An introduction to the Rock Mass index (RMi) and its applications

by Arild Palmström, Ph.D.

1 Introduction

Construction materials commonly used in civil engineering are mostly characterized by their strength properties. In rock engineering, however, no such specific strength characterization of the rock mass is in common use. Most engineering is carried out using various descriptions, classifications and unquantified experience. Hoek and Brown (1980), Bieniawski (1984), Nieto (1983) and several other authors have, therefore, indicated the need for a *strength characterization* of rock masses.

The Rock Mass index, RMi, system has been developed to meet this need. It was developed between 1986 and 1995. The main development is presented in the Ph.D. thesis of Arild Palmström from 1995. A reference list of the RMi publications is shown at the end of this article.

2 The rockmass index, RMi

An important issue in the development of RMi system has been to use input parameters which have the greatest significance in rockmass behaviour. The main principles in the RMi value and the input data used are shown in Figures 1 and 2.

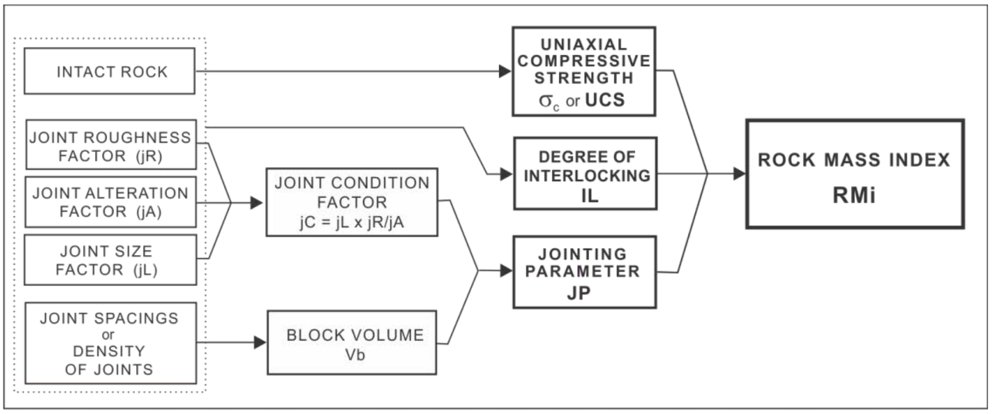

Figure 1.
The layout of the Rock Mass index, RMi. Input for interlocking was introduced in 2005.

