Recent Developments in Rock Support Estimates by the RMi

Arild Palmström
Øvre Smestad veg 35e
N – 0378, Oslo
Norway
Phone: +47 67571286
Fax: +47 67544576
Email: ap@norconsult.no

ABSTRACT

The RMi (rock mass index) system applies input of block size, joint characteristics and strength of intact rock to express the uniaxial compressive strength of a rock mass. From practical use in more than 5 years the RMi rock support method has been further developed. It is now more user-friendly and easier to learn. Preliminary support estimates can be made from input only of block size and the size of the tunnel when only limited knowledge of the ground conditions is available. Later, when more information of ground is available, more accurate support estimates can be made.

Tables and support charts are presented together with several examples. Instructions are given how to make a computer spreadsheet from which the RMi and the support parameters easily can be calculated. As for all systems for evaluating rock support an understanding of the geology of the area and knowledge of the ground conditions at site are important for proper use of the RMi.

1. INTRODUCTION

The RMi (rock mass index) support method was introduced in 1995 as a result of a Ph.D. completed at the University in Oslo, Norway and subsequently published in the Journal of Rock Mechanics and Tunnelling Technology in the year 1995 & 1996. It applies input of the main features influencing on rock mass properties to express the uniaxial compressive strength of rock masses. As earlier presented by Palmström (1995 and 1996), the RMi can be used in several applications in addition to its use in support estimates, such as

- characterisation of rock mass strength and rock mass deformation,
- calculation of the constants in the Hoek and Brown failure criterion for rock masses, and
- assessment of TBM penetration rate.

This paper shows important developments in the RMi rock support method after more than 5 years of practical application. The method is now more user-friendly after a few simplifications and adjustments. It is shown that only input of block volume and tunnel diameter are necessary for making preliminary rock support estimates. This may be useful when only limited information on the ground conditions is available, for example at an early stage of a project. Later, when the values or ratings of the input factors have been measured or observed, more accurate support estimates can be made.

Applying the 3-dimensional block volume as a main input to RMi, several benefits are achieved, both in characterising a rock mass and in rock engineering calculations. Methods to assess the block volume from various types of field measurements are shown in the Appendix.

The great benefit in using computer spreadsheets to calculate the value of RMi and the support parameters is shown together with the instruction to work out a simple spreadsheet (Excel). By this, the calculations can be made quickly, because the relevant equations and input parameters are linked in the spreadsheet. This is shown in the Appendix.

In this paper *rock* = the construction material, i.e. intact rock; *rock mass* = rock(s) penetrated by joints; and *ground* = rock mass subjected to stresses and ground water.

2. THE ROCK MASS INDEX (RMi)

The rock mass index is a volumetric parameter indicating the approximate uniaxial compressive strength of a rock mass. It is expressed as:

- For jointed rock:

$$RMi = \sigma_c \times JP = \sigma_c \times 0.2\sqrt{jC} \times Vb^{D} \qquad (D = 0.37\, jC^{-0.2}) \qquad (1)$$

- For massive rock:

$$RMi = \sigma_c \times f_\sigma = \sigma_c\,(0.05/Db)^{0.2} \approx 0.5\sigma_c \qquad (2)$$

The symbols in the expressions above represent:

σ_c = the uniaxial compressive strength of intact rock, measured on 50 mm samples. Some average strength values are given in Table A1 in the Appendix.

jC = the joint condition factor, which is a combined measure for the joint size (jL), joint roughness (jR), and joint alteration (jA), given as

jC = jL × jR/jA (Ratings are shown in Table 1) (3)

Vb = the block volume, measured in m^3; the average volume is generally applied. ($Db = \sqrt[3]{Vb}$ is the equivalent block diameter, measured in m)

JP = the jointing parameter, which incorporates the main joint features in the rock mass. Its value can be found from the lower diagram in Figure 4 or from eq. (1) ($JP = 0.2\sqrt{jC} \times Vb^D$).

f_σ = the massivity parameter ($f_\sigma = (0.05/Db)^{0.2}$); an adjustment for the scale effect of compressive strength in massive rock. Massive rock occurs generally when Db > approx. 2 m, for which $f_\sigma \approx 0.5$.

When $JP < f_\sigma$, (this is where JP < approx. 0.5) eq. (1) is applied. See lower diagram in Figure 4.

Figure 1 shows connection between the input parameters applied in the RMi. For the most common joint characteristics jC = 1.75 which gives

$$RMi = \sigma_c \times JP = \sigma_c \times 0.26 \sqrt[3]{Vb} \qquad (1a)$$

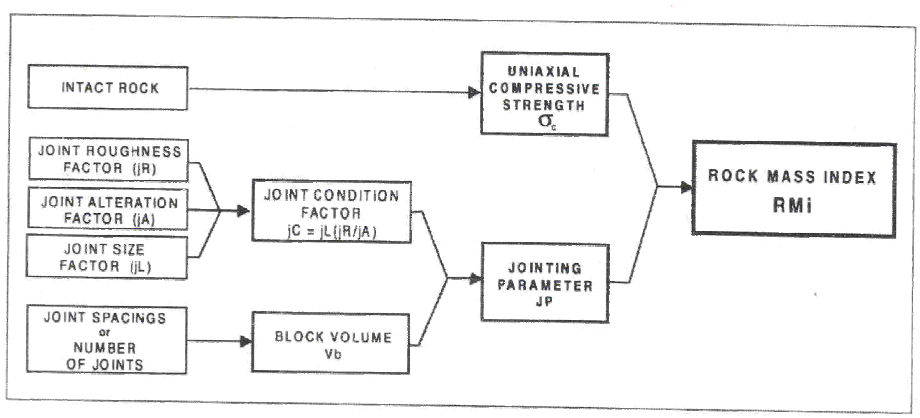

Figure 1 - The input parameters to RMi

This can be used when only limited information is available on the rock mass conditions, see example 1 in Section 5.

The symbols in the expressions above represent:

σ_c = the uniaxial compressive strength of intact rock, measured on 50 mm samples. Some average strength values are given in Table A1 in the Appendix.

jC = the joint condition factor, which is a combined measure for the joint size (jL), joint roughness (jR), and joint alteration (jA), given as

$$jC = jL \times jR/jA \quad \text{(Ratings are shown in Table 1)} \tag{3}$$

Vb = the block volume, measured in m^3; the average volume is generally applied. ($Db = \sqrt[3]{Vb}$ is the equivalent block diameter, measured in m)

JP = the jointing parameter, which incorporates the main joint features in the rock mass. Its value can be found from the lower diagram in Figure 4 or from eq. (1) ($JP = 0.2\sqrt{jC} \times Vb^D$).

f_σ = the massivity parameter ($f_\sigma = (0.05/Db)^{0.2}$); an adjustment for the scale effect of compressive strength in massive rock. Massive rock occurs generally when Db > approx. 2 m, for which $f_\sigma \approx 0.5$.

When $JP < f_\sigma$, (this is where JP < approx. 0.5) eq. (1) is applied. See lower diagram in Figure 4.

Figure 1 shows connection between the input parameters applied in the RMi. For the most common joint characteristics jC = 1.75 which gives

$$RMi = \sigma_c \times JP = \sigma_c \times 0.26 \sqrt[3]{Vb} \tag{1a}$$

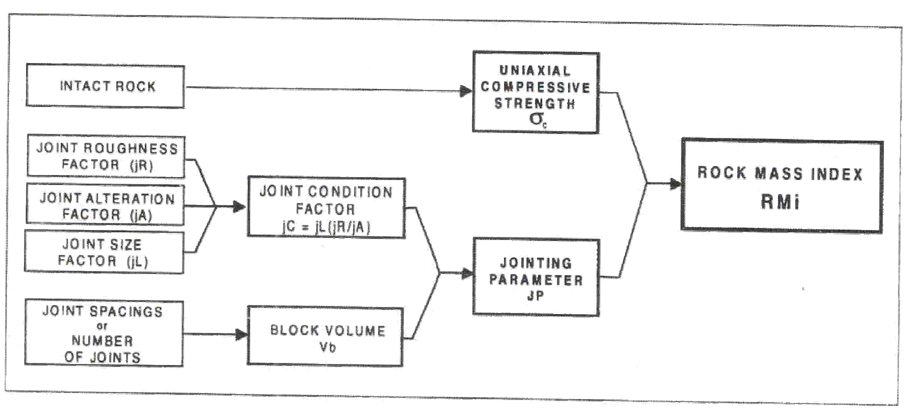

Figure 1 - The input parameters to RMi

This can be used when only limited information is available on the rock mass conditions, see example 1 in Section 5.

