RMi - a system for characterizing rock mass strength for use in rock engineering

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> *"Try always to combine theory and practice and to confront ideas and experience."*
> Leopold Müller (1982)

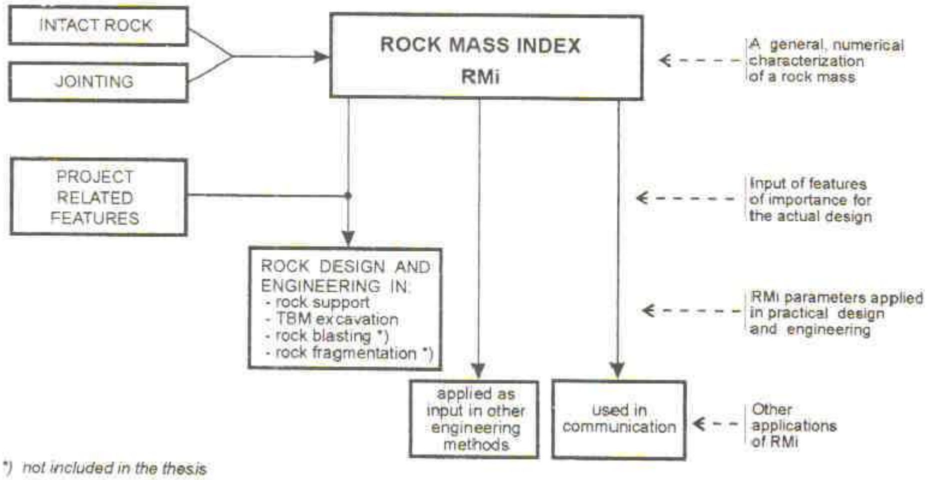
ABSTRACT

The RMi (rock mass index) system is based on well defined inherent rock mass parameters. Basically, it combines the compressive strength of intact rock and a jointing parameter composed of 4 jointing characteristics, namely block volume or density of joints, joint roughness, joint alteration, and joint size. From calibration of measured compressive strength of 7 large samples and 1 back analysis, the 4 jointing features have been combined to express the effect the jointing parameter has in reducing the strength of intact rock. Generally, the block volume forms the most important input to the RMi. Various methods to determine the block volume from different field measurements are described in the appendix. RMi can be applied for various purposes in rock mechanics and rock engineering, such as input to Hoek-Brown failure criterion and to ground reaction curves, assessment of rock support in tunnels and evaluation of the penetration rates of tunnel boring machines. These applications will be presented in a subsequent issue of this journal.

1 INTRODUCTION

> *"We are now faced with severe data limitations in our analyses of rock engineering problems."* Evert Hoek (1994)

The quotation above clearly stresses the need for better quality input data in rock mechanics and rock engineering. This paper, which is based on the original ideas presented by Palmström (1986), meets many of the requirements mentioned by Hoek (1994). The ideas have been further developed in a doctoral thesis "RMi - a rock mass characterization system for rock engineering purposes" (Palmström, 1995) worked out between 1990 and 1995. The main goal of the RMi (Rock Mass index) has been to improve the input data in rock engineering. It makes use of selected inherent parameters in the rock mass which are combined to express a relative rock mass strength index (see Fig. 1). A future paper in this journal will outline how the RMi can be applied in the various purposes shown in this figure.



*) not included in the thesis

Fig. 1. The principles of the Rock Mass index (RMi).

Construction materials such as concrete, most metals, wood, etc. used in civil and mining construction are characterized or classified according to their strength properties. This basic quality information of the material is used in engineering design for various construction purposes. In rock engineering, no such specific strength characterization of the rock mass is applied; the calculations are mostly applying various descriptions, classifications and/or unquantified experience.

The Rock Mass index (RMi) has been developed as a general strength characterization of the rock mass including only its inherent features. The intrinsic parameters of a rock mass *"are the same irrespective of place or circumstances. For this reason it was considered necessary to omit factors related to environment from the classification, although stress applications, pore-water and other influences have a pronounced effect on the behaviour of a rock in any given situation. Just as a structural engineer who is designing a steel structure will establish the stress distributions of the structure separately from the specifications of the steel, so in any specific problem in rock mechanics the environmental factors will be considered and established for that problem in addition to the determination of the nature or classification of the rock."* (Patching and Coates, 1968).

Based on the author's own experience and published papers in this context the following considerations have been important during the development of the RMi system:

- Relatively few input data should be included to arrive at a simple expression.
- Existing methods should be applied for the acquisition of geo-data where possible.
- Simple and practical methods for finding the input values should be preferred.
- Guidelines should be developed for adequate descriptions so that they can be "translated" to numerical values.[1]
- Correlations should be developed so that input data from various types of observations and measurements can be used.

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[1] Not included in this presentation

As the rock mass is an inhomogeneous material built up of smaller and larger blocks/pieces composed of rock material, a great variety exists both in the composition of the rock material and in the structure and occurrence of its discontinuities. The result is that the rock mass is a material exhibiting a wider range in structure, composition and mechanical properties than most other construction materials. Reliable tests of strength properties of such a complex material are impossible, or so difficult to carry out with today's technique, that rock engineering is based mainly on simplified input data determined from observations of the rock mass as described in Section 3 and 5.

2 THE STRUCTURE OF THE ROCK MASS INDEX, RMi

> *"The geotechnical engineer should apply theory and experimentation but temper them by putting them into the context of the uncertainty of nature. Judgement enters through engineering geology."* Karl Terzaghi, 1961

The presence of various defects (discontinuities) in a rock mass that tend to reduce the inherent strength of the rock, constitutes the main feature in its behaviour. This main principle of the Rock Mass index is expressed as

$$\mathbf{RMi} = \sigma_c \cdot \mathbf{JP} \qquad \text{eq. (1)}$$

where σ_c = the uniaxial compressive strength of the intact rock material;
JP = the jointing parameter. It is a reduction coefficient representing the effect of the joints in a rock mass. The value of JP varies from almost 0 for crushed rocks to 1 for intact rock.

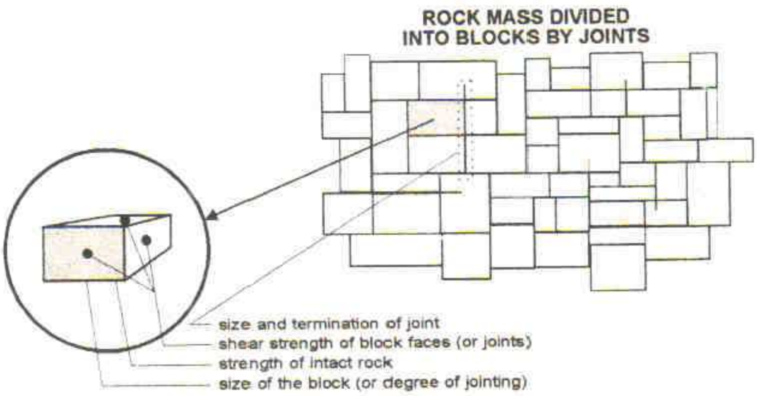

Fig. 2. An aggregate of blocks delineated by joints indicating the parameters selected for a general rock mass characterization

For jointed rock masses, Hoek et al. (1992) are of the opinion that the strength characteristics are controlled by the block shape and size as well as their surface characteristics determined by the intersecting discontinuities. Similar ideas have been set forth by Tsoutrelis et al. (1990), Matula and Holzer (1978), Patching and Coates (1968), and Milne et al. (1992). These considerations have been used in the selection of the following features in the jointing parameter (JP):

- the size of the blocks delineated by joints, measured as block volume;
- the shear strength of the block faces, measured as friction angle; and
- the size and termination of the joints, measured as length and continuity.

Combined with the compressive strength of intact rock it is considered that these parameters together, provide a fairly complete indication of the strength of a given rock mass. This is shown schematically in Fig. 2. Ideally, the block shape should also be selected as input parameter. However, as it has been important to keep the number of parameters to a minimum in order to obtain a simple and understandable scheme, it was found difficult to include the block shape.

2.1 The combination of the input parameters in RMi

The combination of the individual input components in RMi is shown in Fig. 3. The rock strength is measured and the jointing characteristics are measured or given ratings which are combined to deduce the strength of the rock mass aggregate. Results from large scale and field measurements of rock mass strengths have been used to develop a fairly realistic expression of RMi. This is described in Section 3.