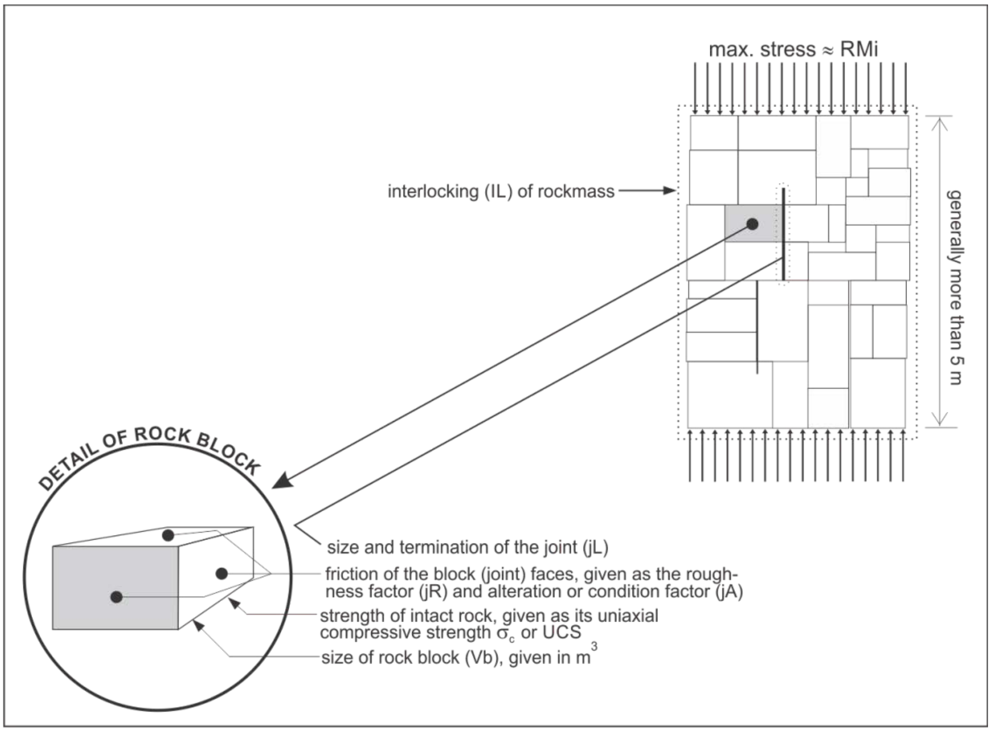

Figure 2
The main parameters in the rock mass are included in the RockMass index, which approximately characterizes the uniaxial compressive strength of a rock mass.

RMi is based on the principle that the joints intersecting a rockmass tend to reduce its strength. Consequently, it is expressed as: RMi = $\sigma_c \times$ JP

Here σ_c = the uniaxial compressive strength of intact rock (in MPa), measured on 50 mm samples. (Often, UCS is used instead of σ_c)

JP = the jointing parameter, expressing the reduction in strength of the intact rock caused by the joints.

The jointing parameter (JP) is composed of the joint condition factor, jC, and the block volume, Vb. The joint condition, jC = jR × jL/jA,

where

- jR, the joint roughness factor, determined by
  - js = smoothness of joint surface factor and
  - jw = joint plane planarity or waviness factor,
- jA, the joint condition or alteration factor, and
- jL, the joint size and continuity factor.

As shown in Figure 1, JP incorporates the main joint features in the rock mass. From the test results presented in Figure 3 the Jointing Parameter was found as