Table 1 The values and ratings of the input parameters to RMi.

INPUT PARAMETERS TO THE RMi

UNIAXIAL COMPRESSIVE STRENGTH (σ_c) of intact rock	**value** (in MPa)	may be found from laboratory tests (or estimated from handbook tables etc.)
BLOCK VOLUME (Vb)	**value** (in m^3)	may be measured at site (from observations or from bore hole cores)

THE JOINT CONDITION FACTOR jC (jC = jR x jL / jA)

THE JOINT ROUGHNESS FACTOR (jR)

(The ratings in **bold** are similar to Jr in the Q-system)

Small scale smoothness of joint surface	Large scale waviness of joint plane: Planar	Slightly undulating	Undulating	Strongly undulating	Stepped or interlocking
Very rough	2	3	4	6	6
Rough	**1.5**	2	**3**	4.5	6
Smooth	**1**	1.5	**2**	3	4
Polished or slickensided *	**0.5**	1	**1.5**	2	3

For filled joints jR = 1 For irregular joints a rating of jR = 6 is suggested

* For slickensided surfaces the ratings given cover possible movement along the lineations. (For movements across lineation, rough or very rough rating should be applied for the surface)

THE JOINT ALTERATION FACTOR (jA) (the ratings are based on Ja in the Q-system)

Contact between joint walls				
CLEAN JOINTS:	Healed or welded joints	filling of quartz, epidote, etc.		jA = 0.75
	Fresh joint walls	no coating or filling, except from staining (rust)		1
	Altered joint walls	- one grade higher alteration than the rock		2
		- two grades higher alteration than the rock		4
COATING or THIN FILLING OF:	Frictional materials	sand, silt calcite, etc. (non-softening)		3
	Cohesive materials	clay, chlorite, talc, etc.		4
Some or no wall contact			**Thin filling (< 5 mm)**	**Thick filling**
THICK FILLING OF:	Frictional materials	sand, silt calcite, etc. (non-softening)	jA = 4	8
	Hard, cohesive materials	clay, chlorite, talc, etc.	6	6 - 10
	Soft, cohesive materials	clay, chlorite, talc, etc.	8	12
	Swelling clay materials		8 - 12	13 - 20

THE JOINT SIZE FACTOR (jL)

		Continuous joints	Discont. joints *
Bedding or foliation partings etc.	length < 0.5 m	jL = 3	jL = 6
Joints	with length 0.1 - 1 m	2	4
	with length 1 - 10 m	1	2
	with length 10 - 30 m	0.75	1.5
(Filled) joint, seam or shear *	length > 30 m	0.5	1

* Discontinuous joints end in massive rock; ** Often a singularity (special feature) and should in these cases be treated separately

Table 2 Ratings of the adjustment factors for rock support estimates in blocky ground. Note that the factors have unit values for their most common occurrence.

ROCK SUPPORT ADJUSTMENT FACTORS

STRESS LEVEL

Very low (in portals, etc.)	(overburden < 10 m)	SL = 0.1
Low	(overburden 10 - 35 m)	0.5
Moderate	(overburden 35 - 350 m)	1
High	(overburden > 350 m)	1.5 *

* For stability in high *walls* a high stress level may be unfavourable. Possible rating SL = 0.5 - 0.75

NUMBER OF JOINT SETS *		NUMBER OF JOINT SETS *	
One set	Nj = 3	Three sets	Nj = 1
One set + random	2	Three sets + random	0.85
Two sets	1.5	Four sets	0.75
Two sets + random	1.2	Four sets + random	0.65

* Means the number of joint sets at the actual location

ORIENTATION OF JOINTS (related to the axis of the tunnel)

IN WALL		IN ROOF	TERM	
for strike > 30°	for strike < 30°	for all strikes		
dip < 30°	dip < 20°	dip > 60°	favourable	Co = 1
dip = 30 - 60°	dip = 20 - 45°	dip = 45 - 60°	fair	1.5
dip > 60°	dip = 45 - 60°	dip = 20 - 45°	unfavourable	2
-	dip > 60°	dip < 20°	very unfavourable	3

INCLINATION OF ACTUAL TUNNEL SURFACE (ROOF or WALL)

Horizontal (roof)	C = 1
30° inclination (roof in shaft)	1.5
45° inclination (roof in shaft)	2.2
60° inclination (roof in shaft)	3
Vertical (walls)	5

The classification of RMi is:

Very low	RMi < 0.01
Low	RMi = 0.01 – 0.1
Medium	RMi = 0.1 – 1
High	RMi = 1 – 10
Very high	RMi > 10

3. THE RMi ROCK SUPPORT METHOD

The principles in the RMi support method are shown in Figure 2. As shown in Figure 3 the number of blocks in the periphery of an underground opening will largely determine whether the surrounding ground will behave:

a) as a *continuous*, bulk material where the magnitude of the rock stresses is important; or
b) as a *blocky* material, dominated by the individual blocks and the character of the joints.

This can be assessed from the ratio CF = tunnel diameter/block diameter, which is called the continuity factor. With a markedly difference in behaviour of these two groups (see Figure 3), the RMi support method applies different calculations and support charts for continuous and blocky ground.

3.1 Blocky ground

The stability in blocky (jointed) ground is mainly influenced by the block size and shape, the shear strength of the joints delineating the blocks, and the orientation of the same joints relative to the opening. The following two support parameters, which include all these features, are used in the support chart in Figure 4:

- The ground quality, given as the *ground condition factor*

$$Gc = RMi \times (SL \times C) = \sigma_c \times JP \times (SL \times C) \quad (4)$$

- The scale factor, expressed as the *size ratio*

$$Sr = CF \times (Co / Nj) = (Dt / Db) \times (Co / Nj) \quad (5)$$

here,

Dt = The diameter or span of the tunnel or cavern, in metre (For walls, the height Wt is used instead of Dt),