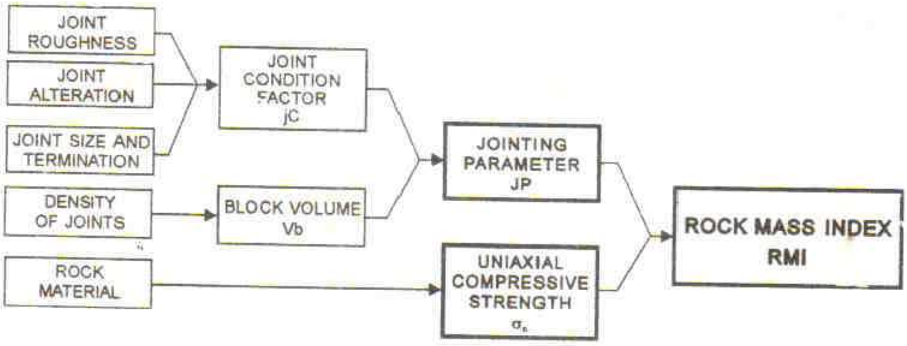

Fig. 3. The principle of the RMi characterizing the compressive strength of a rock mass.

The *uniaxial compressive strength* of intact rock (σ_c) can be determined from laboratory tests, or estimated from standard strength tables. The *jointing parameter* (JP) is a combination of the following features as shown in Fig. 3:

- The ***block volume*** (Vb) is a measure of the degree of jointing or the density (amount) of joints. As it is a 3-dimensional measure it indirectly also expresses of the overall geometry of the rock mass. It can be determined from various field measurements as further described in the Appendix.

  The ***joint condition factor*** (jC) represents the inter-block frictional properties. Barton et al. (1974) in their Q-system have chosen the *roughness and alteration factors* (Jr and Ja) to represent the importance of dilatancy and shear strength of joints. The ratio of the two parameters (Jr/Ja) expresses a fair approximation to the actual *shear strength* of the joint within normal variations of these factors (Barton et al, 1974; Barton and Bandis, 1990). It appears, therefore, logical to make use of the same ratings and combination of these parameters for the joint condition factor in the RMi.[2] A factor for the *joint size and termination* has been added as a size correction factor for joints. The reason for this is the fact that larger joints have a markedly stronger impact on the behaviour of a rock mass than smaller joints. In addition to the length, the termination (or continuity) of the joint has been included. The influence of a discontinuous joint, i.e. joints that terminate in massive rock, is much less as the failure plane must partly pass through intact rock. These important joint characteristics are combined as

$$\mathbf{jC = jL \cdot jR/jA} \qquad \text{eq. (2)}$$

where jL = the joint size and continuity factor.
jR = the joint roughness factor of the joint wall surface and joint planarity. (It is similar to Jr in the Q-system.)
jA = the joint alteration factor, representing the character of the joint wall, i.e. the presence of coating or weathering and possible filling. (It is similar to Ja in the Q system.)

The ratings of these factor can be found from various field observations and measurements as briefly described in Section 4.

3 CALIBRATION OF RMi FROM KNOWN ROCK MASS STRENGTH DATA

> *"The purpose of science is to simplify, not to complicate. The function of an engineering geologist, geotechnical or rock engineer is to examine and observe the complex variables of an area or project site and from this effort arrive at a set of simple, significant generalizations".* Douglas A. Williamson and C. Rodney Kuhn (1988)

It is practically impossible to carry out triaxial or shear tests on rock masses at a scale similar to underground excavations (Hoek and Brown, 1988). The numerous attempts made to overcome this problem by modelling generally suffer from the limitations and simplifications which have to be made in order to permit construction of the models. Consequently, the possibility of predicting the strength of jointed rock masses on the basis of direct in situ tests or of model studies is very limited. This problem resulted in that Hoek and Brown (1980), during development of the Hoek-Brown failure criterion for rock masses, had very few strength data available. Therefore, their criterion for jointed rock masses is based almost wholly on the laboratory tests carried out on Panguna andesite using the test results and description by Jaeger (1969).

For working out the RMi it has been possible to make use of some more test results on large samples of rock masses than the Panguna andesite. These include:

- clay schist, sandstone, and siltstone from various locations in Germany;
- granite from the Stripa test mine, Sweden;
- results from in situ tests of quartzitic sandstone in the Laisvall mine, Sweden; and
- back analysis from a large slide in quartzite and schist in the Långsele mine, Sweden.

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[2] The symbols Jr and Ja have been changed into jR and jA because some minor modifications have been made.

These known strength results from the tests and back analysis have - together with the rock mass characteristics - been used to determine a combination of Vb and jC into JP which expresses its reduction in strength of intact rock. The calibration has been performed in the following way:

1. From the known (measured) data on:
    - the uniaxial compressive strength the rock mass (σ_{cm}) and
    - the uniaxial compressive strength of the intact rock (σ_c),

   the value of the jointing parameter is found from $JP = RMi/\sigma_c = \sigma_{cm}/\sigma_c$
2. Numerical characterizations have been made of the joints and the block characteristics in the actual rock mass 'sample' tested to find
    - the block volume (Vb) and
    - the joint condition factor (jC) found from eq. (2).
3. These data shown in Table 1 have been plotted on the diagram in Fig. 4. Log. scales have been used both for the jointing parameter (JP) along the x-axis and for the block volume (Vb) along the y-axis. As joint spacing (i.e. block size) generally have an exponential distribution, the lines representing jC are expected to be straight in this log. - log. diagram.
4. From the values of block volume (Vb) and jointing parameter (JP) the position of the corresponding joint condition factor (jC) in Fig. 4 is found for each of the data sets. As a best fit to these data the lines representing jC have been drawn.

TABLE 1 THE RESULTS FROM LARGE SCALE TESTS ON ROCK MASSES

Sample	**Location**	**Rock type**	σ_c (MPa)	**jC**	**Vb**	**JP**
1	Panguna	andesite	265	4 - 6	2 - 6 cm^3	0.014
2	Stripa	granitic rock	200	1.5 - 2.5	5 - 15 dm^3	0.04
3	Laisvall mine	sandstone	210	0.75 -1	0.1 - 0.3 m^3	0.095
4	Långsele mine	grey schist and greenstone	110 - 160	0.2 - 0.3	8 - 20 dm^3	0.01
5a	Thüringer wald	clay-schist	55	1.5 - 2	5 - 10 dm^3	0.055 *)
5b	"	"	100	2 - 2.5	5 - 10 dm^3	0.08 **)
6	Hessen	sandstone/claystone	10.5/4.8	5 - 10 (?)	1 - 5 dm^3	0.17
7	Hagen	siltstone	65	3.5 - 4.5	5 - 10 dm^3	0.10

*) Tests parallel to schistosity **) Tests normal to schistosity

The jointing parameter can also be determined by the following expression which has been derived from the lines representing jC in Fig. 4:

$$JP = 0.2\sqrt{jC} \cdot Vb^{D} \qquad \text{eq. (3)}$$

where Vb = the block volume, given in m^3, and $D = 0.37\, jC^{-0.2}$
D has the following values:

jC =	0.1	0.25	0.5	0.75	1	1.5	2	3	4	6	9	12	16	20
D =	0.586	0.488	0.425	0.392	0.37	0.341	0.322	0.297	0.28	0.259	0.238	0.225	0.213	0.203

(The maximum value to be used for JP = 1)