$$JP = 0.2\sqrt{jC} \times Vb^{D} \quad \text{where} \quad D = 0.37jC^{-0.2}$$

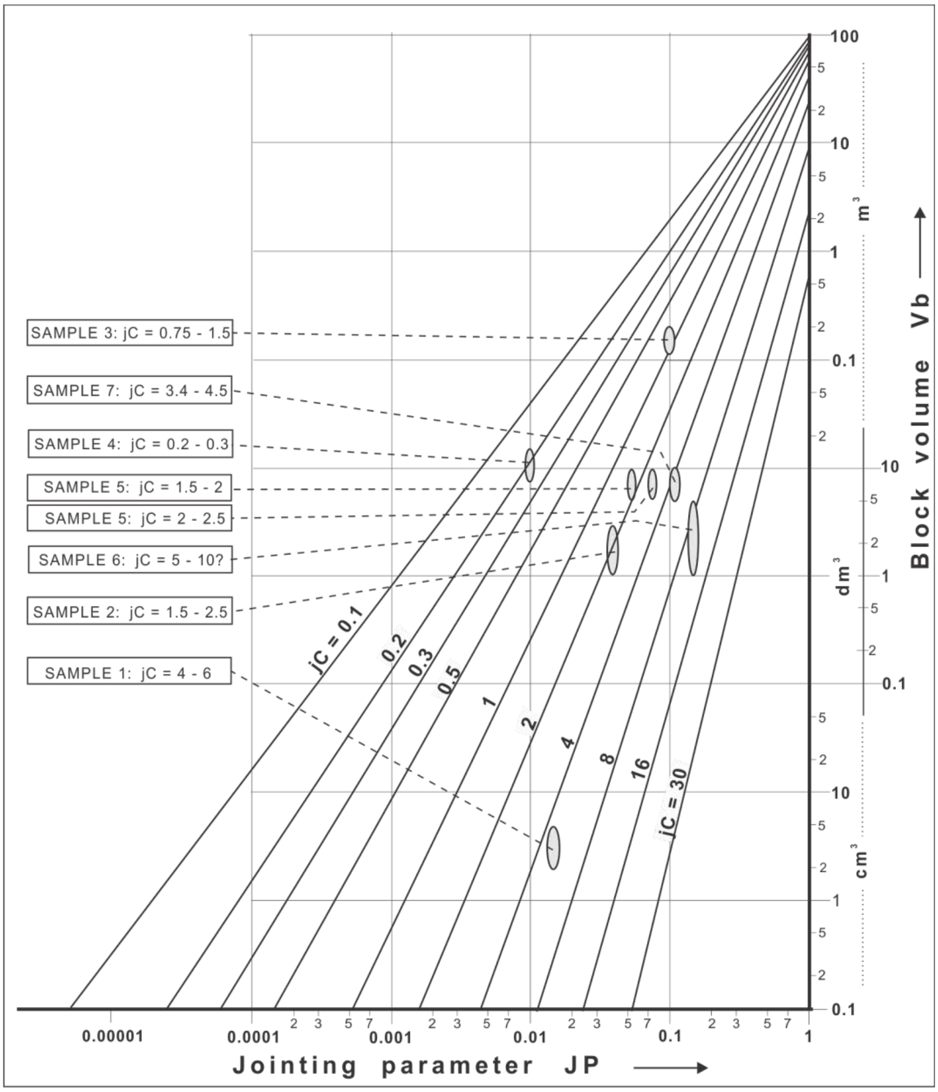

Figure 3.
Test results from 8 large scale compressive strength tests or back calculations were used to find the expression for the jointing parameter, JP. The known data for the samples were plotted in the diagram and the lines for the joint characteristics, jC, were draw as shown. These lines represent the expression for JP.

Unfortunately, it was not possible to detect more than the 8 large scale test results at the time when RMi system was developed, though many organisations and companies were contacted.

The input parameters to RMi are shown in Table 1. They can be determined by commonly used measure-ments and observations, and from empirical relationships. The RMi system has some features similar to those of the Q-system. Thus, jR and jA are almost the same as Jr and Ja in the Q-system. RMi requires more calculations than the RMR and the Q system, but spreadsheets can preferably be used, from which the RMi value can be found directly. This is presented in Figure 4.

Table 1. The input parameters to RMi

Uniaxial compressive strength of rock (UCS or σ_c)	**value** in MPa (from lab. tests or assumed from handbook tables)
Block volume (Vb)	**value** in m³ (from observations at site or on drill cores, etc.)
Joint condition factor (jC)	**jC = jR x jL / jA** (ratings of jR, jA and jL from the tables below)

Joint roughness factor (jR) composed of large scale and small scale undulations (The ratings in ***bold italic*** are similar to Jr in Q-system)	Large scale waviness of joint plane: Planar	Slightly undulating	Undulating	Strongly undulating	Stepped or interlocking
Small scale smoothness of joint surface: 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 apply to possible movement along the lineations*

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. without content of clay		3
		Cohesive materials	clay, chlorite, talc, etc.		4
Partly or no wall contact	THICK FILLING OF:			Thin filling (< 5mm)	Thick filling
		Frictional materials	sand, silt calcite, etc. (non-softening	jA = 4	8
		Hard, cohesive materials	clay, chlorite, talc, etc.	6	5 - 10
		Soft, cohesive materials	clay, chlorite, talc, etc.	8	12
		Swelling clay materials	material exhibits swelling properties	8 - 12	13 - 20

Joint size factor (jL) composed of the length and continuity of the joint		Continuous joints	Discont. joints*)
Bedding or foliation partings	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 and should in these cases be treated separately*

Interlocking of rockmass structure (IL) (the ratings are based on the interlocking used in the GSI system)		
Very tight structure	undisturbed rock mass, well interlocked	IL = 1.3
Tight structure	undisturbed rock mass with some joint sets	**1**
Disturbed / open	folded / faulted with angular blocks	0.8
Poorly interlocked	broken with angular and rounded blocks	0.5

3 RMi in massive rock

In massive rock[1] the RMi value is found from

$$RMi = \sigma_c \times f_\sigma \quad (\text{where } f_\sigma > JP)$$

The massivity parameter, f_σ, represents the scale effect of the uniaxial compressive strength (which for intact rock samples or massive rock has a value of approximately $f_\sigma \approx 0.5$).