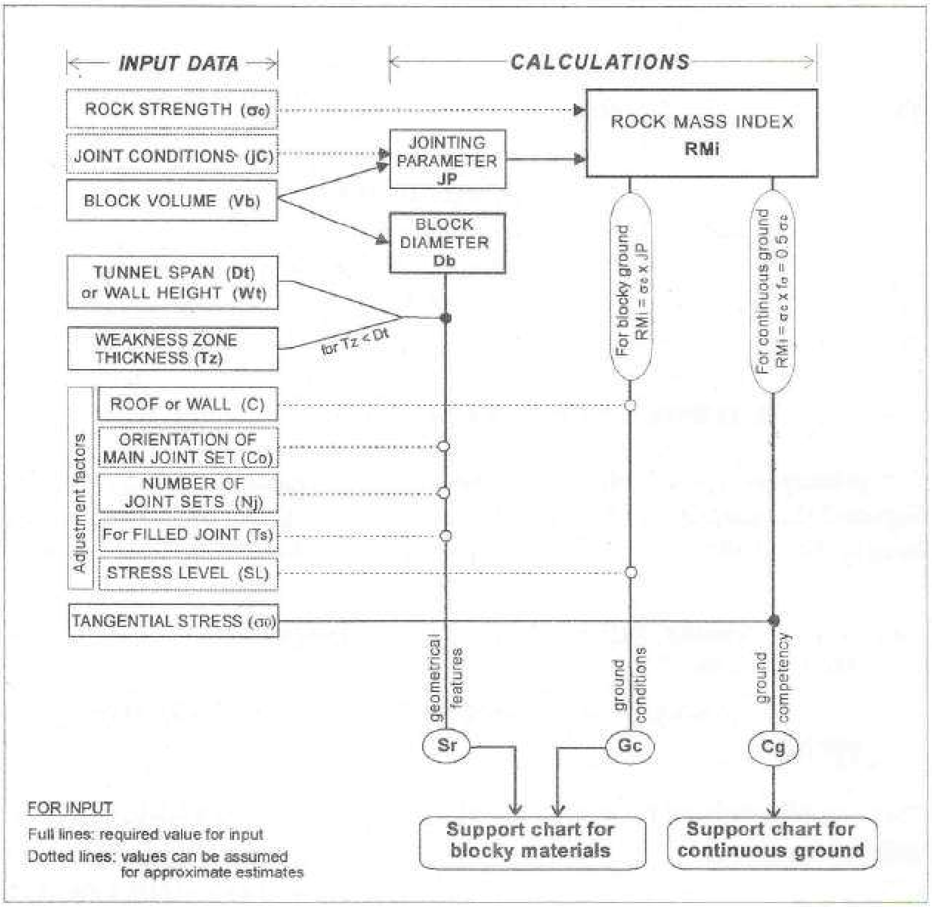

Figure 2 The input data and their use in the RMi rock support system

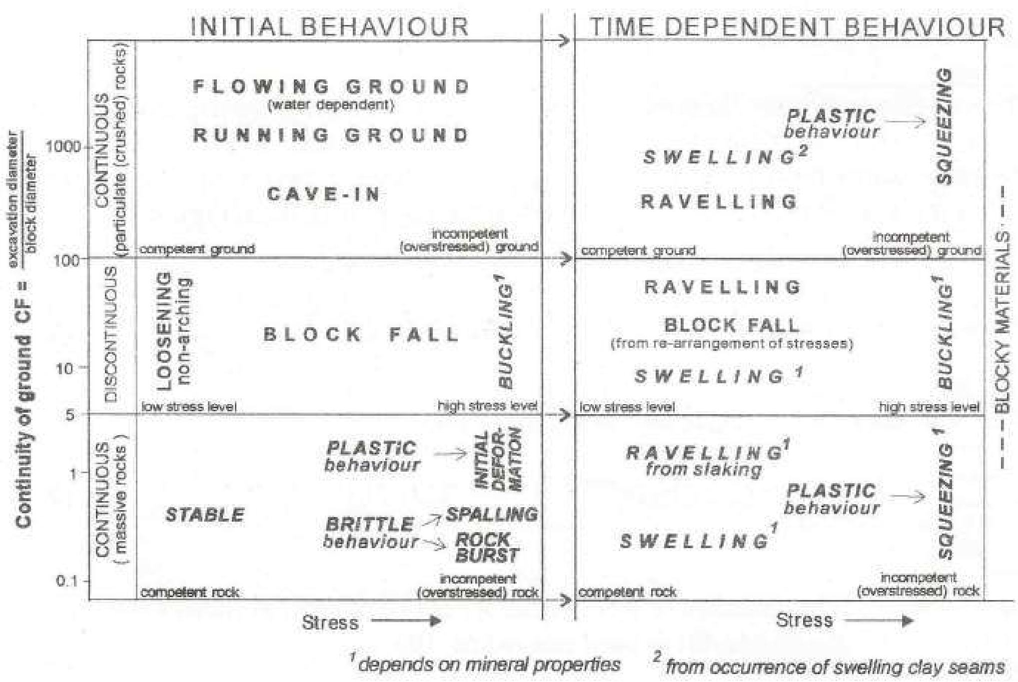

Figure 3 Instability and rock mass behaviour, determined by the stress conditions and the continuity of the ground (i.e.. the number of blocks in the tunnel periphery)

Db	=	The equivalent block diameter[1] $Db = \sqrt[3]{Vb}$ (in metre),
C	=	A gravity adjustment factor for support in the roof or in the walls. Its ratings depend on the inclination of the walls and roof, and can be found from Table 2 or from the expression $C = 5 - 4 \cos \delta$, where δ = angle (dip) of the opening surface measured from horizontal,
SL	=	A stress level adjustment, see Table 2,
Co, Co_s	=	An adjustment factor for the main joint set, or seam, respectively, see Table 2,
Nj	=	An adjustment factor for the number of joint sets; and hence the freedom for the blocks to fall. Its ratings in Table 2 can also be found from $Nj = 3/n_j$ where n_j = the number of joint sets, ($n_j = 1$ for one set; $n_j = 1.5$ for one set plus random joints; $n_j = 2$ for two sets, nj = 2.5 for two sets plus random joints; etc.),
Tz	=	Thickness of the weakness zone in eq. (7).

The ratings in Table 2 of the adjustment factors SL, C, Co, and Nj have unit value for their most common or typical conditions. Thus, eqs. (4) and (5) can be expressed as

$$Gc = \sigma_c \times JP \quad \text{and} \quad Sr = Dt / Db.$$

When the value of these factors are measured or known, more accurate calculations can be made, as illustrated in Section 5.

In cases where a *seam* or *filled joint* (with thickness Ts < 1 m) occurs in the location, the following adjustment of the size ratio may be made:

$$Sr_s = Sr\,(1 + Ts)\,Co_s \qquad (6)$$

Weakness zones should in many cases be treated individually without using support or classification systems. Support assessments for crushed zones with blocky materials (where CF = approx. 1 to 600) may, however, be carried out using the support chart for blocky ground in Figure 4 and input parameters as for blocky ground. In small and medium sized zones (thickness between 1 and approximately 20 m) stability is influenced by the interplay between the zone and the adjacent rock masses. Therefore, the stresses in such zones are generally lower than in the adjacent ground, which will reduce the effect of squeezing.

[1] In earlier RMi publications the expression for Db has been adjusted for the block shape, (the β factor, see Appendix). As experience has shown that this adjustment in most cases does not give more accurate results the expression for Db has been changed. The Y-axis in the support chart in Figure 4 has been adjusted to compensate for this change.

The ground condition factor (Gc) is the same as for blocky ground, while the size ratio for weakness zones is

$$Sr = (Tz / Db)(Co / Nj) \qquad \text{for } Tz < Dt \qquad (7)$$

$$Sr = (Dt / Db)(Co / Nj) \qquad \text{for } Tz > Dt \qquad \text{(which is similar to eq. (5))}$$

For zones with CF > 600 special rock support evaluations should generally be made. Large zones (thickness Tz > approx. 20 m) will often behave similar to continuous ground described in Section 3.2 as there will be little or no arching effect.

For crushes weakness zones some typical RMi values for the most common conditions have been given in Table 3. They may be used for estimates at an early stage of a project or for cases where the composition of the zone is not known, see examples 2 and 4 in Section 5. The approximate RMi_z values are based on assumed representative block volumes for the various types of zones

Table 3 - Typical values of the rock mass index (RMi_z) used for various types of crushed zones

Crushed zones	Average uniaxial compressive strength	Average joint condition factor	Approximate block size volume	Approximate block size diameter	Approximate typical value
	σ_c (MPa)	jC	Vb (m^3)	Db (m)	RMi_z
	of the rock blocks				
Coarse fragmented zones	100	0.5	0.01	0.2	2
Small fragmented zones	100	0.5	0.0001	0.05	0.3
Clay-rich (simple) zones	80	0.1	0.01	0.2	0.3
Clay-rich (complex) zones	40	0.1	0.001	0.1	0.03
	of the clay material				
Clay zones*	0.1	-	1 cm^3 (nom.)	0.01	0.05

* For zones containing mainly clay, approximate support estimates may be carried out using a nominal minimum block volume of $Vb = 1\ cm^3$

3.2 Continuous ground

Continuous ground occurs when CF < approx. 5 (*massive rock*), in which the propert'es of intact rock dominate, and when CF > approx. 100 (*particulate or highly jointed rock*), where the ground behaves as a bulk material. In these types of ground the main influence on the behaviour in an underground opening comes from the stresses. Therefore, a competency factor (Cg = strength of the rock mass/stresses acting) is used. It is expressed as:

- In massive ground

$$Cg = RMi / \sigma_\theta = f_\sigma \times \sigma_c / \sigma_\theta \approx 0.5 \frac{\sigma_c}{\sigma_\theta} \quad (8)$$

- In particulate ground

$$Cg = RMi / \sigma_\theta = JP \frac{\sigma_c}{\sigma_\theta} \quad (9)$$

here,

σ_θ = the tangential stress in the rock masses around the opening. A method to estimate σ_θ in roof and walls of a tunnel in massive rock is shown in the Appendix.

Competent ground occurs where Cg > 1; else the ground is overstressed (incompetent). Cg is applied in the ground support chart (Figure 5).

Massive, competent ground is generally stable, see Figure 3, and does generally not need any support, except for some scaling work in drill & blast tunnels. Massive, *incompetent* (overstressed) ground, however, requires support because the following time-dependent types of deformation and/or failures may take place:

- *squeezing* in overstressed ductile rocks (such as schists);
- *spalling* or *rock burst* in overstressed brittle, hard rocks (such as granite and gneiss).

Particulate materials (highly jointed rocks) require generally immediate support. Their initial behaviour is often similar to that of blocky ground, i.e. the support chart in Figure 4 can be used for CF = 1 to 600. In overstressed *(incompetent)* ground time-dependent squeezing will, in addition to the initial instability, take place. However, for this type of ground the support chart in Figure 5 needs updating when more experience in this type of ground can be made available.

