From Palmström A.: RMi – a rock mass characterization system for rock engineering purposes.
PhD thesis, Oslo University, Norway, 1995, 400 p.

Chapter 7

RMi PARAMETERS APPLIED IN PREDICTION OF TUNNEL BORING PENETRATION

> *"Nothing has been more difficult than evaluating the rock mass characteristics and applying the evaluation to a formula predicting penetration rate."*
> Richard Robbins (1980)

The first tunnel boring machine (TBM) was probably made in Italy in 1846. It used percussive drilling for drilling slots in hard rock (Rostami, 1992). In 1851 Charles Wilson invented a boring machine with disc type cutters. Another machine was built for boring the English channel tunnel between England and France in 1865.

Hard rock tunnel boring came into use after the World War II when in 1947 Jim Robbins redesigned one of the coal borers when he was working as a consultant to a coal company. The disc cutters were first introduced into boring in 1957 on a Robbins TBM. This has allowed the excavation of harder materials, resulting in a wider use of TBM in underground construction.
The new design high performance (HP) TBMs have provided additional improvements in tunnel boring technology in geologies consisting of alternating very hard and relatively soft rocks. In this connection it can be mentioned that from a cutter-ring load of 40 - 50 kN in the beginning of the 70s, the strongest hard rock (HP) machines of today have a maximum load of 320 kN. In the same period the weekly tunnelling advance has increased from a few tens of metres to several hundred metres.

Today, tunnel boring is successfully carried out in rocks with uniaxial compressive strengths exceeding 300 MPa, and with tunnel diameters of 10 m and larger. Technically, TBMs can now be said to have reached a stage of development where a tunnel can practically be bored in any rock and ground (Nilsen and Ozdemir, 1993). Still, however, performance prediction is an important part of any TBM project. This is due to the general need for cost- and schedule-evaluations at the various planning stages of a tunnel project, as well as to develop the information necessary for a reliable comparison between alternative tunnel construction methods (TBM versus drill and blast).

As effective TBM boring is achieved with working thrusts above the critical thrust for the rock mass being bored, the strength of the rock mass will have a marked influence on the boring performance. The RMi - being a relative indicator of the compressive strength of the rock mass - should therefore be suitable in assessment of the tunnel boring penetration in hard and moderately hard rock masses.

7.1 Factors influencing the TBM performance

Some of the main factors influencing on the TBM performance are listed in Table 7-1.

TABLE 7-1 HARD ROCK MASS AND MACHINE FACTORS INFLUENCING TBM PERFORMANCE (from Lislerud, 1988)

Rock mass factors	**Machine factors**
- Rock mass jointing (k_s) ° type and continuity ° frequency ° orientation - Rock porosity - Rock drillability (DRI) - Rock hardness/abrasiveness - Stress in rock	- Thrust per cutter (M) - Cutter edge bluntness (b_r) - Cutter spacing (A) - Cutter diameter (d) - Torque capacity and RPM - The machine's capacity for handling large chips or blocks - General solidity against blows and vibrations - Cutterhead curvature and diameter (D) - Backup equipment

In this work only the effect of the rock mass factors has been analyzed. These can be divided into:

- Intact rock properties, which for excavation with TBM can be characterized in different ways. Chen and Vogler (1992) mention the following methods which are mainly used today:
  - Strength properties, such as uniaxial compressive strength, tensile strength, point load strength index.
  - Hardness, such as Schmidt hardness, total hardness, Mohr hardness, Shore scleroscope, NBC cone indenter.
  - Energy properties, such as fracture toughness, toughness index, critical energy release rate, and acoustic emission properties.
  - Rock internal texture, such as grain size, grain shape, porosity, cementation and orientation of grains.
  - Empirical parameters, such as drillability index, Goodrich drillability, Morris' drillability, specific energy test by instrumented cutting, NTH drillability test, direct cutting testing, etc.
- Jointing properties, which includes the quantity of joints and the joint characteristics. It has long been known that the frequency and orientation of joints in a rock mass is an important factor in TBM tunnelling (Graham, 1976). Rostami (1992) mentions, however, that due to the complexity of jointing, little success in applying this parameter has been achieved to date.

7.2 Prediction models

In general, methods for TBM performance prediction are based on one or more of the following main principles:

1. Field mapping and/or -testing
2. Small scale laboratory testing ("index testing")
3. Large scale laboratory testing
4. Empirical methods
5. Theoretical models

Many researchers have independently worked on their own indices and tests to be able to predict the performance and economic factors associated with boring rock tunnels. Therefore, a wide variety of performance prediction methods and principles are used in different countries and by the various research institutes and TBM manufacturers. Some of the methods are based mainly on one or two rock parameters (for instance uniaxial compressive strength and a rock abrasion value), while others are based on a combination of comprehensive laboratory, field- and machine-data.

The effect on the boring rate from jointing is a factor, which has been pursued for many years. It has always been recognized that the presence of joints improves the boring rate. However, *"in the interest of conservatism in most analyses, the improvement in boring rate due to jointing has been neglected by testing unfractured specimens of solid rock and basing predictions on the strength characteristics of intact rock"* (Robbins, 1980). This has probably caused some of the problems in comparing the various models, which have been mentioned in published papers.

Of the many models presented, the NTH model (Norwegian Institute of Technology, 1994) is considered to be the closest relation to the RMi system and its parameters. The NTH performance prediction model is a combination of the main principles nos. 1, 2, and 4 shown above. A short description of this method is given in the following.

7.2.1 The NTH prognosis model

The main advantages of the NTH model for TBM performance prediction are the generally very comprehensive empirical data-base, where the important influence of rock jointing can be easily taken into account (Nilsen and Ozdemir, 1993).