For most conditions where $jC = 1 - 2$, the jointing parameter will vary between $JP = 0.2\ Vb^{0.37}$ and $JP = 0.28\ Vb^{0.22}$. For $jC = 1.75$ the jointing parameter is simply be expressed as

$$JP = 0.25 \sqrt[3]{Vb} \qquad \text{eq. (4)}$$

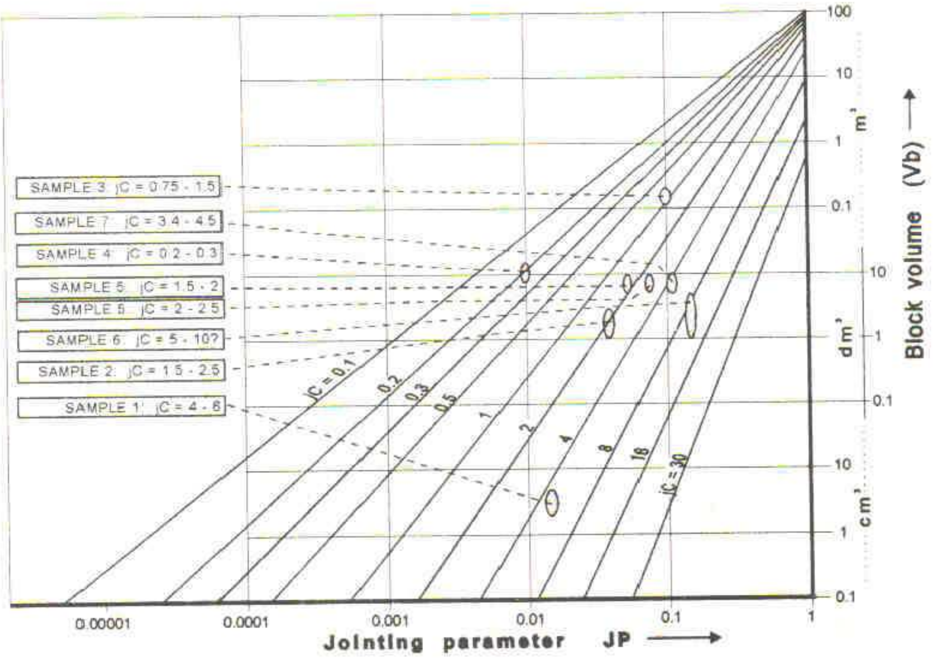

Fig. 4 The connection between block volume, joint condition factor and jointing parameter determined from plots of the data sets described in Table 1 (from Palmström, 1995)

As shown in Fig. 5 significant *scale effects* are generally involved when a 'sample' is enlarged from laboratory size to field size. After the calibration of JP described above, RMi is tied to large samples where the scale effect has be included. For massive rock masses, however, where $JP = 1$, the scale effect for the uniaxial compressive strength must be accounted for, as σ_c in such cases is related to a 50 mm sample size. Barton (1990) suggests that the compressive strength for 'field samples' with diameter (d, measured in mm) may be determined from

$$\sigma_c f = \sigma_c 50\ (50/d)^{0.2} = \sigma_c 50\ (0.05/Db)^{0.2} = \sigma_c 50 \cdot f_\sigma \qquad \text{eq. (5)}$$

where $\sigma_c 50$ = the uniaxial compressive strength for 50 mm sample size, and
$f_\sigma = (0.05/Db)^{0.2}$ is the scale factor for compressive strength.

Eq. (5) is valid for sample diameter up to a few metres, and may therefore be applied for massive rock masses. The block diameter (Db) can be found from

$$Db = \frac{\beta_o}{\beta} \sqrt[3]{Vb} = \frac{27}{\beta} \sqrt[3]{Vb} \qquad \text{eq. (6)}$$

Here β is a block shape factor as presented in the Appendix. More approximately it can be found from

$$Db = \sqrt[3]{Vb} \qquad \text{eq. (7)}$$

or where a pronounced joint sets occurs, Db = S1 the spacing in this set.

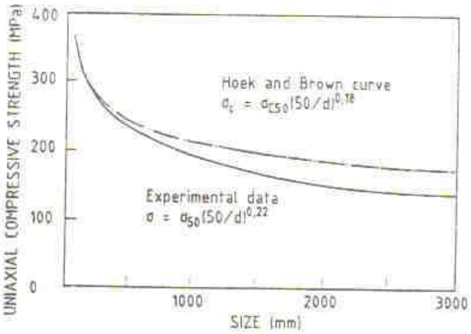

Fig. 5 Empirical equations for the scale effect of uniaxial compressive strength (from Barton (1990), based on data from Hoek and Brown, 1980 and Wagner, 1987). Barton suggests to apply a value of 0.2 for the exponent.

Fig. 6 shows the same diagram as Fig. 4 where also measurements other than block volume can be applied directly. These are located in the upper left part of the figure. Here, the volumetric joint count (Jv) for various block shapes (or numbers of joint sets) can be used instead of the block volume. Also RQD can be used with the limitations of the accuracy in this measure as mentioned in the Appendix.

TABLE 2 CLASSIFICATION OF RMi

CHARACTERIZATION		**RMi VALUE**
Term for RMi	Term for rock mass strength	
Extremely low	Extremely weak	< 0.001
Very low	Very weak	0.001 - 0.01
Low	Weak	0.01 - 0.1
Moderately high	Moderately strong	0.1 - 1
High	Strong	1 - 10
Very high	Very strong	10 - 100
Extremely high	Extremely strong	> 100

Having a general form, RMi is not a quality characterization, but merely as discussed in Section 5, a strength parameter. Its classification is presented in Table 2. Numerical values alone are seldom sufficient for characterizing the properties of a complex material such as a rock mass. Therefore, the RMi and its parameters should be accompanied by supplementary descriptions.

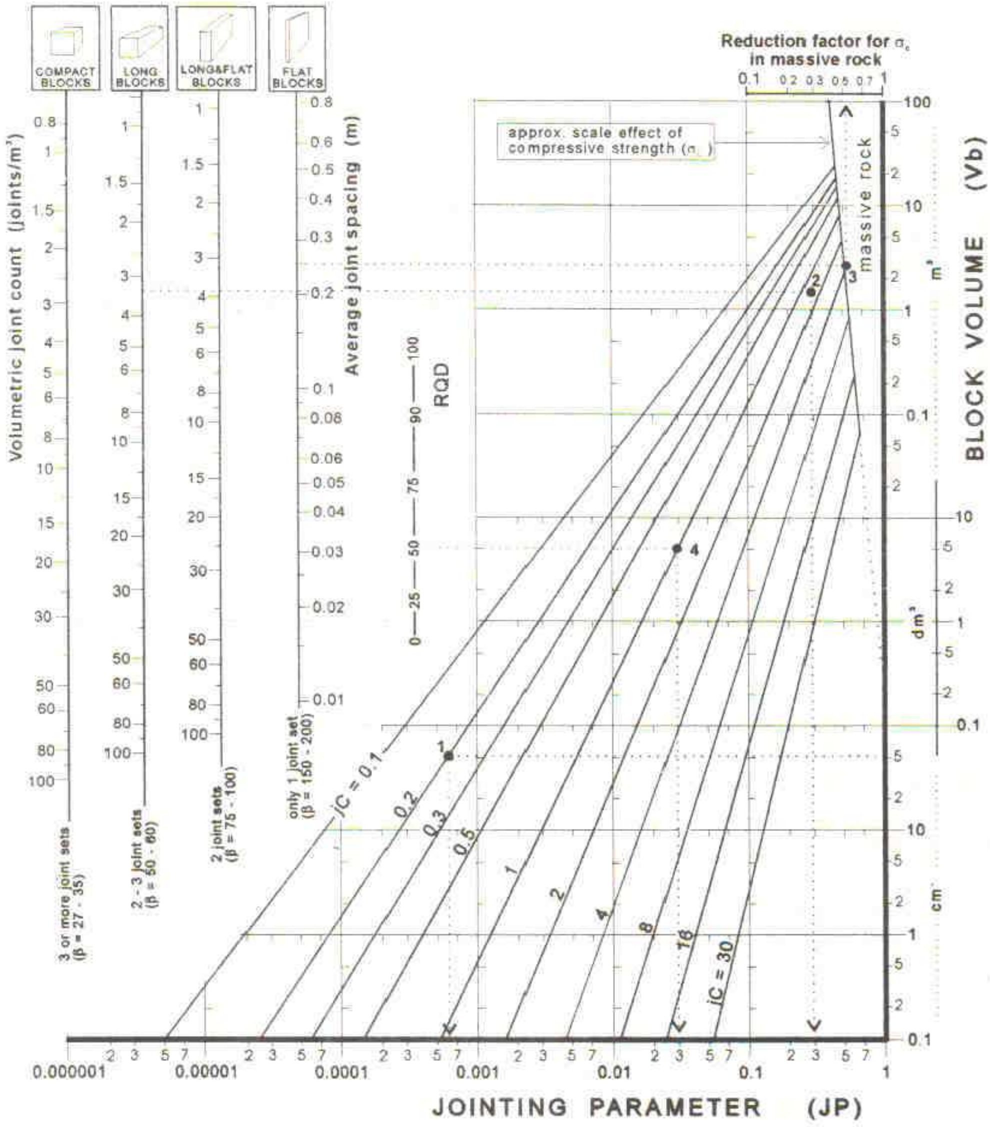

Fig. 6 Diagram for finding the value of the jointing parameter (JP) from the joint condition factor (jC) and various joint density measurements (Vb, Jv, RQD).