4. SUPPORT CHARTS

The support charts in Figures 4 and 5 indicate the estimated amount and types of the total support. They are based on experience from several tunnels and other underground drill & blast excavations in Scandinavia. Figure 6 shows when these two charts should be used.

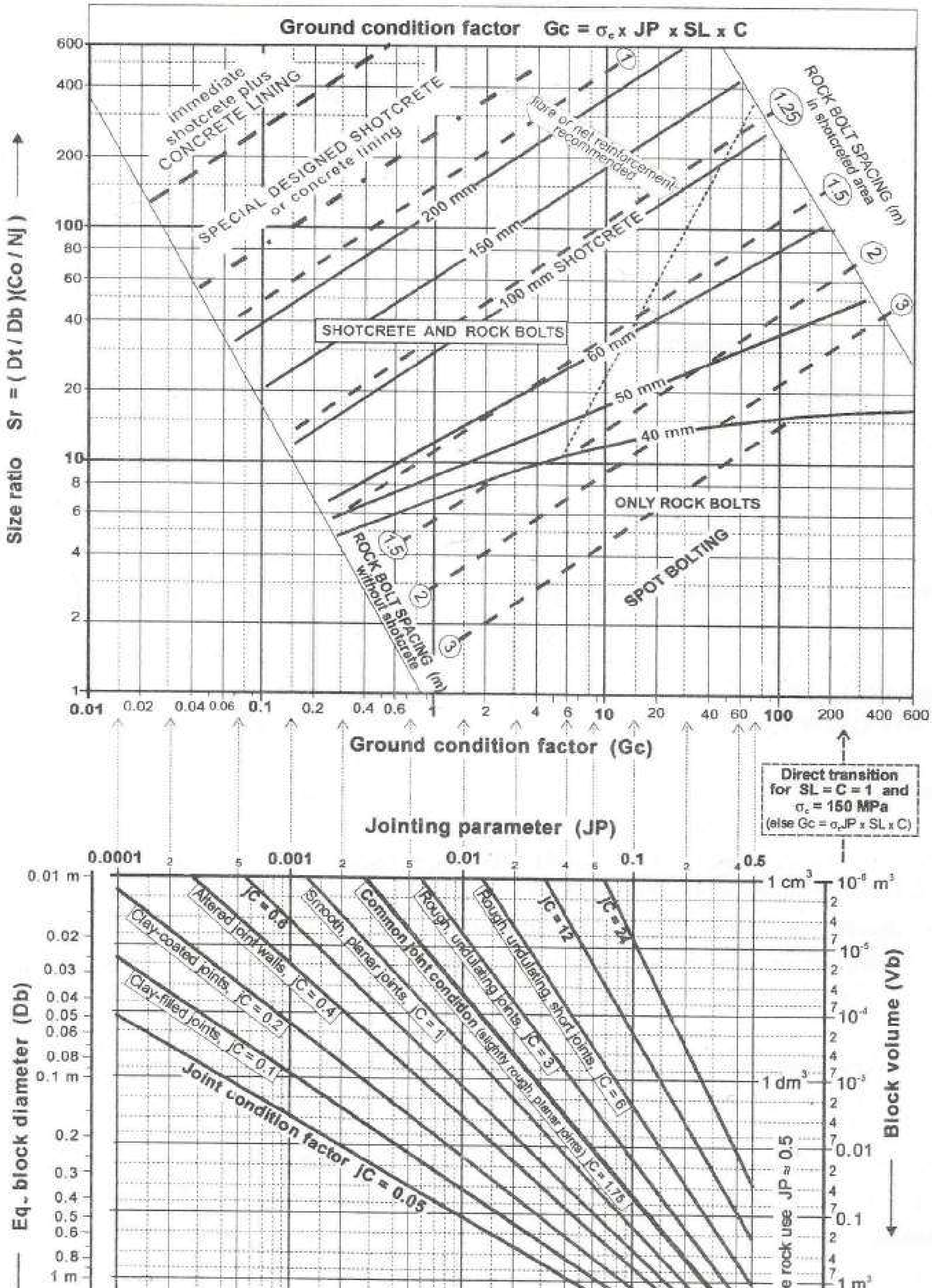

Figure 4 *Upper chart: rock support for blocky ground including weakness zones. The ground condition factor (Gc) for the roof can be found directly from JP when the compressive strength σ_c = 150 MPa and the stress level (SL= 1) are applied (Example: for Vb = 0.2 m^3 and jC = 3, Gc = 35); Else Gc = σ_c x JP x SL x C*
Lower chart: the jointing parameter (JP) found from Vb and jC

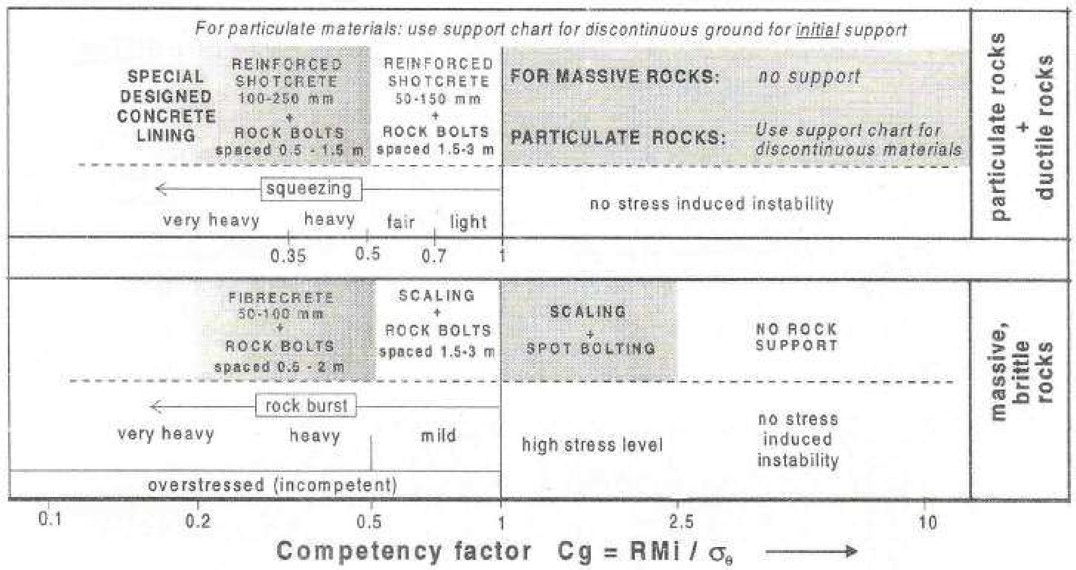

Figure 5 Chart for estimating support in continuous (massive and particulate) ground. Note that the support indicated for overstressed, particulate materials is approximate, as only a limited number of cases have been used

As shown in Section A5 in the Appendix, the calculation of RMi and the support parameters applied in the charts can be quickly and easily made using a computer spreadsheet.

An understanding of the geological conditions at site is a must for a good characterisation of the rock mass and the ground conditions, and in selecting appropriate input values for the calculations. In this connection it should be noted that, being statistically based, a support chart can never accurately represent the ground conditions at site. The many variations in rock composition and properties as well as in geometry, density and structure of joints in a location makes characterization in a single or a few numbers very difficult. The RMi support method includes, however, more parameters of the ground conditions and geometrical features at a site than most other classification systems for rock support, see Table 4.

For swelling and slaking rock the stability may be strongly influenced by local conditions. Therefore, the rock support should be evaluated separately for each of such cases. Other features to be separately assessed are connected to the local safety requirements, i.e. the required lifetime of the tunnel or cavern, and to the influence from vibrations caused by earthquakes or by nearby blasting, or by other impact from the activity of man.