The model is based primarily on empirical correlations between geological/rock mechanical parameters and actual tunnelling performance. Time and cost curves for the various tunnelling operations have been established by collecting and analysing a large amount of data on tunnelling performance and rock mass properties from tunnelling in Europe. The model has been continuously revised and improved as new tunnelling data and TBM modifications become available. Today's model, version no. 5, is based on data from about 230 km of bored tunnels.

Geological field mapping, rock sampling and rock testing form the basis for the performance prediction. It does not deal directly with cutting force requirements; but rather uses data on rock and machine specifications to provide an estimate of machine performance. The model uses the following information as input:

a. Rock parameters, including jointing, drillability index, and abrasiveness. (Abrasiveness is used in the bit wear evaluation.)
b. Machine parameters, consisting of cutter shape and size, cutterhead RPM, cutterhead curvature, number of discs on the cutterhead, and the applied thrust and power on the machine.

The following tests are carried out to find the so-called 'drilling rate index ' (DRI) (refer to Movinkel (1986) and Lislerud (1988)):

- Brittleness test - a rock aggregate impact test.
- Siever's J-value test, a miniature drill test expressing the hardness of the rock surface.

With these input parameters and a parameter for the jointing, the model then produces an estimate of machine advance using empirically developed relationships.

7.3 The use of RMi parameters to characterize rock masses for TBM

According to the NTH model the penetration rate can be estimated by combining the rock material's drilling properties with the jointing of the rock mass and the representative machine factors. The system for applying the RMi to evaluate the TBM boring capacity is shown in Fig. 7-1. Separate parameters have been chosen for:

- The rock material, represented by its compressive strength, σ_c.
- The jointing, represented by the jointing parameter (JP)
- The tunnel /shaft boring machine properties (K), represented by the utilized thrust per disc cutter, and the size of the cutters.

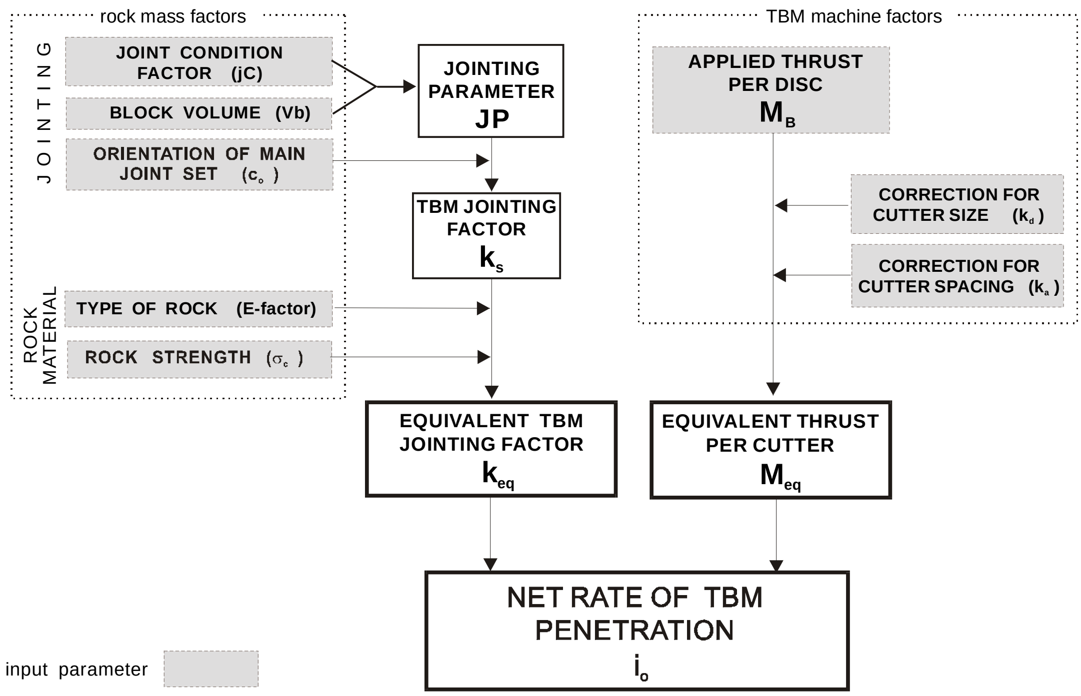


Fig. 7-1 Layout of a method to predict TBM penetration using RMi parameters based on the NTH model.

7.3.1 The rock material properties

As effective TBM boring is achieved with working thrusts above the critical thrust for the rock being bored, the strength of the intact rock is considered as a main parameter influencing the boring performance. The uniaxial compressive strength test is, therefore, the most widely used (and perhaps misused) rock property to determine the drillability of a rock masses. Fig. 7- 2 shows the effect of σ_c in some of the published models.

For rocks with uniaxial compressive strength between 140 MPa and 200 MPa Graham (1976) found that the rate of penetration can be roughly estimated as:

$$p = 3.94\ T/\sigma_c \qquad \text{eq. (7-1)}$$

where p is penetration per revolution (mm)
T is thrust per cutter (kN)
σ_c is compressive strength of intact rock (MPa)

This relationship is approximate for a standard disc cutterhead and will vary with the design and type of cutterhead to be used.