[1] Massive rock is here defines as rocks with low degree of jointing, i.e. block volumes are larger than a few m³

4 RMi in weakness zones

Weakness zones should in many cases be treated individually without using classification systems for support estimate. Support assessments for crushed zones may, however, be carried out using the support chart for blocky ground in Figure 6 and input parameters as for blocky ground. In zones with thickness less than approximately 20 m), the stability is influenced by the interplay between the zone and the adjacent rockmasses. Therefore, the stresses in such zones are generally lower than in the adjacent ground, which will reduce the effect of squeezing.

For crushed weakness zones, some typical RMi values for the most common conditions are given in Table 2. 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. The approximate RMi_z values are based on assumed representative block volumes for the various types of zones.

Table 2. Typical RMi values for various types of crushed zone (assumed common values)

Weakness zone	Average uniaxial compressive strength, σ_c: MPa	Average joint condition factor, *jC*	Approx. block volume, V_b: m^3	Approx. typical value, RMi_z	Approx. block diameter, D_b: m
Coarse fragmented zones	100	0.5	0.01	2	0.2
Small fragmented zones	100	0.5	0.0001	0.3	0.06
Clay-rich (simple) zones	80	0.1	0.01	0.3	0.2
Clay-rich (complex) zones	40	0.1	0.001	0.03	0.12
Clay zones*	0.1	0.1 (nominal)	1 cm^3 (nominal)	0.05	0.01

*For zones with mainly clay, approximate support estimates may be carried out using a nominal block volume of V_b = 1 cm^3 = 0.000001 m^3

5 Finding RMi graphically

The diagram in Figure 3 can be used to find JP when Vb and jC are known from field observations or estimated from site descriptions. The values or ratings of the input joint features incorporated in JP are shown in Table 1.

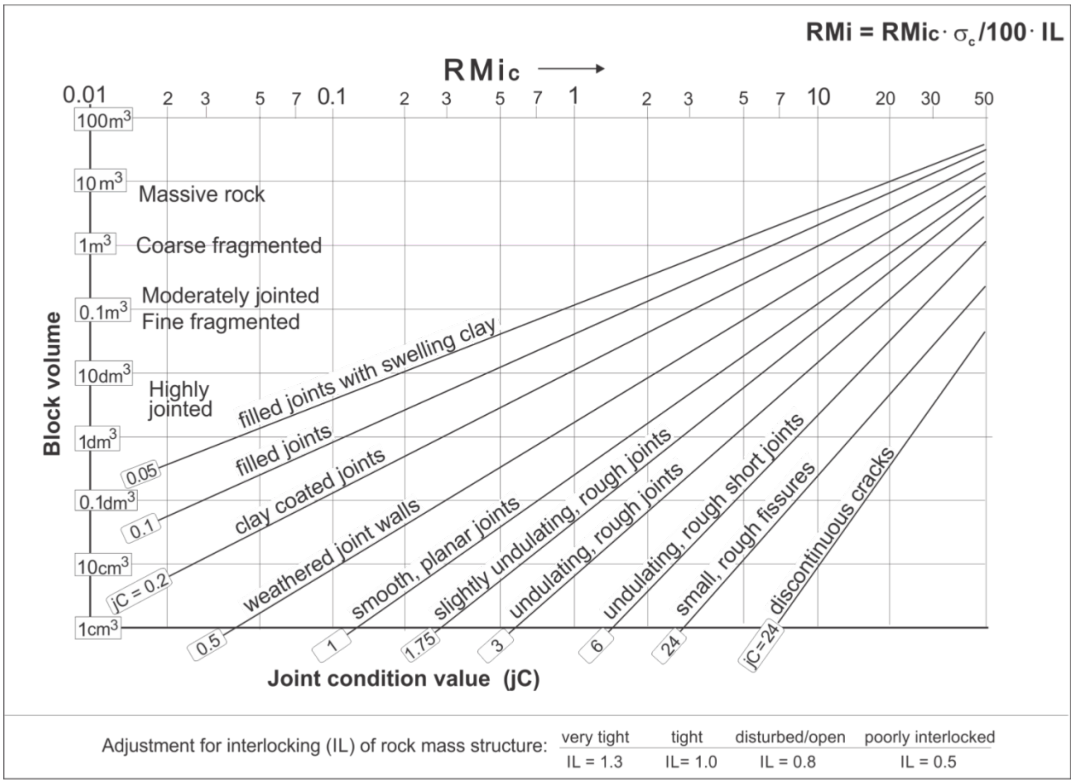

Figure 4. Diagram to find RMi

Example: With block volume Vb = 10dm³ and jC = 0.2 (for clay coated joints), RMic = 1. As the uniaxial compressive strength of rock in this example is σ_c = 150MPa and tight interlocking (IL = 1), the RMi = RMic x 150/100 x 1 = 1.5 (if the joints had been undulating, rough (jC = 3), RMic = 8 and the RMi = 12)