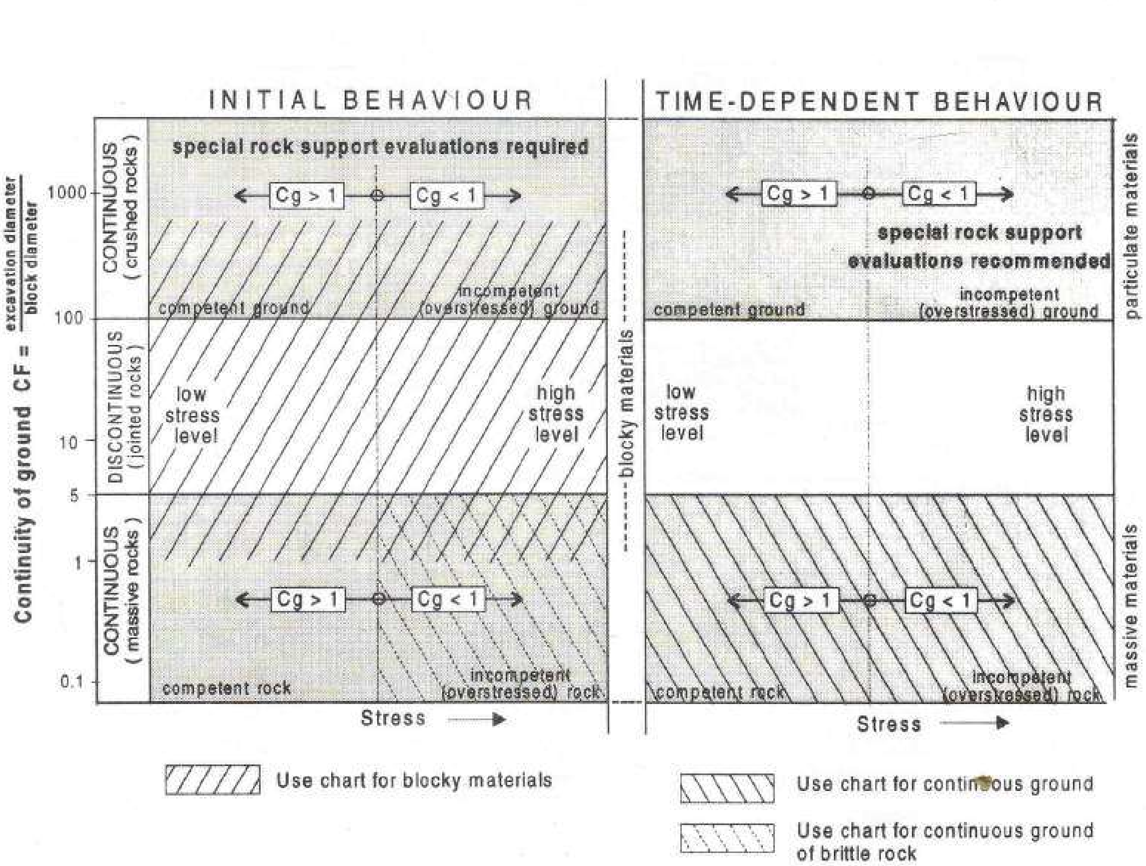

Figure 6 Recommended application of the two support charts, for blocky materials (Figure 4) and for continuous ground (Figure 5)

5. EXAMPLES ON SUPPORT ESTIMATES

The examples are applied to a horse-shoe shaped tunnel with span Dt = 6 m and wall height Wt = 5.5 m

General note:

First, the type of ground should be determined from the ratio between tunnel size and block size. From this the appropriate method for support estimate is made. When only limited information on the ground conditions is available, the value of the joint condition factor is assumed jC = 1.75 as for its most frequent occurrence. Similarly, the value of the adjustment factors SL = Co = Nj = 1. This is used in Examples 1 and 2. The estimates are for the tunnel roof for which the adjustment factor C = 1.

Example 1 *Preliminary estimate (where very few input data are known)*

The tunnel is planned in a moderately jointed granite. What will the rock support be?

Evaluations:

- According to Table A2 in the Appendix the block volume in moderately jointed rock is: $Vb = 0.03 - 1\ m^3$ (average $Vb = 0.5\ m^3$) with equivalent block diameter $Db = \sqrt[3]{Vb} = 0.8$ m . The continuity factor $CF = Dt / Db = 7.5$ which means that the ground is blocky, and equations eq. (4 - 7) can be used.
- From Table A1 the normal uniaxial compressive strength of granite is $\sigma_c = 160$ MPa
- As described in Section 2 the most common joint condition is $jC = 1.75$ for which eq. (1a) gives
- $RMi = \sigma_c \times JP = \sigma_c (0.26 \sqrt[3]{Vb}) = \sigma_c \times 0.21 = 33$ (The value of JP can also be found from the lower diagram in Figure 4)

Assuming unit value of the adjustment factors SL, Co and Nj, the support parameters in *roof* are:

- The ground condition factor: $Gc = RMi \times SL \times C = 33$ (from eq. (4))
- The size ratio: $Sr = (Dt / Db)(Co / Nj) = 7.5$ (from eq. (5))

Using these parameters in the support chart for blocky ground (Figure 4) the estimated roof support is: Rock bolts spaced 3 m. The wall support can be found in a similar way using $C = 5$ in eq. (4) and the wall height Wt in eq. (5) instead of the span Dt.

Example 2 *Preliminary support estimate for a weakness zone (few input data of the zone are known)*

It is assumed that the tunnel will encounter a $Tz = 5$ m thick weakness zone, assumed to be a "coarse-fragmented crushed zone". What is probable rock support?

Evaluations:
From Table 3 the values $RMi_z = 2$ and $Db_z = 0.2$ are found for coarse-fragmented zones. With unit values of the adjustment parameters the *roof* support parameters are:

- $Gc = RMi_z \times SL \times C = 2$ (from eq. (4))
- $Sr = (Tz / Db_z)(Co_z / Nj_z) = 25$ (eq. (5) is applied because $Tz < Dt$)

From Figure 4 the following roof support in the zone is found: Rock bolts spaced 1.25 to 1.5 m and 80 mm thick shotcrete, fibre reinforced. The wall support can be found in a similar way using C = 5 in eq. (4) and Wt instead of Dt in eq. (5).

Example 3 *Rock support estimate during detailed design (where the values of input data are known)*

The tunnel will partly be located with 100 - 150 m overburden. From the field investigations performed, the following ground characteristics have been found representative for a section of the tunnel:

- The granite is fresh with compressive strength $\sigma_c = 125$ MPa.
- The joints have the following characteristics: medium length, rough joint surfaces and undulating with fresh joint walls. This gives the following value of the joint condition factor
  $jC = jL \times jR/jA = 1 \times 3/1 = 3$ (see eq. (3))
- There are two joint sets plus random joints; the main joint set has strike = 60° and dip = 45° (relative to the tunnel axis), i.e. the orientation is *fair* both for the roof and the walls, see Table 2.
- The block volume varies mainly between 0.5 m³ and 2.5 m³, average Vb = 1.5 m³

Evaluations:

- With block diameter [2] $Db = \sqrt[3]{Vb} = 1.14$ m, the continuity factor CF_{roof} = Dt / Db = 5.2 (i.e. blocky ground)
- The following values of the adjustment factors are found from Table 2 using the information above:

  $SL = 1$; $Nj = 1.2$; $Co_{roof} = Co_{wall} = 1.5$

- With input of jC = 3 and Vb = 1.5 m³ in Figure 4 (or using eq. (1)) the jointing parameter JP = 0.4; and $RMi = \sigma_c \times JP = 50$.

From this the support parameters in roof are

- $Gc = RMi \times SL = 50$ (from eq. (4))
- $Sr = (Dt / Db)(Co / Nj) = 6.6$ (from eq. (5))

Estimated support in roof from Figure 4: Spot bolting or rock bolts spaced 2.5 m. Bolt length, according to eq. (13) given in the Appendix, should be $Lb = 1.4 + 0.16Dt(1 + 0.1/Db) = 2.4$ m (or Lb can be found from Figure A2). (In practise,

[2] Db can also be found from the lower diagram in Figure 4

the support parameters Gc and Sr should be calculated both for Vb = 0.3 m^3 and Vb = 3 m^3 and the support determined from that.)

Example 4 *Support estimate for a weakness zone with known characteristics.*

During excavation of the tunnel at a depth of 150 m below surface, a Tz = 8 m wide crushed zone has been encountered. It consists of slightly weathered granite with $\sigma_c \approx 100$ MPa, the blocks in the zone have size Vb = 0.01- 0.1 dm^3 (average Vb = 0.05 dm^3 = 0.00005 m^3) with clay fillings in most of the joints. There are 4 joint sets in the zone mainly of short joints. The orientation of the zone is: strike = 60°, dip = 25° related to the axis of the tunnel.