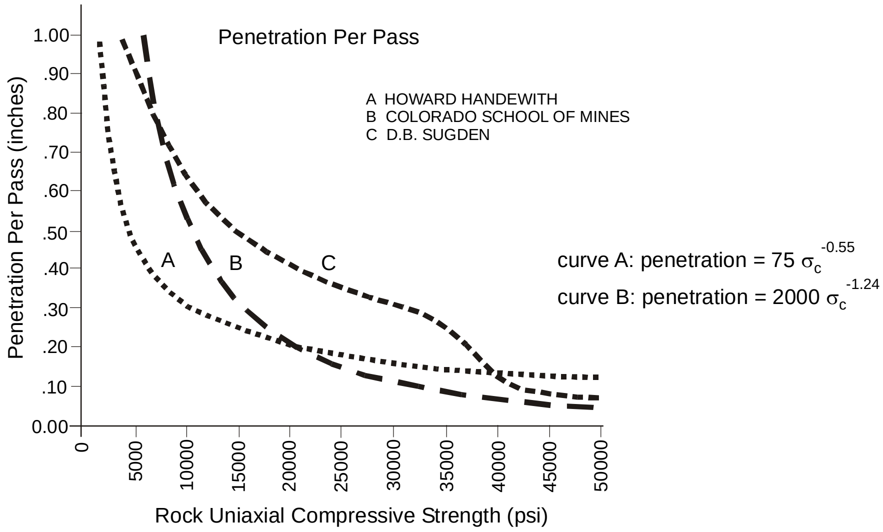


Fig. 7-2 The penetration per pass of a TBM equipped with 15½" disc cutters and 164 kN thrust/cutter, found in some prediction models (from Robbins, 1980).

The compressive strength, together with other physical properties of the rock are used by the Robbins Company (now a subsidiary of Atlas Copco) for estimating the penetration rates of tunnel and raise boring machines built by the Robbins Company. This is done using computer models of performance developed within the Robbins Company. The models are theoretically derived and have been extensively checked against data from both laboratory disc cutting tests and field performance measurements.

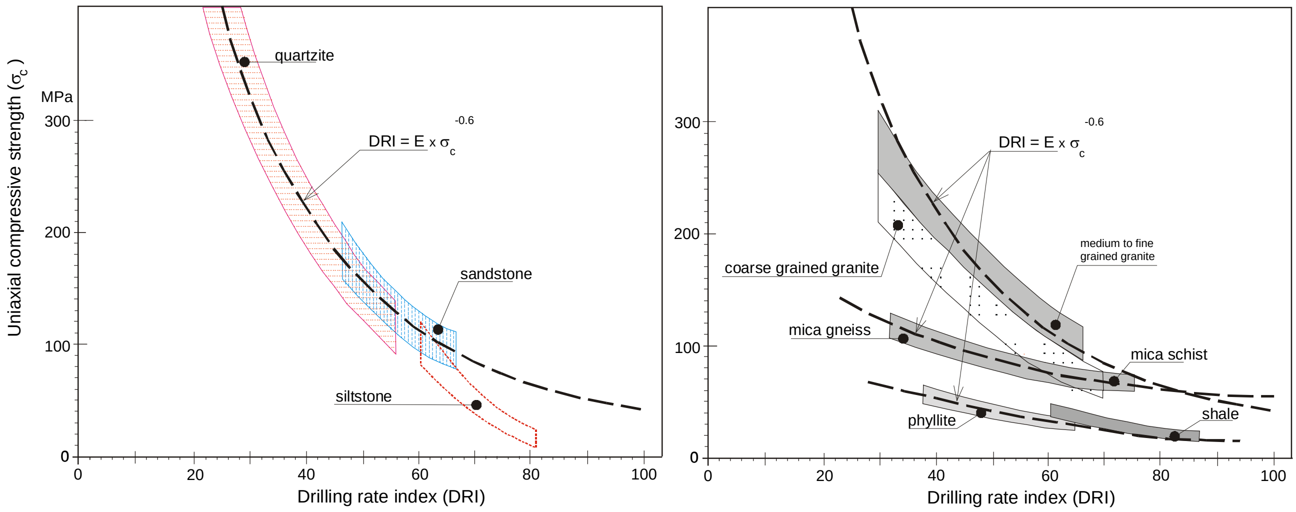


Fig. 7-3 Correlation between drilling rate index DRI and the compressive strength of the rock (from Movinkel and Johannessen, 1986).

Though Hustrulid (1971), Graham (1976), and other authors have found some correlation between the rock compressive strength and the cutting performance, Rostami (1992) is of the opinion that, in general, the compressive strength is not a good indicator of boreability. This might be due to the fact mentioned earlier that many of the prediction models do not include the effect of jointing in their models.

As mentioned earlier, the NTH model uses the drilling rate index (DRI) to represent the properties of intact rock. The correlation between the DRI and the compressive strength of the rock material is shown in Fig. 7-3. The three dotted curves here can be expressed as

$$DRI = E \times \sigma_c^{-0.6} \qquad \text{eq. (7-2)}$$

where E is a factor representing various groups of rocks. It has the following values:

E = 1000 for most non-schistose, hard rocks (compressive strength $\sigma_c > 40$ MPa)
E = 750 for metamorphic schists ($\sigma_c = 30 - 150$ MPa)
E = 500 for argillaceous rocks ($\sigma_c = 10 - 100$ MPa)

7.3.2 The jointing features

Jointing is often the most important parameter regarding the drillability and hence on the advance of tunnel boring (Norwegian Institute of Technology, 1994). In the NTH model great emphasis is placed on joint mapping during field investigations. The model applies the following types of jointing:

- Systematically jointed rock masses:
  - parallel-oriented joints [1] (one set),
  - parallel-oriented fissures [1] and foliation planes or bedding planes (one set).
  - two or more joint sets and/or fissure sets
- Massive rock masses. [1]

Thus, by this division some kind of joint openness, roughness and continuity has been included. The jointing factor (k_s) for joints and fissures is shown in Fig. 7-4. Penetration rates are more or less proportional to the factor (k_s), which is adjusted for other values of DRI than 49 as shown in the upper diagram in Fig. 7- 4 by curve 1 and 2.