Examples shown in Fig. 6:

1: For Vb = 0.00005 m³ (50 cm³) and jC = 0.2, JP = 0.0006;

2: For Jv = 3.2 (long blocks) and jC = 1.5, JP = 0.3;

3: For joint spacing S = 0.2 (one joint set) and jC = 4, JP = 0.5 (determined by the scale effect);

4: For RQD = 50 and jC = 1, JP = 0.03.

4 THE INPUT PARAMETERS TO RMi

> *"The success of the field investigation will depend on the geologist's ability to recognise and describe in a quantitative manner those factors which the engineer can include in his analysis."* Douglas R. Piteau (1970)

The great spacial variability and large volumes involved in rock mass utilizations result in only a limited number of measurements can be made. Thus, *before construction* the subsurface has to be described by a limited number of imprecisely known parameters. Considerable uncertainties may be introduced from the interpretation and extrapolation made to describe the geological setting. Also, the fact that horizontal weakness zones and other features which do not outcrop, may be overlooked, is added to these errors. Although extensive field investigation and good quality descriptions will enable the engineering geologist to predict the behaviour of a tunnel more accurately, it cannot remove the risk of encountering unexpected features.
A good quality characterization of the rock mass will, however, in most cases except for wrong interpretations, improve the quality of the geological input data to be applied in evaluations, assessments or calculations and hence lead to better designs.

After the rock mass has been "*opened*" during excavation, the actual rock masses can be studied. In these cases the quality of the input data used in evaluations, calculations and modelling mainly depends on the way they are measured and characterized.

The large volumes involved also cause that the values of the input parameters generally have to be determined from observations rather than tests. An exception is the compressive strength of intact rock.

4.1 The compressive strength of intact rock (σ_c)

Several authors have stressed the importance of compressive strength of rock material as a classification parameter (Deere et al., 1969; Coates, 1964; Bieniawski, 1973, 1984, 1989; Piteau, 1970).

The uniaxial compressive strength of rock can be determined in the laboratory according to the specifications given by the ISRM. Other ways of assessing this strength is indicated in Fig. 7. Wet specimens are used where the location of interest is below the ground water table. It should be noted whether the strength value used represents wet or dry conditions. Where no indication is given, dry specimens have normally been tested. For anisotropic rocks, *the lowest compressive strength should be applied* which generally will be at a test direction 25 - 45° to the schistocity or layering.

The value of the uniaxial compressive strength (σ_c) related to 50 mm sample diameter, is applied directly in RMi. For massive rocks the scale effect of (σ_c) shown in eq. (5) and in Fig. 6 should be applied.

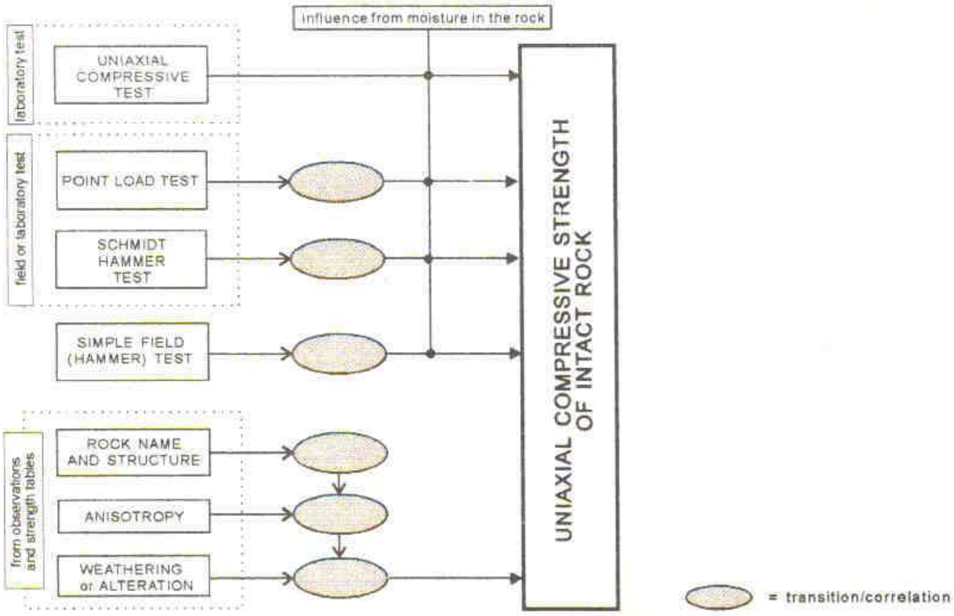

Fig. 7. Various methods to assess the uniaxial compressive strength of intact rock.

4.2 The block volume (Vb)

The discontinuities cut the rock masses in various directions and delineate a bulk unit, which is simply referred to as the block. The block volume is, therefore, intimately related to the degree of jointing. Each one of such blocks is more or less completely separated from the others by various types of discontinuities.

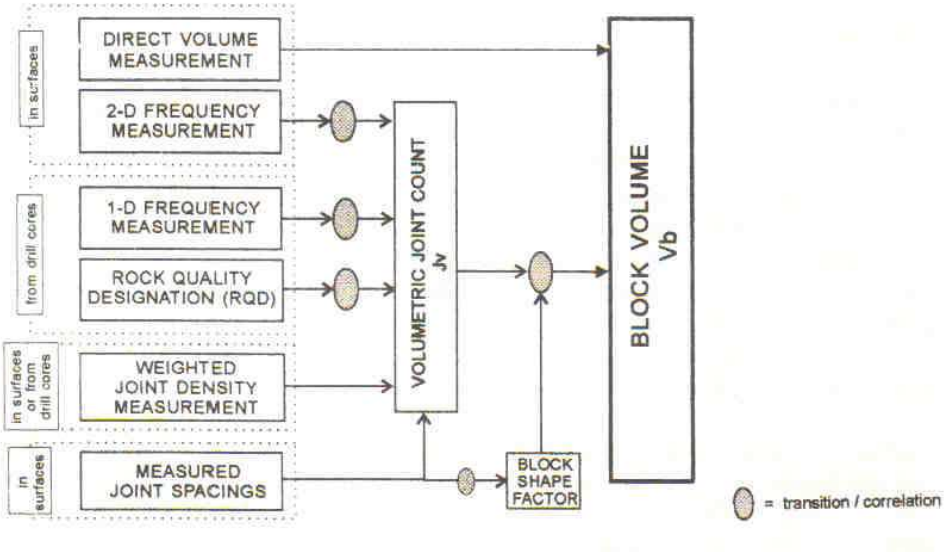

Fig. 8 Various methods to assess the block volume Vb outlined in the Appendix.

A great variation range will mostly be found between the sizes of the smaller and the larger blocks in a location; the characterization of the block volume should, therefore, indicate their volume range. Simplifications have often to be made during this measurement as it is not possible to measure all blocks and their dimensions. Block volume is, however, often the most important parameter in the RMi and emphasis should be placed on this measurement. Fig. 8 shows various ways for estimating the block volume described in the Appendix in which also a new, improved technique for block size registration - *the weighted joint density measurement* - is presented.

The variation range for three main methods for joint density characterization is shown in Fig. 9. RQD covers a significantly smaller range than the volumetric joint count (Jv) and block volume (Vb).

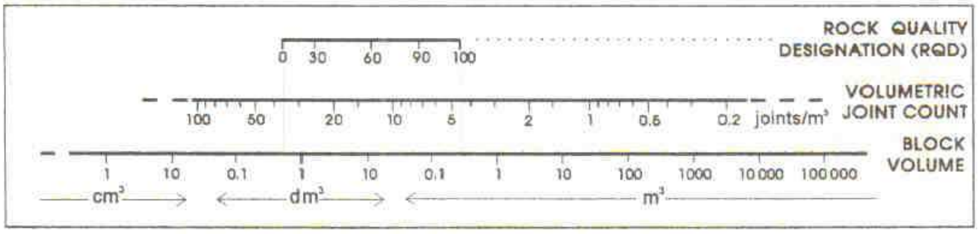

Fig. 9 A rough correlation between three methods for joint density measurements

4.3 The joint condition factor (jC)

The joint condition factor is meant to represent the friction properties of the block faces (i.e. joints) and the relative scale effect imposed by the joints. The works of Patton (1966) have emphasized the importance of the surface character of joints in determining their shear strength. Of particular importance was Patton's recognition that the friction forces resulting from asperities on the joint surfaces had to be overcome during deformation either by sliding or by shearing through them.