Evaluations:

- From the description given the zone can be characterized as a clay-rich crushed zone. With average Vb = 0.00005 m^3 (= 50 cm^3) the block diameter Db = $\sqrt[3]{Vb}$ = 0.04 m.
- From Table 2 the following ratings are found: SL = 1; Nj = 0.75; Co_{roof} = 2, Co_{wall} = (unfavourable zone orientation in roof and favourable for walls)
- The joint characteristics from Table 1 are: jL = 2, jR = 1 (nominal), jA = 10, which gives jC = jL x jR / jA = 0.2
- The jointing parameter JP = 0.00057 is found from Figure 4 or eq. (1) and RMi = $\sigma_c \times$ JP = 0.057.

From this the roof support parameters for blocky ground are:

- Gc = RMi × SL × C = 0.057 (from eq. (4))
- Sr = (Dt / Db) (Co_z / Nj_z) = 400 (as Tz > Dt, eq. (5) is used)

Using Figure 4, the roof support of the zone is: Shotcrete quickly applied after blasting and concrete lining. (In practise, the support parameters Gc and Sr should be calculated for the variation range of Vb)

Example 5 *Support estimate for massive, hard rock subjected to high rock stresses.*

A part of the tunnel is located in massive granite (σ_c = 130 MPa) where the overburden is z = 1000 m.

Evaluations:

- Massive rock means Vb = 8 m^3 or larger. The block diameter is Db = $\sqrt[3]{Vb}$ = 2 m (or larger). This gives CF = Dt / Db = 3 (or less), i.e., the ground is continuous.

- The magnitude of tangential stress around the tunnel is estimated using the method described in Section A3 in the Appendix:
  Theoretical, vertical stress $p_v = 0.027 \times z = 27$ MPa (eq. 15). From eq. (13) and assumed $k = 1.5$ the tangential stress in the tunnel roof is $\sigma_\theta = p_v (A \times k - 1) = 102.6$ MPa

In massive rock RMi $\approx 0.5\,\sigma_c = 65$ (eq. (2)), hence the competency of the ground is:

- $Cg = RMi / \sigma_\theta = 65/102.6 = 0.63$ (from eq. (8))

According to Figure 5 the behaviour of the brittle granite is: Mild rock burst, which requires the following support: Rock bolts spaced 1.5 to 3 m.

6. DISCUSSION – CONCLUSION

This paper presents some simplifications in the RMi support method. One changes in the support parameters for weakness zones, making it easier to calculate the support parameters Gc and Sr.

Another simplification is the application of unit values for the adjustment factors in blocky ground if their values are not known as in preliminary support estimates. Some of the advantages achieved from this are:

- The sampling of input properties is strongly reduced, as only input of the block volume is needed (in addition to tunnel size).
- It leads to easier and quicker calculations of the support parameters.
- More accurate results can be achieved, when field investigations have been performed and real values of the input factors are used.

It is no direct correlation between the Q-system and the RMi support method. A main reason is that they partly use different input parameters (see Table 4) and that the principles in the support parameters and charts are different. In many of the cases where both the RMi support method and the Q-system have been applied, RMi method indicates more (stronger) support. A reason may be that the RMi support chart is developed later than the Q-chart and that it includes recent requirements for support.

An important feature in the RMi system is the use of the block volume as a main input. Another is that the two support parameters constitute real ground properties (rock mass strength and geometrical ratio). By this it is possible to understand the structure of the support method and the use of the input factors. The RMi requires, however, experienced users, which will reduce possible misuse.

Table 4 - The various parameters applied in the Q, RMi, and RMR rock support systems

	PARAMETER	APPLICATION				
		in the Q system		*in the RMi support method*		*in the RMR system*
Rock	Rock strength	-		σ_c	uniaxial compressive strength	uniaxial compressive or point load strength
Jointing	Degree of jointing	RQD	rock quality designation	Vb	block volume	rock quality designation (RQD) joint spacing
	Joint sets (pattern)	Jn	joint set number	Nj	joint set factor	-
	Joint character	Jr	joint roughness number	jR	joint smoothness and waviness factor	joint roughness
	Joint coating or infilling	Ja	joint alteration number	jA	joint coating, filling and weathering factor	joint infilling, gouge joint weathering
	Joint size	-		jL	joint length and continuity	joint length, persistence
	Joint aperture	-	(partly in Ja)	-	(partly in jA)	joint separation
	Joint orientation	-		Co	joint orientation factor	orientation of joints
Water	Ground water	Jw	joint water reduction factor	-		leakage condition
Stress	Rock stresses	SRF	stress reduction factor	SL	stress level factor	-
Tunnel	Tunnel dimensions	Dt Wt ESR	span wall height excavation support ratio	Dt Wt	span or diameter wall height	-
Ground	Rock mass strength	-		$RMi = 0.2\,\sigma_c\sqrt{jR \times jL/jA} \times Vb^D$ or $RMi = 0.5\sigma_c$ (for massive rock)		-
	Ground competency			$Cg = RMi / \sigma_\theta$		
	Ground quality (in roof)	$Q = RQD/Jn \times Jr/Ja \times Jw/SRF$		$Gc = RMi \times SL$		RMR = sum of the ratings for each factor above
	Ground quality (in wall)	$Q_{wall} = Q \times K$		$Gc_{wall} = Gc \times C$		
	Scale factor (in roof)	$De = Dt/ESR$		$Sr = (Dt/\sqrt[3]{Vb})(Co/Nj)$		-
	Scale factor (in wall)	$De = Wt/ESR$		$Sr = (Wt/\sqrt[3]{Vb})(Co/Nj)$		-

K = adjustment of Q-value for walls. It varies with the Q-value; C = adjustment factor for walls (and for all inclinations of the tunnel surface)
$D = 0.37\,(jR \times jL / jA)^{-0.2}$

Some of the *benefits* in the RMi support method are:

- The use of the three-dimensional block volume will generally improve the characterization of the rock mass and hence lead to better estimates, compared to the use of RQD and joint spacing applied in other support methods.
- In addition, the RMi support method includes all important ground parameters; more than other main classification systems used for rock support estimates, see Table 4.
- The use of different methods for support estimates in ground of different behaviour is reflected in different equations and calculations.

Some of the *limitation* or problems in the RMi support method are:

- The RMi support method does not generally cover soil or soil-like materials, except where the material occurs in seams or small weakness zones with thickness less than a few metres.
- It is difficult to calculate the magnitude of tangential stresses in blocky ground, which in turn reduces the quality of the support assessments, especially to assess appropriate time-dependent rock support. (This is also the case for other methods for rock support in this type of ground.) More studies are needed to improve estimates here.
- The calculation of the parameters is more difficult than for the RMR and the Q systems as it involves exponential equations. However, from the diagrams the RMi value can easily be found. Using computer spreadsheet the various parameters needed for support estimates can be found directly, see Section A5 in the Appendix.

Acknowledgement

The author wants to thank Prof. Håkan Stille at Royal Technical University (KTH), Stockholm, Prof. Björn Nilsen, Norwegian Technical University, and especially cand.scient. Olav Hval for valuable comments and suggestions during preparation of this paper.

References

Barton, N., Lien, R. and Lunde, J. (1974): "Engineering classification of rock masses for the design of rock support". Rock Mechanics 6, 1974, pp. 189-236.

Bieniawski Z.T. (1989): "Engineering rock mass classifications". John Wiley & Sons, New York, 251 p.

Cecil O.S. (1970): "Correlations of rock bolt - shotcrete support and rock quality parameters in Scandinavian tunnels". Ph.D. thesis Univ. of Illinois 1970.

Deere D. and Miller R.D. (1966): "Engineering classification and index properties for intact rock". Univ. of Illinois, Tech. Rept. No. AFWL-TR-65-116, 1966.

Hoek E. and Brown E.T. (1980): "Underground excavations in rock". Institution of Mining and Metallurgy, London 1980, 527 pp.

Palmström, A. (1982): "The volumetric joint count - a useful and simple measure of the degree of jointing". Proc. IV Int. Congr. IAEG, New Delhi, 1982, pp V.221-V.228.

Palmström A. and Berthelsen O. (1988): "The significance of weakness zones in rock tunnelling". Proc. Int. Conf. Rock Mechanics and Power Plants, Madrid 1988, 8 pp.

Palmström, A. (1995): "RMi - a rock mass characterization system for rock engineering purposes". Ph.D. thesis, Univ. of Oslo, Norway, 400 pp.

Palmström, A. (1995): "RMi - A system for characterising rock mass strength for use in rock engineering", J. of Rock Mech. & Tunnelling Technology, New Delhi, India, Vol. 1, No. 2, pp 69-108.