As for other types of rock engineering, a well defined description of jointing is important as its influence is the dominating rock mass property. In the revised model of NTH (Norwegian Institute of Technology, 1994), the three-dimensional occurrence of jointing is partly included as the value of (k_s) is found from

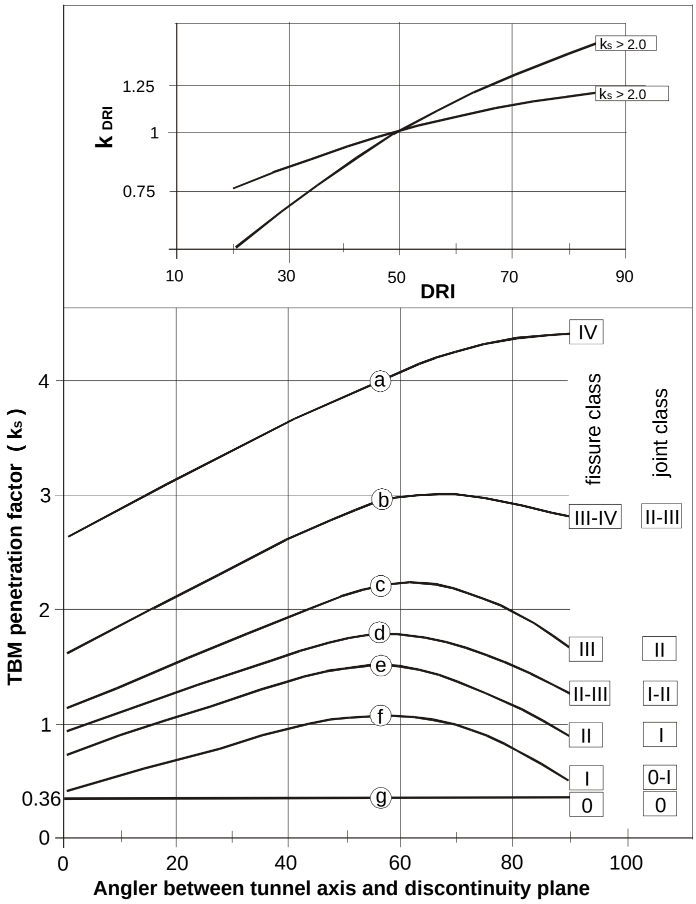
$$k_{s\text{-}tot} = \Sigma\, k_{si} - (n - 1)\, 0.36 \qquad \text{eq. (7-3)}$$

where k_{si} is the value of k_s for each joint set given in Fig. 7-4.

Although this is a significant improvement from the earlier NTH prognosis models, where only the spacing of one joint set was included, it seems that this revision does not yet fully include the effect of the three-dimensional occurrence of joints. As the degree of jointing and the jointing characteristics are not clearly defined by SINTEF, it is hardly possible to correctly convert the NTH characterization of jointing to three-dimensional block volume measurements.

---

[1] The following definitions are applied in the NTH model:
Joints are defined as pervasive joints, which can be traced around the whole tunnel profile. They can be open (as in stress relief joints) or clay-coated with weak/smooth minerals (as calcite, chlorite).
Fissures include discontinuous joints which only partly can be observed around the tunnel profile, in addition healed joints with low shear strength and foliation or bedding partings (as in mica schist and mica gneiss)
Massive rock includes rock masses without joints or fissures, or with healed joints with filling of high shear strength (for example joints filled with hydrothermal minerals as quartz, epidote, etc.)



NTH class	Joint/fissure spacings
0	-
0-I	1.6 m
I-	0.8 m
I	0.4 m
I-II	0.3 m
II	0.2 m
II-III	0.15 m
III	0.1 m
IV	0.05 m

Fig. 7-4 The rating of the jointing factor k_s as a function of the spacing of joints and fissures. In the upper figure is shown the adjustment of k_s for other DRI values than 49. (from Norwegian Institute of Technology, 1994)

Eq. (A3-27) [$Vb = \beta \times Jv^{-3}$] has been applied in the transitions made from the NTH fissure and joint classes in Fig. 7-4. As the classes here consist of spacings related to one joint set eq. (A3-27) can be written

$$Vb = \beta(1/S)^{-3} = \beta \times S^3 \qquad \text{eq. (7-4)}$$

where S is the spacing of the joints or fissures in the set.

Many of the tunnels used in the development of the NTH model have mostly one joint set. In such cases the blocks have flat (tabular) shape; this is especially the case for small joint spacings where β = 150 - 200 have been used. For large spacings where possibly other joint sets may occur, β = 50 has been applied. This is shown in Table 7-2.

TABLE 7-2. THE BLOCK SHAPE FACTOR USED TO FIND BLOCK VOLUME FROM THE SPACING GIVEN IN THE NTH DISCONTINUITY CLASS

NTH discontinuity class	**0-I**	**I**	**I-II**	**II**	**II-III**	**III**	**III-IV**	**IV**
Spacing (S) of discontinuities (m)	1.6	0.4	0.3	0.2	0.15	0.1	0.075	0.05
Equivalent block volume (m^3)	200	10	4	1.5	0.6	0.2		
Applied block shape factor β	50	150	150	175	175	175	200	200

By applying the ratings for (k_s) for the least favourable angle (i.e. $\alpha = 0^o$ in Fig. 7-4) in Fig. 7-5 the following correlation has been found for common characteristics of *joints*

$$k_s = 1.6\ c_o \times Vb^{-0.33} \qquad \text{eq. (7-5)}$$

where Vb is the block volume in m^3.

c_o is a factor representing orientation of the main joint set. The values of c_o given in Table 7-3 have been found from Fig. 7-4. The most favourable angles are for joints intersecting the tunnel at 45 - 70^o.