As RMi is a measure for the strength of a rock mass it can be applied in several applications. The main ones are shown in Figure 5.

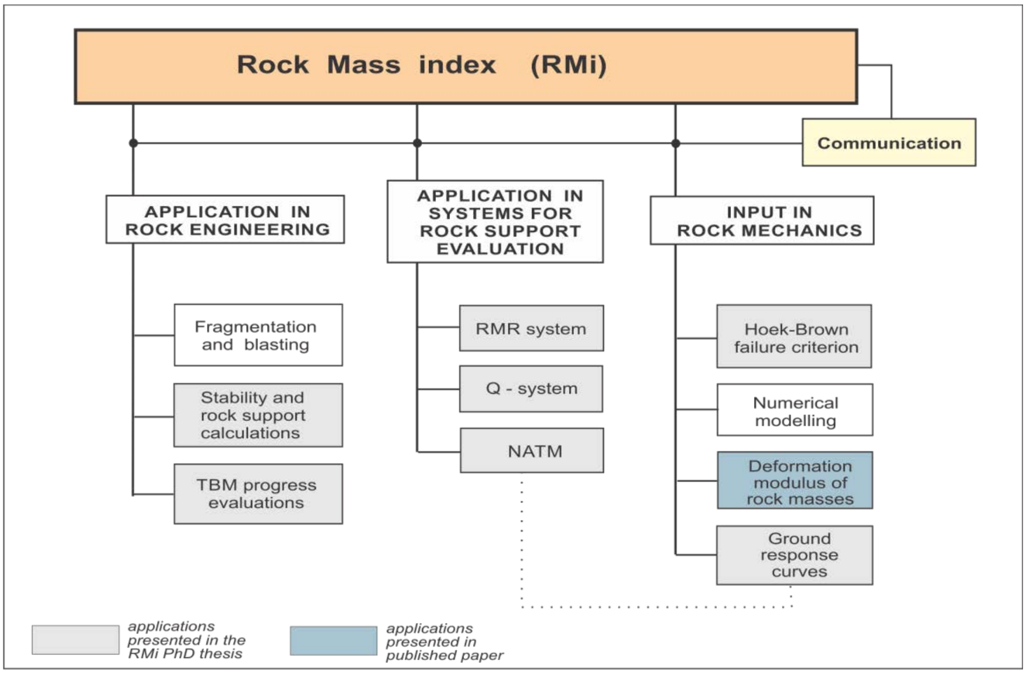

Figure 5. Applications of the RMi

The RMi value expresses the quality (approximate strength) of the rockmass (rock penetrated by joints) as a material in dry condition as in principle shown in Figure 2.

The site specific ground condition (similar to the Q-value) is expressed in the Ground condition factor as

$$Gc = RMi \times GW \times SL \times C$$

where GW = groundwater conditions given as the water inflow into the underground opening
SL = stress level
C = an adjustment factor for wall or inclined roof (as in a shaft)

Table 3. The adjustment parameters used in the RMi support method. Note that the use of unit values = 1 for normal or common conditions

K1	Roof and wall (C)					roof	45° *)	60° *)	wall
						1	2.2	3	5
	Stress level (SL)			very low	low	moderate	high	very high	**)
				0.1	0.5	1	1.5		
	Groundwater (GW)				influence on stability →	low	moderate	significant	
						1	2.5	5	
K2	Orientation of joints and zones (Co)				very favourable	favourable	slightly un-favourable	un-favourable	very un-favourable
					0.75	1	1.5	2	3
	Number of joint sets (Nj)	1 set	1+random	2 sets	2+random	3 sets	3+random	4 sets	4+random
		3	2	1.5	1.2	1	0.85	0.75	0.5
K1 = C x SL x GW; K2 = Co / Nj				*) roof in inclined shaft		**) in massive rock, very high stresses may cause rock burst (covered in the support for continuous ground)			