Palmström A. (1996): "Characterizing rock masses by the RMi for use in practical rock engineering", Part 1: Tunnelling and Underground Space Technology, Vol. 11, No. 2, pp. 175-186.

Palmström A. (1996): "Characterizing rock masses by the RMi for use in practical rock engineering", Part 2: Tunnelling and Underground Space Technology, Vol. 11, No. 3, pp. 287-303.

Palmström A. (1996): "The rock mass index (RMi) applied in rock mechanics and rock engineering", J. of Rock Mech. & Tunnelling Technology, New Delhi, India, Vol. 2, No. 1, pp 1-40.

Piteau D.R. (1973): "Characterizing and extrapolating rock joint properties in engineering practice". Rock Mechanics, Suppl. 2, pp. 5-31.

APPENDIX

A1. UNIAXIAL COMPRESSIVE STRENGTH OF INTACT ROCK

Where there are no test results of the uniaxial compressive strength (σ_c) available, it may be estimated from strength tables. Table A1 shows values for some typical rocks.

Table A1 Average uniaxial compressive strength (σ_c) of some rocks, measured on 50 mm samples

Type of rock	σ_c (MPa)	Type of rock	σ_c (MPa)	Type of rock	σ_c (MPa)	Type of rock / soil	σ_c (MPa)
Andesite (I)	150	Garnet micaschist (M)	<105>	Marble (M)	<100>	Shale (S, M)	95
Amphibolite (M)	<160>	Granite (I)	160	Micagneiss (M)	90	Siltstone (S, M)	<80>
Amphibolitic gneiss (M)	160	Granitic gneiss (M)	100	Micaquartzite (M)	85	Slate (M)	<190>
Augen gneiss (M)	160	Granodiorite (I)	160	Micaschist (M)	<80>	Syenite (I)	150
Basalt (I)	160	Granulite (M)	<90>	Mudstone (S)	10	Talcschist (M)	<65>
Clay schist (S, M)	55	Gneiss (M)	130	Phyllite (M)	<50>	Tuff (S)	<25>
Diorite (I)	140	Greenschist (M)	<75>	Quartzite (M)	<190>	Ultrabasic (I)	160
Dolerite (diabase) (I)	200	Greenstone (M)	110	Quartzitic phyllite (M)	100	Clay (hard)	0.7
Dolomite (S)	<100>	Greywacke (M)	80	Rhyolite (I)	85 (?)	Clay (stiff)	0.2
Gabbro (I)	240	Limestone (S)	90	Sandstone (S, M)	<100>	Clay (soft)	0.03
				Serpentinite (M)	135	Silt, sand (approx.)	0.0005

(I) = igneous, (M) = metamorphic, (S) = sedimentary rock; < > large variation

A2. MEASUREMENTS OF THE BLOCK VOLUME (Vb)

The block volume (Vb) can be measured by different methods performed in the underground opening, on the surface, in rock cuttings, or in drill cores. Direct measurement can be made where the structure of the rock mass can be observed from measurements of joint spacings, from assessment of representative blocks at each observation point. The volumes will generally vary considerably at each site, and it is often a practice to measure the variation in volumes in addition to the average volume.

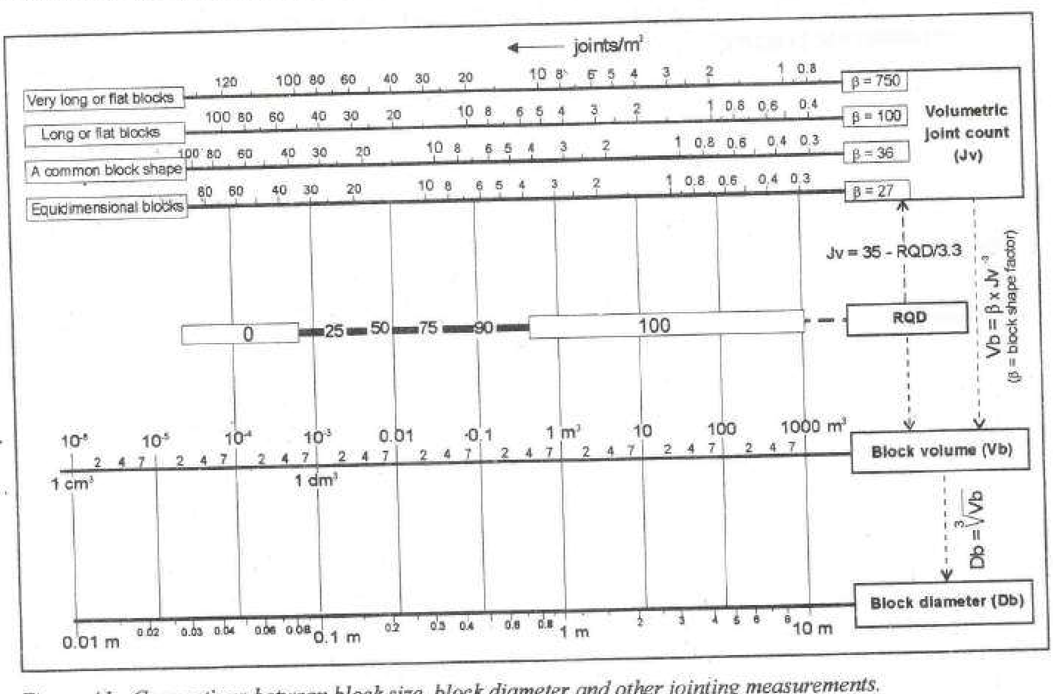

Figure A1 Connections between block size, block diameter and other jointing measurements.
Examples: For flat blocks with $Jv = 5$ the block volume $Vb \approx 0.7\ m^3$. For equidimensional blocks with $Jv = 5$ the block volume $Vb \approx 0.2\ m^3$. For $RQD = 25$ the block volume $Vb \approx 2\ dm^3$.

Often, it is not possible to observe the whole individual block in an outcrop or in the surface of an underground opening, especially where less than three joint sets occur. Random joints or cracks formed during the excavation process will often result in defined blocks. In such cases a spacing of random joints 5 to 10 times the spacing of the main set can often be used to estimate the block volume.

Example: Where only one joint set (S1) can be seen, $Vb \approx S1 \times 5S1 \times 10S1 = 50\ S1^3$
For two joint sets (S1 and S2), $Vb \approx S1 \times S2 \times 10S1 = 10\ S1^2 \times S2$

Table A2 Classification of the degree of jointing

DEGREE OF JOINTING (or DENSITY OF JOINTS)	VOLUMETRIC JOINT COUNT TERM	Jv	BLOCK VOLUME TERM	Vb
Massive / no joints	Extremely low	< 0.3	Extremely large size	> 1000 m³
Massive / very weakly jointed	Very low	0.3 - 1	Very large size	30 - 1000 m³
Weakly jointed	Low	1 - 3	Large size	1 - 30 m³
Moderately jointed	Moderately high	3 - 10	Moderate size	0.03 - 1 m³
Strongly jointed	High	10 - 30	Small size	1 - 30 dm³
Very strongly jointed	Very high	30 - 100	Very small size	0,03 - 1 dm³
Crushed	Extremely high	> 100	Extremely small size	< 30 cm³

Correlation between block volume (Vb) and volumetric joint count (Jv):

- General expression $Vb = \beta \times Jv^{-3}$ (10)
- Expression for the most common block shape (where $\beta = 36$) $Vb = 36\ Jv^{-3}$ (11)

here β = the block shape factor, representing the jointing pattern.
It can be estimated from $\beta \approx 20 + 7(S_{max} / S_{min})$ (12)
(S_{max} and S_{min} are the longest and shortest dimension of the block)

A3. A METHOD TO ESTIMATE THE TANGENTIAL STRESSES AROUND AN UNDERGROUND OPENING

The magnitude of the tangential stresses (σ_θ) depends on the overall stress level, the stress anisotropy and the shape of the opening and can be found from rock stress measurements and Kirch's equations. Stresses around openings in massive rock may also be estimated using the following simplified expressions presented by Hoek and Brown (1980):

- in roof: $\sigma_\theta = p_v(A \times k - 1)$ (MPa) eq. (13)
- in walls: $\sigma_\theta = p_v(B - k)$ (MPa) eq. (14)

here k = horizontal stress/vertical stress
p_v = the vertical stress in MPa at tunnel level, often found from $p_v \approx 0.027\ z$ [eq. (15)] (z = overburden in m)
A and B are tunnel factors given in Table A3.