TABLE 7-3 RATINGS OF THE JOINT ORIENTATION FACTOR FOR TBM

angle between tunnel axis and joint set	0-15^o	15 - 30^o	30- 45^o	45 - 75^o	75 - 90^o
average value of c_o =	1	1.25	1.5	1.75	1.5 (c_o = 1.75 for Vb < 0.1 m^3)

According to NTH the angle between a (horizontal) tunnel axis and joint plane can be found from

$$\delta = \arcsin(\sin\beta_j\ \sin(\alpha_t - \alpha_j)) \qquad \text{eq. (7-6)}$$

where α_t is the strike of the tunnel,
α_j is the strike of the joint, and
β_j is the dip of the tunnel.

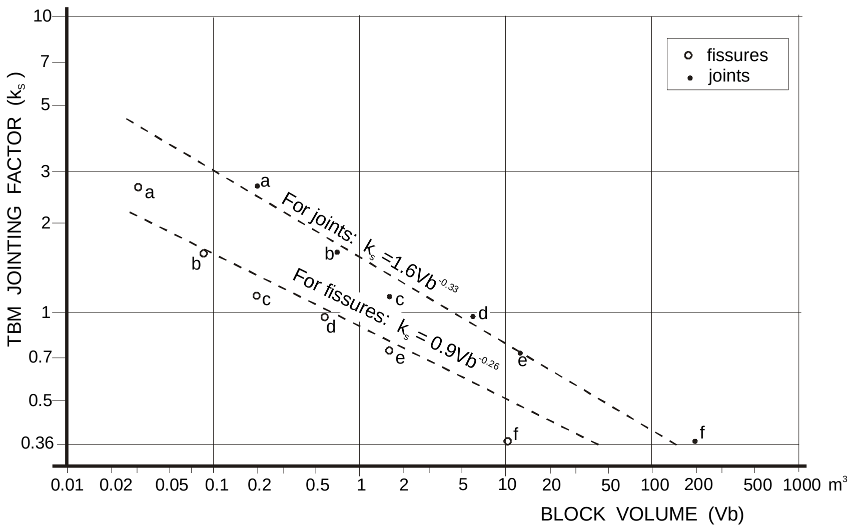


Fig. 7-5 The correlation between the TBM jointing factor k_s and the block volume Vb. The k_s and the Vb values for the points a - f have been found from Fig. 7-4 and Table 7-2 respectively.

As described in Chapter 4, Section 4.2 an average joint condition factor jC = 1.75 often represents common joint characteristics. This gives $JP = 0.2\sqrt{jC} \times Vb^D = 0.265\ Vb^{0.33}$. Thus eq. (7-5) can be expressed as

$$k_s = 0.424\ c_o \times JP^{-1} \qquad \text{eq. (7-7)}$$

Similar, for *fissures* in Fig. 7-4 with assumed average joint condition factor jC = 6, the TBM jointing factor is

$$k_s = 0.9 \times Vb^{-0.26} \times c_o = 0.432\ c_o \times JP^{-1} \qquad \text{eq. (7-8)}$$

which is close to eq. (7-6) considering the degree of accuracy connected to the quality of the input data.

The factor k_s represents, as mentioned, rocks with drilling rate index DRI = 49. For other values k_s is adjusted by a factor (k_{DRI}) as given in the upper diagram in Fig. 7-4. An average expression for the two curves, curve 1 and 2, is

$$k_{DRI} = 0.14\sqrt{DRI} \qquad \text{eq. (7-9)}$$

Using eq. (7-7) and (7-8) the 'equivalent TBM jointing factor' can be expressed as
$k_{eq} = k_s \times k_{DRI} = (0.43\ c_o \times JP^{-1})(0.14\ \sqrt{DRI})$. As $DRI = E \times \sigma_c^{-0.6}$ (see eq. (7-2)), the 'equivalent TBM jointing factor' for *jointed* rock masses is

$$k_{eq} = (0.43 c_o \times JP^{-1})(0.14(E \times \sigma_c^{-0.6})^{0.5}) = \frac{0.06 c_o \sqrt{E}}{JP \times \sigma_c^{0.3}} \qquad \text{eq. (7-10)}$$

For *massive* rock masses (Vb > approx. 10 m^3) the rock properties, expressed as DRI, have a relatively stronger influence on the TBM performance. This is expressed in curve 1 in the upper diagram in Fig. 7-4. By applying eq. (7-2) this curve can mathematically be expressed as

$$k_{DRI} = 0.06\ DRI^{0.72} = 0.06\ (E \times \sigma_c^{-0.6})^{0.72} = 0.06\ E^{0.72} \times \sigma_c^{-0.43} \qquad \text{eq. (7-11)}$$

As $k_s = 0.36$ (see Fig. 7-4) the 'equivalent TBM jointing factor' for *massive* rock is [2]

$$k_{eq} = k_s \times k_{DRI} = 0.36\ (0.06\ E^{0.72} \times \sigma_c^{-0.43}) = 0.022\ E^{0.72} \times \sigma_c^{-0.43} \qquad \text{eq. (7-12)}$$

7.3.3 Assessment of the net advance of boring

The penetration rate (i_o) per revolution is found from the equivalent TBM jointing factor (k_{eq}) and the equivalent thrust per cutter (M_{eq}) in Fig. 7-6. This factor is for cutter diameter 483 mm (19 inches) and a mean cutter spacing 70 mm. For diverging cutter dimensions the equivalent thrust is found from

$$M_{eq} = M_B \times k_d \times k_a \qquad \text{eq. (7-13)}$$

where M_B is the applied thrust per disc (given in kN),
k_d is the correction factor for cutter diameter as given in Fig. 7-7, and
k_a is the correction factor for cutter spacing as given in Fig. 7-8.