6 Support estimate by the RMi system in discontinuous (blocky) ground

The following two support parameters are used in the support chart in Figure 6:

I. The ground condition factor. The adjustments (K1) to RMi may be found from Table 3: RMi × K1
II. The geometrical factor, expressed as the size ratio between the size of the opening (tunnel etc.) and the rock blocks with adjustments for orientation and joint pattern (number of joint sets), given as

$$Sr = (D_t/D_b) \times (C_o/N_j) = (D_t/D_b) \times K2$$

where D_t = The diameter or span of the tunnel or cavern (m). (For walls, the wall height W_t is used instead of D_t).

D_b = The equivalent block diameter $Db \approx \sqrt[3]{Vb}$ (in metre).

C_o = An adjustment factor for orientation of the main joint set related to the tunnel or cavern, see Table 3.

N_j = an adjustment factor for the number of joint sets; and hence the freedom for the blocks to fall. Its ratings in Table 3 can also be found from $N_j = 3/n_j$, where n_j is 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; n_j = 2.5 for two sets plus random joints; etc.).

Table 4. Classification of joint orientation.

Term	In one wall		In opposite wall		In roof	
	Strike: °	Dip: °	Strike: °	Dip: °		Dip: °
Very favourable	≥ 70	All	> 60	All	All strikes	> 60
Favourable	< 70	≤ 20	30-60	All		45-60
Fair	50-70	> 20	≤ 30	≤ 45		30-45
	≤ 50	20-45	≤ 30	≤ 45		
Unfavourable	30—50	≥ 45	≤ 30	> 45		15-30
Very unfavourable	≤ 30	≥ 45	≤ 30	> 45		≤ 15