Table A3 Values of the tunnel shape factor

Tunnel factor	Tunnel shape				
A	4.0	3.2	3.1	3.0	1.9
B	1.5	2.3	2.7	3.0	1.9

A4. RECOMMENDED LENGTH OF ROCK BOLTS

Suggested expressions for calculating the length of rock bolts from tunnel dimensions and the block size:

$Lb_{roof} = 1.4 + 0.16\ Dt\ (1 + 0.1 / Db)$ (16)

$Lb_{wall} = 1.4 + 0.08\ (Dt + 0.5Wt)(1 + 0.1 / Db))$ (17)

here Db = the block diameter in metre;
Dt = the tunnel span or diameter in metre;
Wt = the wall height in metre.

These equations are graphically solved in Figure A2

Note: The block diameter used should be given for the representative block size at the actual location.

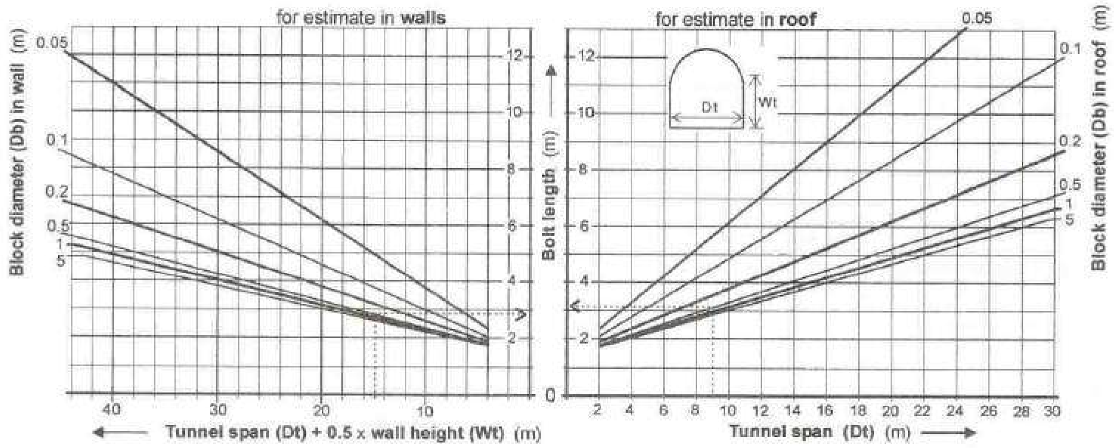

Figure A2 Bolt length determined from tunnel dimensions and block size.
Example shown: In a tunnel with 9 m span and 12 m wall height and average block diameter Db = 0.5 m, the bolt length will be 3.2 m in roof and 2.8 m in walls.

A5. DESCRIPTION OF A COMPUTER SPREADSHEET TO CALCULATE THE VALUE OF THE RMi AND THE SUPPORT PARAMETERS

Table A3 The support parameters in Examples 1 – 5 are calculated in a spreadsheet (Excel). Required input factors both for blocky and for continuous ground are written in italic

			EXAMPLE 1	EXAMPLE 2	EXAMPLE 3	EXAMPLE 4	EXAMPLE 5
INPUT FACTORS		*Symbol*	*input values or ratings*				
Tunnel diameter or span (m)		*Dt*	*6*	*6*	*6*	*6*	*6*
Tunnel wall height (m)		*Wt*	*5.5*	*5.5*	*5.5*	*5.5*	*5.5*
Compressive strength of intact rock (MPa)		σ_c	*160*	*100*	*125*	*100*	*130*
Joint roughness factor		*jR*	*1.75*	*1*	*3*	*1*	*1.75*
Joint alteration factor		*jA*	*1*	*2*	*1*	*10*	*1*
Joint length and termination factor		*jL*	*1*	*1*	*1*	*2*	*1*
Block volume (m3)		*Vb*	*0.5*	*0.01*	*1.5*	*0.00005*	*8*
Joint set factor		*Nj*	*1*	*1*	*1.2*	*0.75*	
Orientation factor of main joint set	*- in roof*	*Co*	*1*	*1*	*1.5*		
	- in walls	*Co*	*1*	*1*	*1.5*		
Orientation factor of weakness zone	*- in roof*	*Co*		*1*	*1*	*2*	
	- in walls	*Co*		*1*	*1*	*2*	
Thickness of weakness zone (m)		*Tz*		*5*		*8*	
Stress level factor		*SL*	*1*	*1*	*1*	*1*	
Tangential stress (MPa)	*- in roof*	σ_θ					*102.6*
	- in walls	σ_θ					
CALCULATIONS OF:			results				
Block diameter		Db	0.79	0.22	1.14	0.04	2.00
Joint condition factor		jC	1.75	0.5	3	0.2	1.75
Jointing parameter		JP	0.2104	0.0200	0.3907	0.0006	0.5264
Rock Mass index		RMi	33.657	1.997	48.843	0.057	65.000
Ground condition factor	- in roof	Gc	33.66	2.00	48.84	0.06	0.00
	- in walls	Gc	168.29	9.99	244.21	0.28	0.00
Size ratio	- in roof	Sr	7.6		6.6		
	- in walls	Sr	6.9		6.0		
Size ratio for weakness zone	- in roof	Sr		23.2		434.2	
	- in walls	Sr		23.2		398.0	
Competency factor	- in roof	Cg					0.634
	- in walls	Cg					

The RMi system is well applicable for computer spreadsheets as all parameters involved have mathematical expressions and input of numerical values. Spreadsheets can be worked out using the flowchart in Figure and the equations presented in this paper. Thus the value of RMi as well as the parameters involved in the support system can very easily be found.

Table A3 shows a simple *spreadsheet with calculation of the* support parameters in the *five 5 examples in* Section 5.

Table A4 shows the expressions used for calculation in Table A3. You may work out your own spreadsheet from Table A4. Hints when making a spreadsheet:

- Start to write in box A2 (with *INPUT FACTORS*), then A3 (with *Tunnel diameter or span (m)*) etc.
- It is important that the expressions (in cells D20 to D31) are written correctly.

Table A4 *Spreadsheet (Excel) showing the equations applied in Table A3. The input values in Example 1 have been inserted.*

	A	B	C	D
1				EXAMPLE 1
2	**INPUT FACTORS**		**Symbol**	***input values or ratings***
3	*Tunnel diameter or span (m)*		*Dt*	*6*
4	*Tunnel wall height (m)*		*Wt*	*5.5*
5	*Compressive strength of intact rock (MPa)*		σ_c	*160*
6	*Joint roughness factor*		*jR*	*1.75*
7	*Joint alteration factor*		*jA*	*1*
8	*Joint length and termination factor*		*jL*	*1*
9	*Block volume (m3)*		*Vb*	*0.5*
10	*Joint set factor*		*Nj*	*1*
11	*Orientation factor of main joint set*	*- in roof*	*Co*	*1*
12		*- in walls*	*Co*	*1*
13	*Orientation factor of weakness zone*	*- in roof*	*Co*	
14		*- in walls*	*Co*	
15	*Thickness of weakness zone (m)*		*Tz*	
16	*Stress level factor*		*SL*	*1*
17	*Tangential stress (MPa)*	*- in roof*	σ_θ	
18		*- in walls*	σ_θ	
19	**CALCULATIONS OF:**			**results**
20	Block diameter		Db	=D9^0.3333
21	Joint condition factor		jC	=D6*D8/D7
22	Jointing parameter		JP	=0.2*(D21)^0.5*(D9)^(0.37*(D21)^-0.2)
23	Rock Mass index		RMi	=IF(D22<0.5,D22*D5,0.5*D5)
24	Ground condition factor	- in roof	Gc	=IF(OR(D10="",D11="",D12=""),"",D23*D16)
25		- in walls	Gc	=IF(D24="","",5*D24)
26	Size ratio	- in roof	Sr	=IF(OR(D24="",D15>0),"",D3/D20*D11/D10)
27		- in walls	Sr	=IF(OR(D24="",D15>0),"",D4/D20*D12/D10)
28	Size ratio for weakness zone	- in roof	Sr	=IF(D15>D3,D15/D20*D13/D10,"")
29		- in walls	Sr	=IF(D15>D4,D15/D20*D14/D10,"")
30	Competency factor	- in roof	Cg	=IF(D17="","",D23/D17)
31		- in walls	Cg	=IF(D18="","",D24/D18)