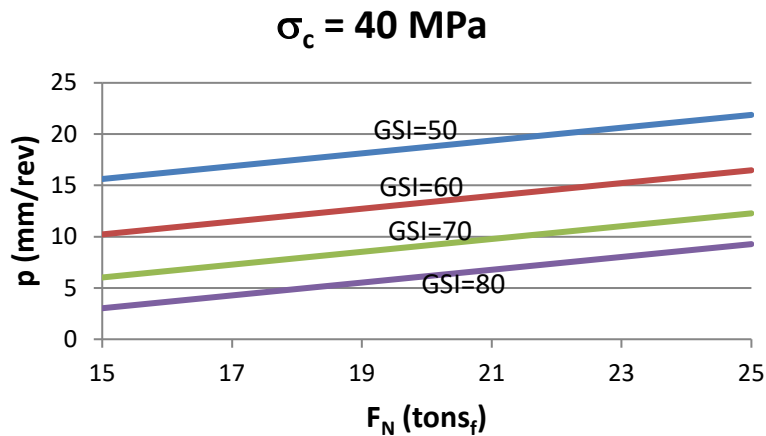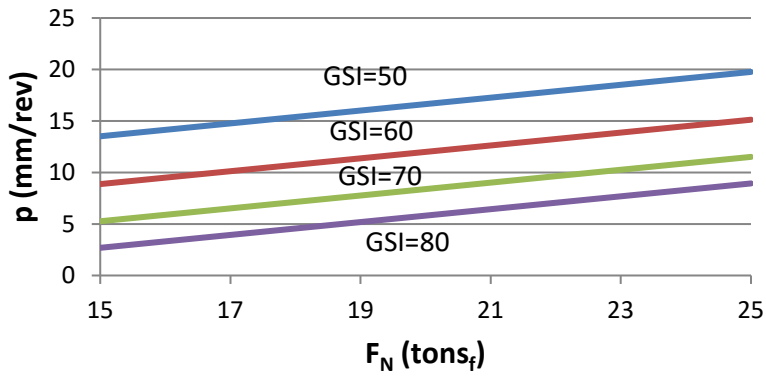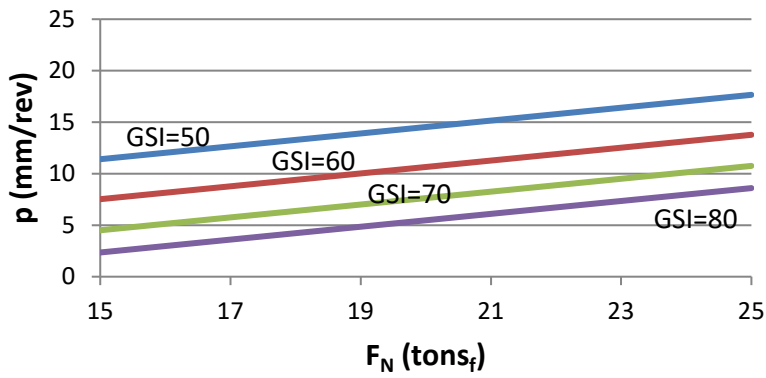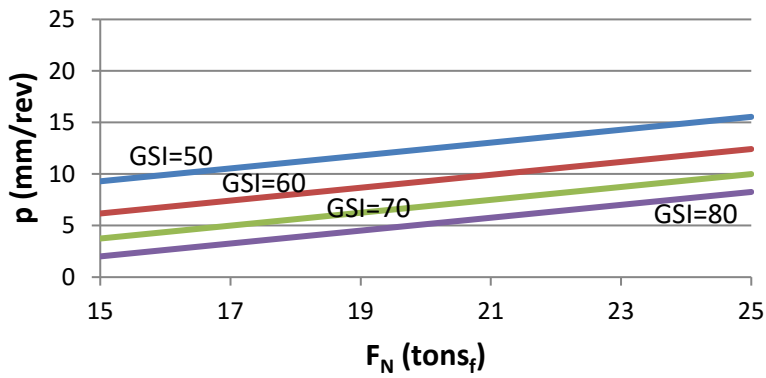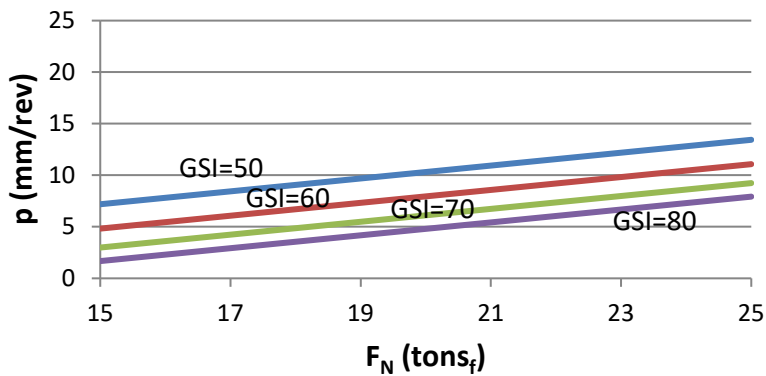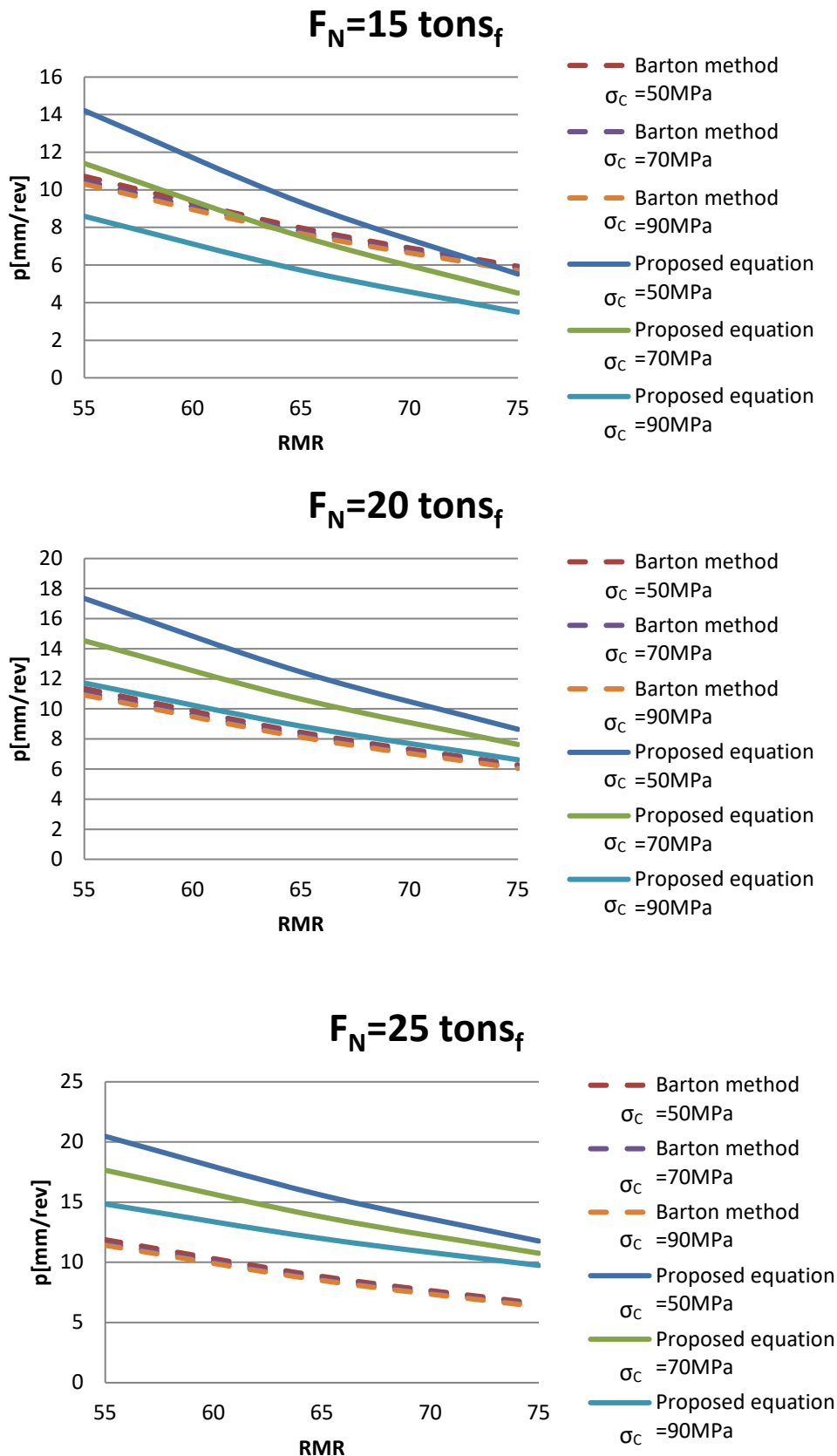
Figure 7: Comparison between the penetration per revolution determined by the Norwegian School Method for intact rock and the penetration per revolution calculated by the eq. 4, using varying uniaxial compressive strength of the intact rock and varying Rock Mass Rating (RMR) indexes: a) contact force of 15 tons_f; b) contact force of 20 tons_f; c) contact force of 25 tons_f;