The characteristics of the joints, particularly where the walls are in direct rock to rock contact as in the case of unfilled joints, has a direct bearing on the strength of the rock mass (ISRM, 1978). The nature of *asperities*, particularly those of roughness and hardness, are likely to be dependent on the mineralogical and lithological make-up of the rock. Mineral *coatings* will affect the shear strength of discontinuities to a marked degree if the walls are planar and smooth (Piteau, 1970). The *distance* between the two matching joint walls controls the extent to which these can interlock. In the absence of interlocking, the shear strength of the joint is that of the filling material. As separation decreases, the asperities of the rock wall gradually become more interlocked, and both the filling and the rock material contribute to the shear strength. According to Barton et al. (1974) the function $\tan^{-1}(Jr/Ja)$ in the Q system is a fair approximation to the friction angle of the joint.

During several years of geological engineering practice the author has experienced that the *length and continuity* of joints often have a significant influence on the rock mass behaviour. Also Lardelli (1992) and Kleberger (1992) have stressed the importance of this features, in particular the difference between partings and joints.

From the ratings of the joint characteristics found in the subsequent tables the joint condition factor is found from the following expression:

$$jC = jL \cdot jR/jA = jL\ (js \cdot jw)\ /jA \qquad \text{eq. (8)}$$

Often, rough and inexpensive investigations are carried out where only an approximate estimate of the rock mass characteristics is sufficient. In such cases, there is often limited information of the parameters involved in the joint condition factor (jC). As each of the parameters included in this factor have given unit rating for common occurrences,[3] the RMi value can be found where some of or even all parameters in jC are absent using jC = 1. The RMi value will, of course, be less accurate in such cases where only input from the rock strength and the block size is applied.

The joint roughness factor (jR)

As mentioned, the roughness factor is similar to Jr in the Q system. Roughness here includes both the small scale asperities (smoothness) on the joint surface and the large scale planarity (waviness) of the joint plane. It has been found appropriate to divide the roughness into these two different features, as it is often easier to characterize them separately during the joint survey.

Surface *smoothness* or unevenness is the nature of the asperities in the joint surface which can be felt by touch. This is an important parameter contributing to the condition of joints; asperities that occur on joint surfaces interlock, if the surfaces are clean and closed, and inhibit shear movement along joint surfaces. Asperities usually have a wave length and amplitude measured in millimetres. The applicable descriptive terms are defined in Table 3.

TABLE 3 THE RATINGS OF THE SMOOTHNESS FACTOR (js).

TERM	**DESCRIPTION**	**rating of js**
Very rough	Near vertical steps and ridges occur with interlocking effect on the joint surface.	3
Rough	Some ridge and side-angle steps are evident; asperities are clearly visible; discontinuity surface feels very abrasive (like sandpaper grade approx. < 30)	2
Slightly rough	Asperities on the discontinuity surfaces are distinguishable and can be felt (like sandpaper grade approx. 30 - 300).	1.5
Smooth	Surface appear smooth and feels so to the touch (smoother than sandpaper grade approx. 300).	1
Polished	Visual evidence of polishing exists, or very smooth surface as is often seen in coatings of chlorite and specially talc.	0.75
Slickensided	Polished and often striated surface that results from friction along a fault surface or other movement surface.	0.6 - 1.5

The description is partly based on Bieniawski (1984) and Barton et al. (1974).

Most commonly the value of jC = 1 - 2. Using unit values of jC may generally be somewhat ative, i.e. 'on the safe side'.

Waviness of the joint wall appears as undulations from planarity. It can be found from a simplified undulation measurement given as

$$u = \frac{\text{measured max. amplitude (a)}}{\text{measured length along joint (L)}} \qquad \text{eq. (9)}$$

Because undulation measurements are time-consuming the waviness factor (jw) is often determined from visual observations based on Table 4.

The joint roughness factor is found from jR = js · jw, as is presented in Table 5. As the ratings of these parameters are based on the Q system, the joint roughness factor (Jr) in the Q system is, as mentioned, similar to jR.

Joint roughness includes the condition of the joint wall surface both for filled and unfilled (clean) joints. For joints with filling thick enough to avoid contact of the two joint walls, any shear movement will be restricted to the filling and the joint roughness will then have minor or no importance. Therefore, in the cases of filled joints the roughness factor is defined as jR = 1 (as in the Q system where Jr = 1).

The joint alteration factor (jA)

This factor is for a major part based on Ja in the Q-system. It represents both the strength of the joint wall and the effect of filling and coating materials. The strength of the surface of a joint is a very important component of shear strength and deformability where the surfaces are in direct rock to rock contact as in the case of unfilled (clean and coated) joints (Bieniawski, 1984, 1989). The strength of the joint surface is determined by the following:

- the condition of the surface in clean joints,
- the type of coating on the surface in closed joints,
- the type, form and thickness of filling in joints with separation.

When *weathering* or *alteration* has taken place, it can be more pronounced along the joint wall than in the block. This results in a wall strength that is often some fraction of what would be measured on the fresher rock found in the interior of the rock blocks. The state of weathering or alteration of the joint surface where it is different from that of the intact rock, is therefore essential in the characterization of the joint condition.

TABLE 4 THE RATINGS OF THE JOINT WAVINESS FACTOR (jw).

TERM FOR WAVINESS	undulation	**rating of jw**
Interlocking (large scale)		3
Stepped		2.5
Large undulation	u > 3 %	2
Small - moderate undulation	u = 0.3 - 3 %	1.5
Planar	u < 0.3 %	1

TABLE 5 RATINGS OF THE JOINT ROUGHNESS FACTOR (jR)

small scale smoothness *) of joint surface	large scale waviness *) of joint plane				
	planar	slightly undulating	strongly undulating	stepped	interlocking (large scale)
very rough	3	4	6	7.5	9
rough	2	3	4	5	6
slightly rough	1.5	2	3	4	4.5
smooth	1	1.5	2	2.5	3
polished	0.75	1	1.5	2	2.5
slickensided**)	0.6 - 1.5	1 - 2	1.5 - 3	2 - 4	2.5 - 5
	For irregular joints a rating of jR = 5 is suggested				

*) For filled joints: jR = 1 **) For slickensided joints the highest value is used for marked striations.

TABLE 6 RATINGS OF THE JOINT ALTERATION FACTOR (jA).

A. CONTACT BETWEEN THE TWO ROCK WALL SURFACES

TERM	DESCRIPTION	jA
Clean joints		
-Healed or welded joints	Softening, impermeable filling (quartz, epidote etc.)	0.75
-Fresh rock walls	No coating or filling on joint surface, except of staining	1
-Alteration of joint wall:		
1 grade more altered	One class higher alteration than the intact rock	2
2 grades more altered	Two classes higher alteration than the intact rock	4
Coating or thin filling		
-Sand, silt, calcite, etc.	Coating of friction materials without clay	3
-Clay, chlorite, talc, etc.	Coating of softening and cohesive minerals	4

B. FILLED JOINTS, PARTLY OR NO JOINT WALL CONTACT

TYPE OF FILLING MATERIAL	DESCRIPTION OF FILLING MATERIAL	Partly wall contact thin filling (< 5 mm*)) jA	No wall contact thick filling jA
-Sand, silt, calcite, etc.	Friction materials without clay	4	8
-Compacted clay	"Hard" clayey material	6	10
-Soft clay	Medium to low over-consolidation of filling	8	12
-Swelling clay	The material shows clear swelling properties	8 - 12	12 - 20

*) Based on joint thickness division in the RMR system (Bieniawski, 1973)

TABLE 7 RATINGS OF THE JOINT SIZE AND CONTINUITY FACTOR (jL).