These correction factors can also be found from the expressions

$$k_d = 2.35 - 0.0028\ D_c \qquad \text{eq. (7-14)}$$

$$k_a = 1.35 - 0.005\ S_c \qquad \text{eq. (7-15)}$$

(D_c is the cutter diameter, and S_c is the spacing between the cutters.)

The net advance rate (in m/h) is found from

$$I = i_o \times RPM \times 60/1000 \qquad \text{eq. (7-16)}$$

where the value of i_o is found from Fig. 7-6. i_o can also be calculated using

$$i_o = F \times k_{eq}^{G} \quad \text{(mm/rev.)} \qquad \text{eq. (7-17)}$$

where $F = 0.0015\ M_{eq}^{1.5}$ and $G = 30\ k_{eq}^{-0.5} \times M_{eq}^{-0.8}$ (for $k_{eq} < 3.5$) [3]

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[2] If JP =1 is applied in eq. (7-9), the following expression is found: $k_{eq} = 0.022\sqrt{E} \times \sigma_c^{-0.3}$
Its difference from eq. (7-11) is small.

[3] A rough extrapolation of Fig. 7-6 gives $i_o = 0.03\ M \times k_{eq}^{0.18}$ for $k_{eq} \geq 3.5$

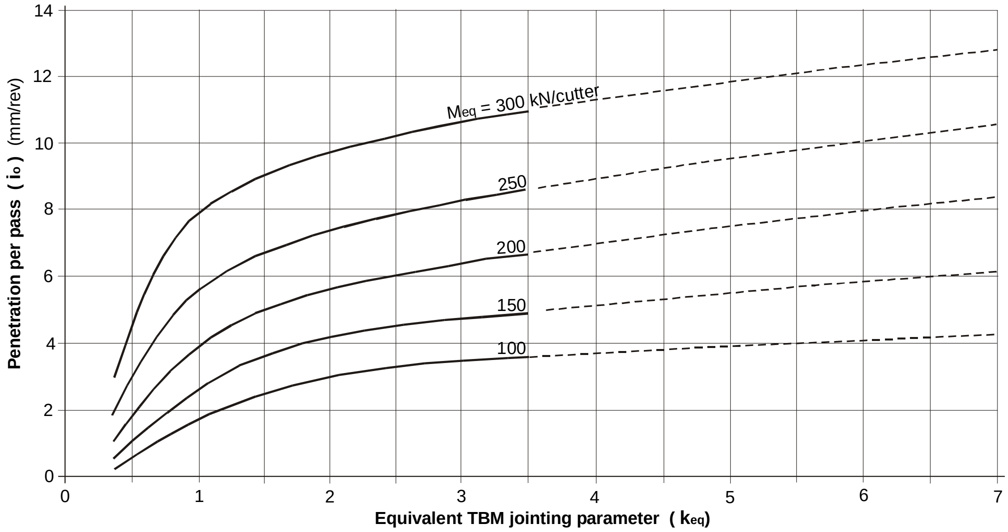

Fig. 7-6 The influence of jointing on the TBM boring (from Norwegian Institute of Technology, 1994).

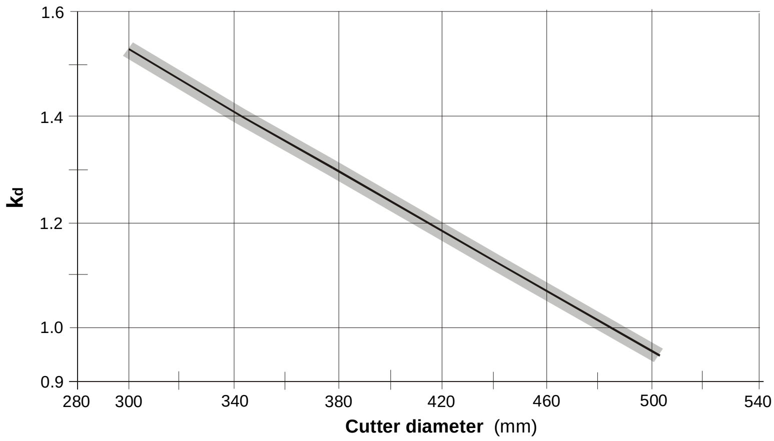

Fig. 7-7 Correction factor k_d for the size of the cutters (from Norwegian Institute of Technology, 1994)

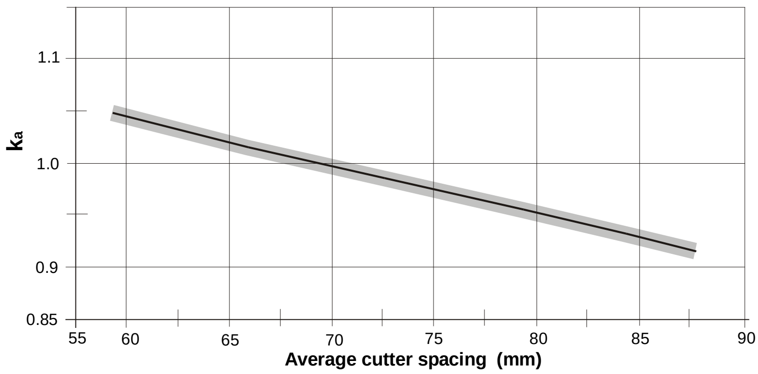

Fig. 7-8 Correction factor k_a for the mean spacing of the cutters. (from Norwegian Institute of Technology, 1994).