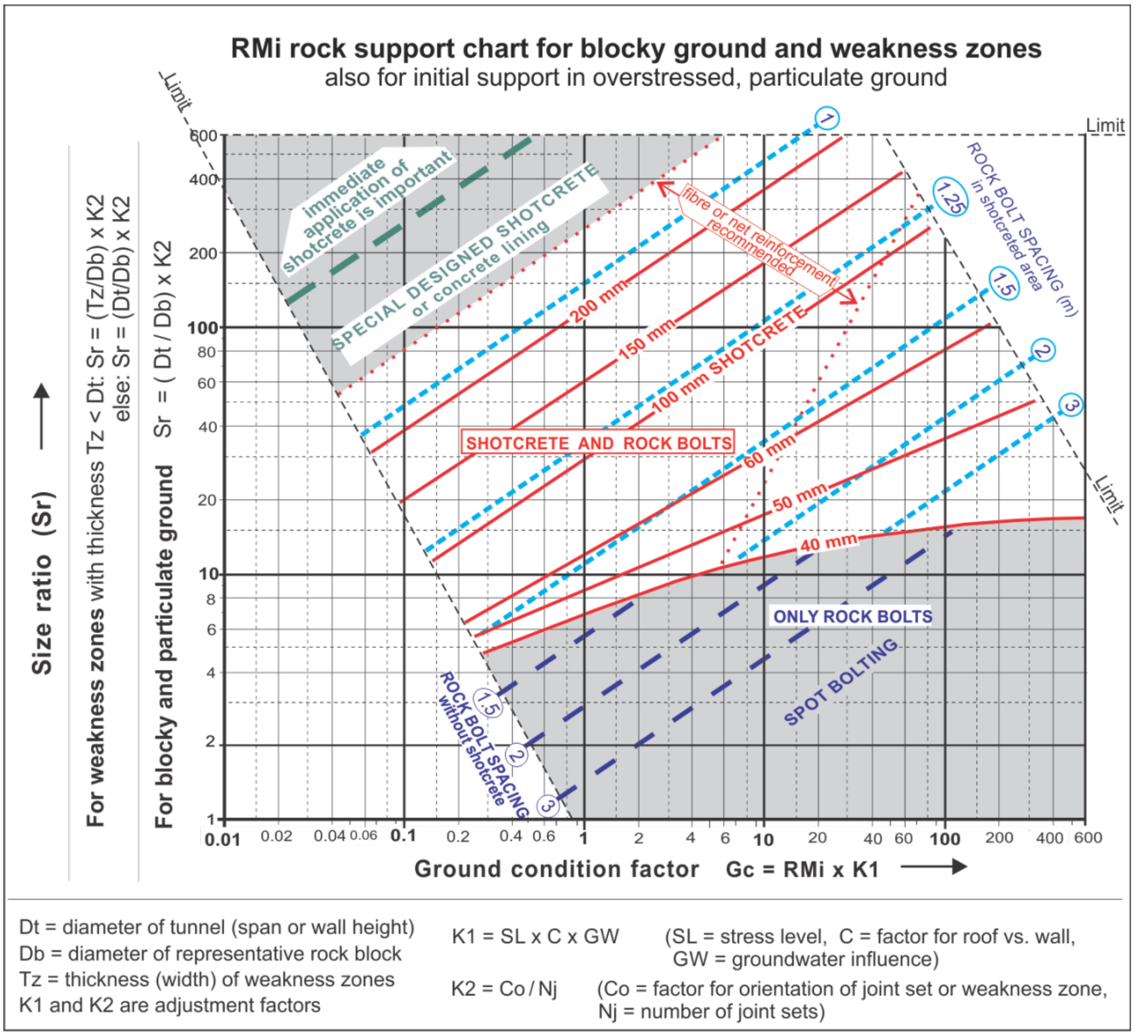

Figure 6. The RMi charts for estimates of rock support in blocky ground and weakness zones and continuous ground (massive or highly jointed)

The support chart in Figure 6 shows the estimated total amount and types of support. It is based on installed support in several tunnels in addition to the authors' experience from several tunnels and other underground drill and blast excavations in Scandinavia.

7 Support estimate by the RMi system in continuous ground

Massive ground (i.e. rockmass with few joints) in moderate stress conditions has generally stable conditions (see Figure 7), and does generally not need any support, except for some scaling work in drill and blast tunnels. Massive, 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, clayey rocks) and particulate rockmasses (broken rocks)
- *slabbing* (spalling) or *rock burst* in overstressed brittle, hard rocks (such as granite, quartzite, marble and gneiss).

Particulate materials (highly jointed rocks) generally require immediate support. Their initial behaviour is often similar to that of blocky ground, i.e. the support chart in Figure 6 can be used. In overstressed (*incompetent*) ground, time-dependent squeezing may, in addition to the initial instability, take place. However, for this type of ground the support chart in Figure 7 needs updating, when more experience in this type of ground is available; or separate calculations and convergence measurements should be performed.