JOINT LENGTH	TERM	TYPE	jL	
			continuous joints	discontinuous joints**)
< 0.5 m	very short	bedding/foliation partings	3	6
0.1 - 1.0 m	short/small	joint	2	4
1 - 10 m	medium	joint	1	2
10 - 30 m	long/large	joint	0.75	1.5
> 30 m	very long/large	(filled) joint , seam*) or shear*)	0.5	1

*) Often a singularity, and should in these cases be treated separately. **) Discontinuous joints end in massive rock

The alteration factor (jA) is, as seen in Table 6, somewhat different from Ja in the Q system. The values of Ja can be used - provided the alteration of the joint wall is the same as that of the intact rock material. The various classes of rock weathering/alteration can be determined from field observations as shown in Table 8.

TABLE 8 CHARACTERIZATION OF WEATHERING AND/OR ALTERATION (from Lama and Vutukuri, 1978).

Grade	Term	Description
I	**Fresh**	No visible signs of weathering. Rock fresh, crystals bright. Few discontinuities may show slight staining.
II	**Slightly**	Penetrative weathering developed on open discontinuity surfaces but only slight weathering of rock material. Discontinuities are discoloured and discoloration can extend into rock up to a few mm from discontinuity surface.
III	**Moderately**	Slight discoloration extends through the greater part of the rock mass. The rock material is not friable (except in the case of poorly cemented sedimentary rocks). Discontinuities are stained and/or contain a filling comprising altered materials.
IV	**Highly**	Weathering extends throughout rock mass and the rock material is partly friable. Rock has no lustre. All material except quartz is discoloured.Rock can be excavated with geologist's pick.
V	**Completely**	Rock is totally discoloured and decomposed and in a friable condition with only fragments of the rock texture and structure preserved. The external appearance is that of a soil.
VI	**Residual soil**	Soil material with complete disintegration of texture, structure and mineralogy of the parent rock.

The joint length and continuity factor (jL)

The *joint length* can be crudely quantified by observing the discontinuity trace lengths on surface exposures. It is often an important rock mass parameter, but is one of the most difficult to quantify in anything but crude terms. Frequently, rock exposures are small compared to the length of persistent discontinuities, and the real persistence can only be guessed. The size or the length of the joint is often a function of the thickness or separation of the joint, and can sometimes be evaluated from this feature, as has been described by Palmström (1995).

As the exact length of a joint seldom can be found, a solution is to estimate the size range of the joint. Often it is no problem to observe the difference between partings and medium or large sized joints during field observations. The factor jL also includes the effect of the *joint continuity*, which is divided into two main groups:

- continuous joints that terminate against other joints
- discontinuous joints that terminate in massive rock.

The ratings of jL shown in Table 7 can also be expressed as

$$\mathbf{jL = 1.5\ jc \cdot L^{-0.3}} \qquad \text{eq. (10)}$$

where L = the length of the joint in metre, and
jc = joint continuity (jc = 1 for continuous and jc = 2 for discontinuous joints)

5 DISCUSSION

5.1 Possible fields for application of RMi

The main purpose during development of the RMi has been to work out a system to characterize rock masses which is applicable in rock engineering. Being is a strength index RMi is suitable for application in rock engineering, design or other evaluations connected with utilization of rocks. The following application have been developed by Palmström (1995), (see Fig. 1):

- stability assessments for rock support analysis;
- capacity evaluation of tunnel boring machines (TBM);
- determination of rock mass behaviour in overstressed rock masses;
- RMi used for input to Hoek-Brown failure criterion and ground response curves
- RMi used for numerical characterization in the NATM system.

The RMi value cannot be used directly in classification systems as many of them are systems suitable for a particular purpose. Some of its input parameters are sometimes similar to those used in these classifications and may then be applied more or less directly. Finally, it should be mentioned that the system for characterizing block geometry (volume, shape factor, angles) may be of use in numerical models.

5.2 Limitations of the RMi

The RMi is meant to express the relative variations in the strength of a rock mass. As determination of the strength of an in situ rock mass by laboratory type testing for many reasons is not practical, the RMi makes use of input from geological observations and test results on individual rock pieces or rock surfaces.

RMi is restricted to expressing only the compressive strength. Hence, it has been possible to arrive at a simple expression, contrary to, for example, the general failure criterion for jointed rock masses developed by Hoek and Brown (1980) and Hoek et al. (1992). Because simplicity has been preferred in the structure and in selection of parameters in RMi; it is clear that such an index may result in inaccuracy and limitations, the most important of which are connected to:

A. *The range and types of rock masses covered by the RMi.*
Both the intact rock material as well as the joints exhibit great directional variations in composition and structure which results in an enormous range of properties for a rock mass. It is, therefore, not possible to characterize all these combinations in one, single number. However, it should be added that the RMi probably characterizes a wider range of materials than most other numerical characterization and classification systems.

B. *The accuracy in the expression of the RMi.*
The value of the jointing parameter (JP) is calibrated from a few large scale compression tests. Both the evaluation of the various factors (jR, Ja and Vb) in JP and the size of the samples tested - which in some of the cases did not contain enough blocks for being representative for a continuous rock mass - have resulted in that certain errors are connected to the expression developed for the JP. In addition, the test results used were partly made on dry, partly on wet samples which further

may have reduced the accuracy of the data used. The value of RMi found can, therefore, be very approximate. In some cases, however, the errors in the various parameters may partly cancel out.

C. *The effect of combining parameters that vary in range.*
The input parameters to the RMi express generally a certain range of variation related to changes in the actual representative volume of the rock mass. The combination of such ranges in a single RMi value may cause additional errors.

The result of the foregoing is that RMi in many cases will give an inaccurate value for the strength of such a complex assemblage of different rocks and defects comprising a rock mass. For this reason, the RMi is regarded as a *relative* expression of the rock mass strength. It should, therefore, preferably be used in communication and characterization, or where continuous rock masses are involved.

RMi can, as mentioned, seldom be directly applied in engineering and design. Some modification or supplementary adjustments have generally to be made as where RMi is used in rock support assessments and in other applications. This will be shown in a subsequent paper that will outline the practical use of RMi.

5.3 Other similar rock mass characterization methods

The RMi has been developed during a process that has involved a critical examination of rock mass characteristics and available literature. The main philosophy has been to take account of the effect of discontinuities in reducing the strength of intact rock. Earlier, a similar approach to a strength characterization of rock masses has been proposed by Hansagi (1965, 1965b), who introduced a reduction factor comparable to the jointing parameter (JP) to arrive at an expression for the *compressive strength* of the rock mass, expressed as

$$\sigma_{mc} = \sigma_c \cdot C_g \qquad \text{eq. (11)}$$

where σ_c = uniaxial compressive strength of intact rock.

C_g is a reduction factor which Hansagi named 'gefüge-factor' (joint factor) being "*representative for the jointed effect of a rock mass*". This factor consists of two inputs: a factor for the "structure of jointing" (core length), and a scale factor. Hansagi (1965b) mentions that the value of C_g is 0.7 for massive rock and 0.47 for jointed rock (containing small joints) for two test locations in Kiruna, Sweden. Hansagi did not, however, - as far as the author knows - publish more on his method.

From Fig. 10 it is seen that the expression for the RMi is similar in structure to the expression of unconfined *compressive strength of rock masses* (σ_{cm}), which is a part of the Hoek-Brown failure criterion for rock masses expressed as

$$\sigma_{cm} = \sigma_c \cdot s^{1/2} \qquad \text{eq. (12)}$$

Here σ_c = the uniaxial compressive strength of the intact rock material,
s = an empirical constant. The value of s ranges from 0 for jointed rock masses to 1 for intact rock. The value of s is found from the RMR or the Q classification system as described by Hoek (1983), Hoek and Brown (1980, 1988), and Wood (1991).

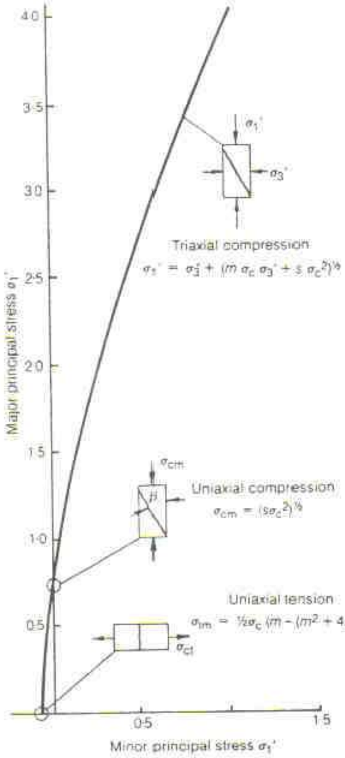

Fig. 9. The uniaxial compressive strength of the rock mass is a special mode of the Hoek-Brown failure criterion for rock masses (from Hoek, 1983).