7.3.4 Example

The following data have been given on rock mass conditions and TBM factors:

Rock mass factors mapped:	***Evaluations made:***
- Rock type: mica schist	Assumed compressive strength σ_c = 80 MPa, For mica schist the rock factor E = 750 (eq. (7-2)
- Foliation partings spaced: 0.2 m	Block volume $Vb = \beta \times Jv^{-3} = 200\ (1/0.2)^{-3} = 1.6\ m^3$ (eq. (A3-27)
- Joint characteristics: smooth and slightly undulating; fresh walls; discontinuous short joints	Joint condition factor: $jC = jL \times jR/jA = 3 \cdot 2/1 = 6$ (eq. (4-8)
- Angle between tunnel and partings: 45°	TBM joint orientation factor $c_o \approx 1.5$ (Table 7-3)
TBM machine factors:	
- Diameter of TBM: 4.5 m - Max. gross thrust per cutter: M_B = 290 kN - Cutter spacing: S_c = 75 mm - Cutter size: D_c = 483 mm (19 inches) - Cutterhead RPM: 11.1 rev/min	Correction factor: k_a = 0.975 (Fig. 7-9) or eq. (7-15) Correction factor: k_d = 1 (Fig. 7-10) or eq. (7-14)

Calculations:

The jointing parameter in RMi is

$$JP = 0.2\sqrt{jC} \times Vb^D = 0.55 \qquad \text{(eq. (4-4))}$$

where D = 0.26 for jC = 6 (eq. (4-5))

The 'equivalent TBM jointing factor' for jointed rock masses is

$$k_{eq} = (0.06c_o\sqrt{E})/(JP \times \sigma_c^{\,0.3}) = (0.06 \times 1.5\sqrt{750})/(0.55 \times 80^{\,0.3}) = 1.2 \qquad \text{(eq. (7-10))}$$

The equivalent thrust per cutter

$$M_{eq} = M_b \times k_a \times k_d = 290 \times 1 \times 0.975 = 283\ kN \qquad \text{(eq. (7-13))}$$

Using M_{eq} and k_{eq} the penetration is

i_o = 7.8 mm/rev (Fig. 7-6)

(or i_o = 7.7 mm/rev when eq. (7-17) is applied)

The net boring rate is then

$$I = i_o \times RPM \times 60/1000 = 7.8 \times 11.1 \times 60/1000 = 5.2\ m/h \qquad \text{(eq. (7-16))}$$

As all calculations shown in the example above can be performed using equations given in the text, a spreadsheet has been developed as shown in Table 7-4. The same input values as used in the example have been used.

Table 7-4 THE BORING PENETRATION RATE CAN BE CALCULATED APPLYING A SPREADSHEET USING THE EQUATIONS DEVELOPED

ESTIMATING TBM PENETRATION RATE (valid for disc cutters)

Tunnel:

INPUT TBM PARAMETERS	TBM type:		
TBM diameter =	4,5 m	Spacing between cutters Sc =	75 mm
Number of cutters =		RPM = 11,1	Cutter diameter Dc = 483 mm

INPUT PARAMETERS			Location:	example
			Rock:	mica schist
Rock group	[1 = non-shistose hard rock, 2 = metamorphic schist, 3 = argillaceous rock]			2
Compressive strength of rock		(MPa)	σ_c	80
Joint size	[very short, short, medium, long]			short
Joint continuity	[cont(inuous), discont(inuous)]			discont
Joint surface condition	[smooth, slightly rough, rough, very rough]			smooth
Joint planarity	[planar, slightly (undulating), undul(ating), stepped]			slightly
Possible coating on joint wall	[none, sand, clay]			none
Possible filling in joint	[none, sand, clay, thick clay]			none
Block volume		(m^3)	Vb	1,60
Block shape	[compact, long, flat, very (flat or long)]			very
Orientation [1] of main joint set	[fav(ourable); fair; unfav(ourable); very unfav(ourable)]			fair
Applied thust per cutter		(kN)	M_B	290

CALCULATIONS			
Penetration rate per revolution	(mm/rev)	i_o =	7,70
Penetration rate per hour	(m/h)	I =	5,13

CALCULATIONS		**Reference**
E =	750	eq. (7-2)
f_s =	0,760	eq. (4-7)
js =	1,0	Table 4-3
jw =	1,5	Table 4-4
jL =	4,0	Table 4-8
jA =	1,0	Table 4-6
jC =	6,00	eq. (4-2)
JP =	0,553	eq. (4-4)
RMi =	44,256	eq. (4-1)
Db =	0,197	eq. (6-8)
c_o =	1,5	Table 7-3
Structure:	jointed	
k_{eq} massive	-	eq. (7-12)
k_{eq} jointed	1,2	eq. (7-10)
M_{eq} =	282	eq. (7-13)
kd =	0,998	eq. (7-14)
ka =	0,975	eq. (7-15)
F	7,11	eq. (7-17)
G	0,45	eq. (7-17)

[1] [Orientation: 0-15° = very unfav(ourable); 15-30° = fair; 30-45° and 75 - 90° = fav(ourable); 45-75° = very favourable]

7.3.5 Discussion of the RMi method for TBM penetration assessment

Rock mass conditions and TBM data from two tunnel projects have been compiled in Appendix 8, and advance rates have been calculated using the method developed in the foregoing. The results are shown in Fig. 7-9.