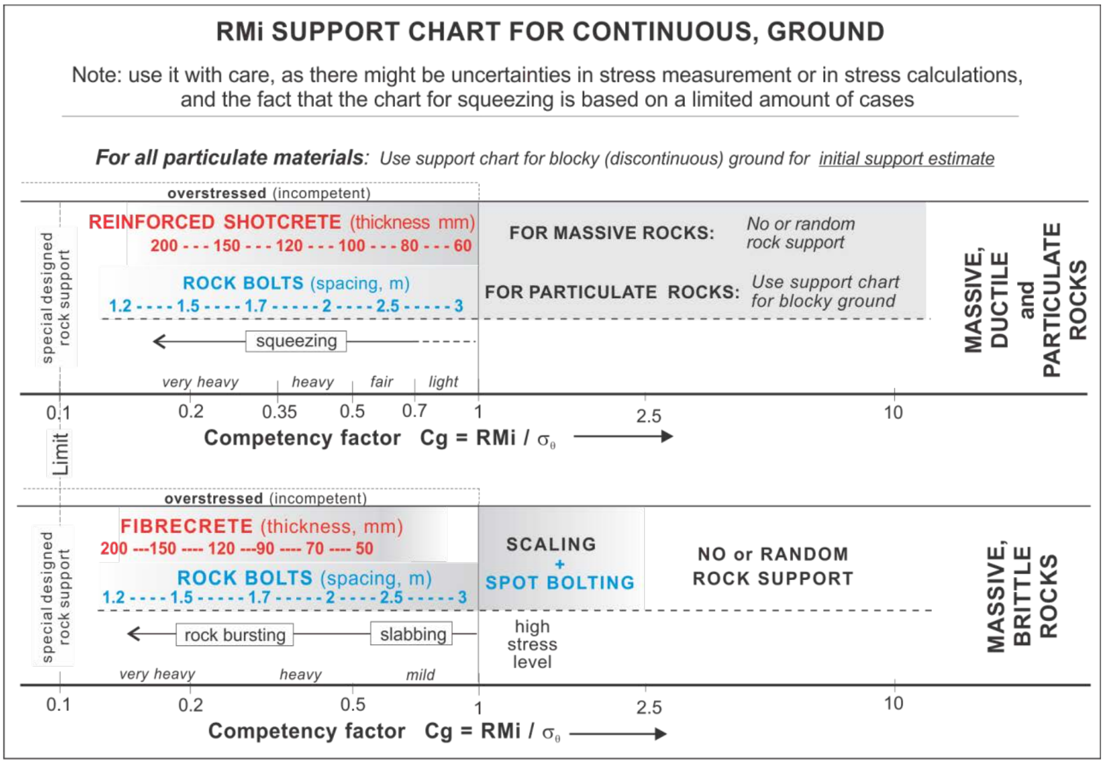

Figure 7. RMi support chart for continuous ground.

8 RMi input applied in Hoek-Brown faiure criterion for rockmasses

The criterion applies the two factors *m* and *s*. Hoek and Brown (1980) adapted the RMR and/or the Q classification systems as input of the ground conditions. However, it is easier to use the parameter JP of the RMi for this, as shown below.

As RMi is similar[2] as the unconfined *compressive strength* expressed in the criterion the factor *s* can be expressed by the jointing parameter (JP) as:

$$s = JP^2$$

In the beginning of the 1990s Hoek et al. introduced the ratio m_b / m_i, where the constant m_b is the same as *m* in the original criterion. It varies with the jointing and can be mathematically expressed as:

[2] The unconfined *compressive strength* of a rock mass according to the criterion is: $\sigma_{cm} = \sigma_c \times s^{½}$ and $RMi = \sigma_c \times JP$

a) for undisturbed rock masses $m_b = m_i \times JP^{0.64}$
b) for disturbed rock masses $m_b = m_i \times JP^{0.857}$

m_i varies with the intact rock and can be found from laboratory tests or from published tables (Hoek et al, 2002,or 2006, see reference list).

It should be born in mind that the Hoek-Brown failure criterion is only valid for continuous rock masses (Hoek and Brown, 1980), i.e. massive rock or highly jointed rock masses.

8.1 Papers presented on the RMi system

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

Palmström A.: Characterizing the strength of rock masses for use in design of underground structures. Int. Conf. on Design and Construction of Underground Structures, New Delhi, 1995.

Palmström A.: Characterizing rock burst and squeezing by the rock mass index. Int. Conf. on Design and Construction of Underground Structures, New Delhi, 1995.

Palmström A.: RMi - a system for characterizing rock mass strength for use in rock engineering. Journal of Rock Mechanics and Tunnelling Technology, Vol. 1, Number 2, 1995, pp. 69-108.

Palmström A.: The weighted joint density method leads to improved characterization of jointing. Int. Conf. on Recent Advances in Tunnelling Technology, New Delhi, India, 1996, pp. 9-14.

Palmström A.: Application of seismic refraction survey in assessment of jointing. Conference on Recent Advances in Tunnelling Technology, New Delhi, 1996.

Palmström A.: RMi - a new practical characterization system for use in rock engineering. Conf. Svenska Bergmekanikdagen 1996, Stockholm, pp. 39-63.

Palmström A.: The rock mass index (RMi) applied in rock mechanics and rock engineering. Journal of Rock Mechanics and Tunnelling Technology, Vol. 2, Number 1, 1996

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

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