Thus, the connection between the jointing parameter (JP) and the constant s in the Hoek-Brown failure criterion is $JP = s^{½}$. s is more accurately found using JP than the existing classification systems as JP involves only features that have a direct impact on s.

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APPENDIX

METHODS TO DETERMINE THE BLOCK VOLUME

The block size is considered the most important input parameter in the RMi. Therefore the accuracy of this measure has a significant impact on the quality of RMi. In this Appendix, methods are described for estimating the block volume from various types of observations and measurements.

The block size is a result of the detailed jointing in a rock mass formed mainly by the small and moderate joints (Selmer-Olsen, 1964). The block dimensions are determined by joint spacings and the number of joint sets. Individual or random joints and possible other planes of weakness may further influence the size and shape of rock blocks. Impact from blasting may also influence the block size.

A1 TYPES OF BLOCK VOLUME AND JOINT DENSITY MEASUREMENTS

Different methods have been developed over the years to measure the quantity or density of joints in the rock mass. The selection of the method(s) to be applied at an actual site is often a result of the a) availability to observe the rock and its jointing in an exposure, b) the requirement to the quality of the collected data, c) the type and cost of the investigation or survey, and d) the experience of the engineering geologist.

If all the blocks in a rock mass could be measured or "sieved" a block size distribution can be found similar to the particle sizes distribution of a soil. As the joint spacings generally vary greatly, the difference in size between the smaller and the larger blocks can be significant, refer to Fig. A.1. Therefore the characterization of block volume should rather be given as an interval than as a single value.

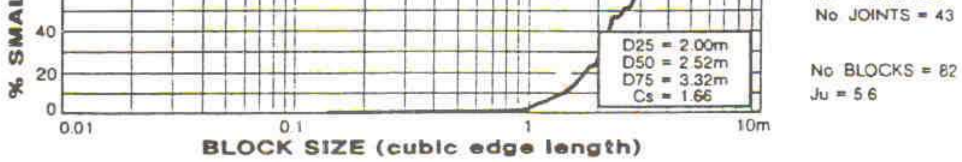

Fig. A.1 Example of a block size distribution curve for a rock mass (from Milne et al 1992)

Where less than 3 joint sets occur, it is often expected that defined blocks will not be found. However, in many cases the presence of random joints or other weakness planes may contribute so that definite blocks occur. Also where the jointing is irregular, or many of the joints are discontinuous, it can sometimes be difficult to recognize the actual size and shape of individual blocks. From time to time the block size and shape therefore have to be determined from some sort of simplifications where an *equivalent block volume* is used as described in Section A8.

TABLE A1 CLASSIFICATION OF BLOCK VOLUME RELATED TO PARTICLE SIZE (VOLUME) FOR SOILS

TERM FOR DENSITY OF JOINTS	**TERM FOR BLOCK SIZE**	**block volume$^{*)}$ (Vb)**	**TERM FOR SOIL PARTICLE**	**approx. particle volume**
			coarse sand	0.1 - 5 mm^3
			fine gravel	5 - 100 mm^3
Extremely high	Extremely small	$<$ 10 cm^3 . . .	medium gravel	0.1 - 5 cm^3
Very high	Very small	10 - 200 cm^3 . . .	coarse gravel	5 - 100 cm^3
High	Small	0.2 - 10 dm^3 . . .	cobbles	0.1 - 5 dm^3
Moderate	Moderate	10 - 200 dm^3 . . .	boulders	5 - 100 dm^3
Low	Large	0.2 - 10 m^3. . .	blocks	$>$ 0.1 m^3
Very low	Very large	10 - 200 m^3		
Extremely low	Extremely large	$>$ 200 m^3		

$^{*)}$ $Vb = 0.58\ Db^3$ has been applied in the correlation between particle diameter and volume.

Observations made on surfaces or on drill cores are most commonly used to characterize the density or amount of joints in a rock mass. The most common are:

A. Surface observations, made as:
  - Field registration of block volume,
  - Joint spacing or frequency measurements
  - 3-D jointing density (as for the volumetric joint count, Jv)
  - 2-D jointing density (as for the number of joints in a surface)
  - 1-D jointing density (as for the number of joints along a scanline)

B. Drill core logging, recorded as:
  - RQD (Rock Quality Designation)
  - 1-D jointing density (the number or length of core pieces)

C. Geophysical measurements; the jointing density is mainly estimated from
  - Sonic velocities recorded by refraction seismic measurements.[4]

Some of the measurements that can be made on rock outcrops, excavated surfaces and drill cores are shown in Table A2. The correlations between the various measurements, which are shown in this appendix, enable block volume to be determined from different sources.

As the blocks generally have varying sizes and shapes, the measurements of characteristic dimensions can be time-consuming and laborious. To remedy this, easy recognizable dimensions of the blocks and simple correlations between the different types of jointing measurements have been worked out.

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[4] Not shown in this presentation.

TABLE A2 THE MAIN TYPES OF OBSERVATIONS AND MEASUREMENTS WHICH CAN BE USED TO ESTIMATE THE JOINT DENSITY AND THE BLOCK SIZE.

PARAMETER MEASURED	**SURFACE OBSERVATIONS**		**DRILL CORE or SCANLINE OBSERVATIONS**
	3-D registrations	2-D registrations	1-D registration
BLOCK SIZE	Block volume estimated from defined joint spacings (and angles between joint sets).		
- Block volume	Block volume estimated from Jv (see eq. (A-5))		
	Block volume measured in the field.		Block volume of drill core fragments[1].
- Equivalent block diameter		Estimated block diameter (Ib) according to ISRM (1978).	Indirect block diameter measure (given as RQD).
DEGREE OF JOINTING		Measured number of joints intersecting an area.	Measured number of joints intersecting a line.
- Joint frequency	Registration of the volumetric joint count (Jv).	*Weighted joint density measurement.	*Weighted joint density measurement.
			Density of joints estimated from refraction seismic velocities.[2]
- Joint spacing	Measured spacings for each joint set. (Normally used to express the block size (Vb) or the volumetric joint count (Jv)).	Measured mean joint spacings related to a plane.	Measured length of core bits along a line (fracture intercept (ISRM, 1978))

* Measurement introduced by Palmström (1995), see Section A7.

[1] The block volume refered to has the size of core diameter or less (gravel or pebble size)

[2] Not included in this presentation

A1.1 Block volume measurements

The block volume is intimately related to the density of joints, to the intensity, or to the degree of jointing. Each one of such blocks is more or less completely separated from the others by various types of discontinuities. The greater the block size, the smaller will be the number of joints penetrating the rock masses. Hence, there is an inverse relationship between the block volume and the number of joints.

Especially where irregular jointing occurs, it is time-consuming to measure all (random) joints in a joint survey. In such cases, as well as for other jointing patterns, it is often much quicker - and also more accurate - to measure the block volume directly in the field. Where three or more regular joint sets occur, the block volume can easily be found from the joint spacings.

For each of the joint sets the spacings vary within certain ranges. The block volume in a rock mass should be characterized by a modal size together with the range i.e. typical largest and smallest block indices. (ISRM, 1978; Burton, 1965). Ideally, the range should be between 25% and 75% of the block sizes. This is similar to what is often practiced to characterize particle distribution of soils, Fig. A.1.

Block volume found from joint spacings

For three or more joint sets the block volume is determined by the jointing pattern and joint spacings in each set. Individual or random joints may influence the type and shape of blocks. For less than 3 joint sets the block volume is often determined by the random joints in addition to the spacings in the joint sets.

The volume of a block determined by 3 joint sets is given as

$$Vb = \frac{S1 \cdot S2 \cdot S3}{\sin\gamma 1 \cdot \sin\gamma 2 \cdot \sin\gamma 3} = \frac{Vb_0}{\sin\gamma 1 \cdot \sin\gamma 2 \cdot \sin\gamma 3} \qquad \text{eq. (A-1)}$$

where $\gamma 1$, $\gamma 2$, $\gamma 3$ are the angles between the joint sets, and
S1, S2, S3 are the spacings between the individual joints in each set.
Vb_o is the volume where joints intersect at right angles.