Although it can be said that there is a generally fair connection between the calculated and the real data, there are few calculated advance rates, which are the same as those experienced in the field. For some locations the calculated results diverge up to approximately 50% from the boring rate experienced. There may be several reasons for this, the main being:

1. The 'RMi method' and the combination of data may have limitations,
2. The input data on ground conditions may be inaccurate
3. The registration of measured boring rates and applied thrust may be inaccurate.

Ad. 1. As the RMi method is developed from the NTH model, it has the same structure. Therefore, they both suffer from possible deficiencies in the selection of parameters and how they are structured.

There are also uncertainties connected to the development of the RMi method where transition from one-dimensional spacings applied in the NTH model to three-dimensional block size applied in RMi. The assumed value of β = 100 - 200 for the block shape factor here may cause additional inaccuracy in the RMi method. Fig. 7-9 shows, however, that the calculations carried out by the 'RMi method' generally give more accurate results than the NTH model.

In the NTH model the drilling rate index (DRI) represents the properties of the rock material. The determination of this feature, which has to be measured in the laboratory, is time-consuming and costly. Therefore, average values of this parameter have to be applied which do not include variation in the rock

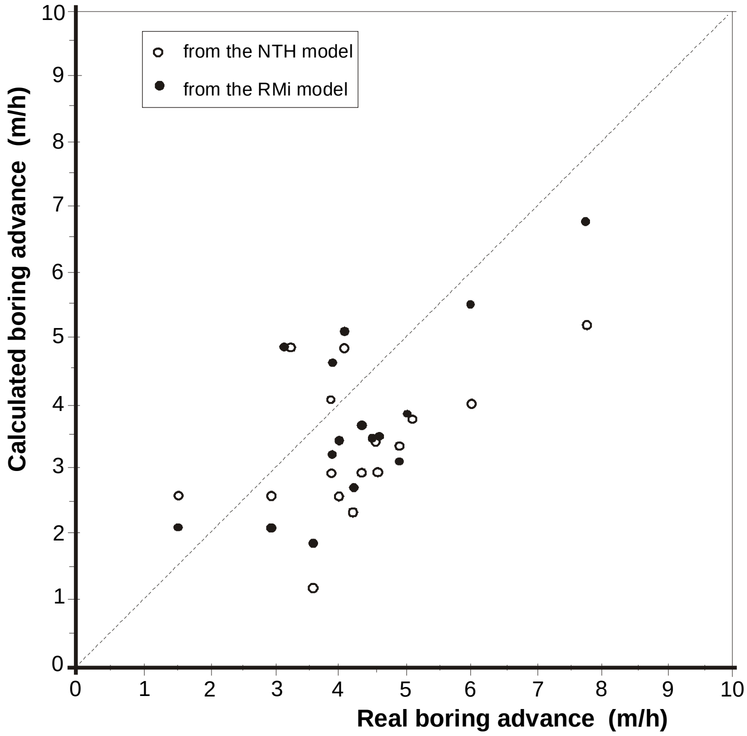

Fig. 7-9 The calculated and real TBM boring advance using the NTH model and the 'RMi method'.

Ad. 2. It is very difficult to characterize and apply the great variations in rock mass properties in a simple model or method. Often, rapid changes occur in the rock properties as well as in the jointing features as described in Section 3 in Chapter 3. Hence, simplifications of the real conditions using average values may introduce errors.

In addition, there may be errors connected to the way descriptions and characterizations are performed and how they are quantified. The use of block volume as the measure of the degree of jointing causes a problem where the joints do not delimit defined blocks. This happens when only one or two joint sets occur, for instance in schistose rocks (such as mica schist and mica gneiss) without other discontinuities than foliation partings. In such cases an equivalent block volume has been estimated applying eq. (7-4) with a block shape factor β = 100 - 200. (Using β = 100 instead of β = 200 gives an error in k_{eq} of only 14%.) Other methods to calculate equivalent block volume are described in Appendix 3, Section 3.2.3.

Errors may also be introduced in the laboratory tests. Farmer and Kemeny (1992) write that apart from a few simple physical property tests, virtually none of the methods used in rock testing give reliable data. Testing of small samples introduces in addition significant scale effects. The error from the compressive strength in the TBM advance calculation is reduced because this rock property is only applied to the power of 0.3 in eq. (7-9) and 0.43 in eq. (7-11).

Ad. 3 Stang and Aadal (1991) writes that errors may be introduced in the recording of actual boring advance rate as well as in registration of applied power during boring. Especially the latter may have important consequences for the calculated boring advance.

The 1994 version of the NTH's TBM model clearly states that, in addition to the specifications and construction of the TBM, the jointing generally has the strongest influence on boring penetration rate. The benefits in applying RMi parameters in assessment of TBM tunnel boring are mainly connected with how RMi is characterized:

- The RMi characterization of joints and jointing includes their three-dimensional occurrence. It therefore incorporates the effect of more than one joint set.
- The RMi parameters also include joint characteristics of importance for the shear strength of the joints, which generally has a marked influence on the TBM boring rate.

The NTH model would be significantly improved by a better joint and jointing characterization. The TBM jointing factor (k_s) may, therefore, be adjusted in the future when better jointing descriptions are applied. This may cause that eq. (7-9) and eq. (7-11) may be reworked and changed.

It is generally much easier and less costly to measure the compressive strength or to find the compressive strength from point load strength than to measure the drilling rate index, DRI. Another advantage using the compressive strength is that it often forms a part of the required rock mass description. Thus, this information may be available at an early stage in the project. As shown in Section 1 in Appendix 3 the compressive strength can be estimated in several ways. The use of the point load test or the Schmidt hammer may in many cases give the required accuracy for the rock strength.