For a rhombohedral block with two angles between 45 - 60°, two between 135 - 150° and the last two being 90°, the volume will be $Vb = 1.3\ Vb_o$ to $Vb = 2\ Vb_o$ Compared to the variations caused by the joint spacings, the effect from the intersection angle between joint sets is relatively small.

As earlier mentioned, no defined blocks will theoretically be formed where only one or two joint sets occur and where random joints are very few or absent. Section A8 outlines methods to establish an equivalent block volume in such cases.

Block volume measured directly in situ or in drill cores

Where the individual blocks can be observed in a surface, their volume can be directly measured from relevant dimensions by selecting several representative blocks and measuring their average dimensions (ISRM, 1978). From this, the range in the block volumes can be determined.

For small blocks or fragments having volumes in dm^3 or less, this method of block volume registration is often beneficial as it is much easier to estimate volume compared to all the measurements which have to be made to include all joints. Block volume can also be found in drill cores where small fragments have been formed as a result of crushed rock. The laborious and time-consuming measurements of the many joints in the core in such cases is often a main reason for using a simple method for core logging like the RQD. By applying block volume in characterization, a more accurate registration of the joint density or frequency is achieved, especially if it is combined with the weighted joint density measurement method described in Section A7.

Also where irregular jointing occurs it may be much more convenient to directly measure the block size by eye during field inspection than to record all the joints and their locations.

A2 THE VOLUMETRIC JOINT COUNT (Jv)

The volumetric joint count, Jv, has been described by Palmström (1982, 1985, 1986) and Sen and Eissa (1991, 1992). It is a measure for the number of joints within a unit volume of rock mass, defined by

$$\mathbf{Jv = \Sigma\ (1/S_i)} \qquad \text{eq. (A-2a)}$$

where S = the joint spacing in metres for the actual joint set.

Also random joints can be included by assuming a 'random spacing' for these. Experience indicates that this should be set to Sr = 5 m; thus, the volumetric joint count can be generally expressed as

$$\mathbf{Jv = \Sigma\ (1/S_i) + Nr/5} \qquad \text{eq. (A-2b)}$$

where Nr = the number of random joints adjusted for their length (see Section A5.1).

Jv can easily be calculated from joint observations, since it is based on common measurements of joint spacings or frequencies. In the cases where mostly random or irregular jointing occur, Jv can be found by counting all the joints observed in an area of known size, see Paragraph A5.1. Table A3 shows the classification of Jv.

TABLE A3 CLASSIFICATION OF THE VOLUMETRIC JOINT COUNT (Jv)
(revised after Palmström, 1982)

TERM FOR JOINTING	TERM FOR Jv	Jv
massive	extremely low	< 0.3
very weakly jointed	very low	0.3 - 1
weakly jointed	low	1 - 3
moderately jointed	moderately high	3 - 10
strongly jointed	high	10 - 30
very strongly jointed	very high	30 - 100
crushed	extremely high	> 100

2.1 Block volume (Vb) estimated from the volumetric joint count (Jv)

Since both the volumetric joint count (Jv) and the size of blocks in a rock mass vary according to the degree of jointing, there exist a correlation between them (Palmström 1982). Jv varies, however, with the joint spacings, while the block size also depends on the type of block as shown in Fig. A2. A correlation between the two parameters has therefore, to be adjusted or corrected for the block shape and the angle between the joint sets, as shown below.

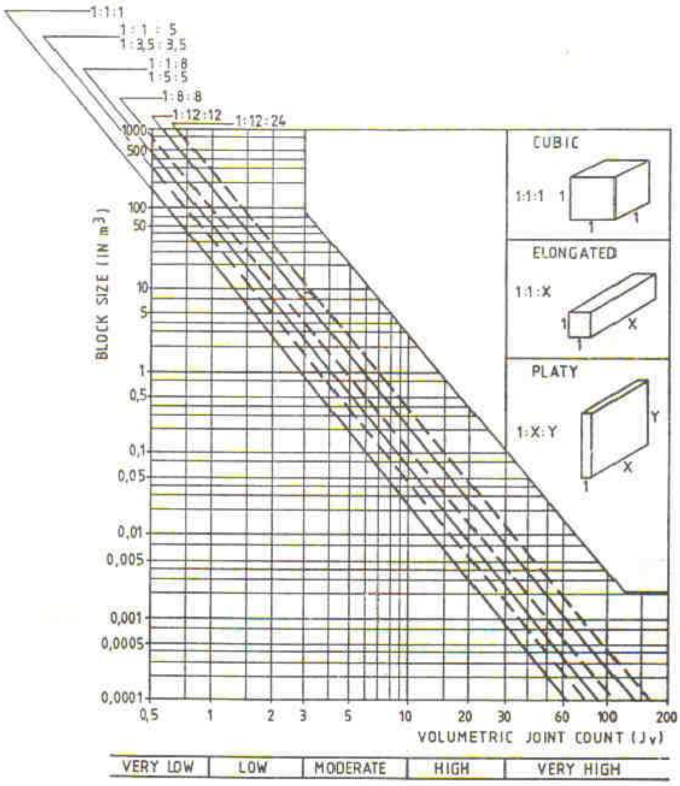

Fig. A.2. The relation between block size and volumetric joint count, Jv for various block shapes (from Palmström, 1982).

The volumetric joint count determined from three joint sets intersecting at right angles, is expressed as

$$\begin{aligned} Jv &= \frac{1}{S1} + \frac{1}{S2} + \frac{1}{S3} = \frac{S2 \cdot S3 + S1 \cdot S3 + S1 \cdot S1}{S2 \cdot S2 \cdot S3} \\ &= \frac{S2 \cdot S3 + S1 \cdot S3 + S1 \cdot S2}{Vb_o} \end{aligned} \qquad \text{eq. (A-3)}$$

where S1, S2, S3 are the joint spacings.

Using $Vb_o = Vb \cdot \sin\gamma 1 \cdot \sin\gamma 2 \cdot \sin\gamma 3$ for intersections at other angles, eq. (A-3) can be expressed as

$$Jv = \frac{S2 \cdot S3 + S1 \cdot S3 + S1 \cdot S2}{Vb \cdot \sin\gamma 1 \cdot \sin\gamma 2 \cdot \sin\gamma 3} \qquad \text{eq. (A-4a)}$$

By applying the ratio $\alpha 2 = S2/S1$, and $\alpha 3 = S3/S1$, provided $S3 > S2 > S1$, and $S1^3 = Vb_o/(\alpha 2 \cdot \alpha 3)$ eq. (A-4a) can also be expressed as

$$\begin{aligned} Jv^3 &= \frac{(\alpha 2 + \alpha 2 \cdot \alpha 3 + \alpha 3)^3}{(\alpha 2 \cdot \alpha 3)^2} \cdot \frac{1}{Vb \cdot \sin\gamma 1 \cdot \sin\gamma 2 \cdot \sin\gamma 3} \\ &= \frac{\beta}{\sin\gamma 1 \cdot \sin\gamma 2 \cdot \sin\gamma 3} \end{aligned} \qquad \text{eq. (A-4b)}$$

The factor

$$\beta = \frac{(\alpha 2 + \alpha 2 \cdot \alpha 3 + \alpha 3)^3}{(\alpha 2 \cdot \alpha 3)^2} \qquad \text{eq. (A-5)}$$

which depends mainly on the differences between joint spacings has been named the *block shape factor*. It is further described in Section A3.

From eq. (A-4b) the block volume is

$$Vb = \beta \cdot Jv^{-3} \cdot \frac{1}{Vb \cdot \sin\gamma 1 \cdot \sin\gamma 2 \cdot \sin\gamma 3} \qquad \text{eq. (A-6a)}$$

In the cases where all angles are 90° between the block faces, the block volume is given as

$$Vb_o = \beta \cdot Jv^{-3} \qquad \text{eq. (A-6b)}$$

As the volumetric joint count (Jv) by definition takes into account in an unambiguous way all the occurring joints in a rock mass, it is often appropriate to use, Jv, in the correlation between jointing frequency registrations and block volume estimates (Palmström, 1982). Important in these is the block shape factor β which is included in all equations to estimate the block volume.

3 BLOCK TYPES AND SHAPES

Methods to determine the block shape factor β in eq. (A-5) and its characterization are described in this section. The *type and shape* of blocks are determined by:

- the number of joint sets;
- the difference in joint spacings; and
- the angles between the joints or joint sets.

For a rock mass with 3 joint sets intersecting at right angles the values of β are given Fig. A.3.

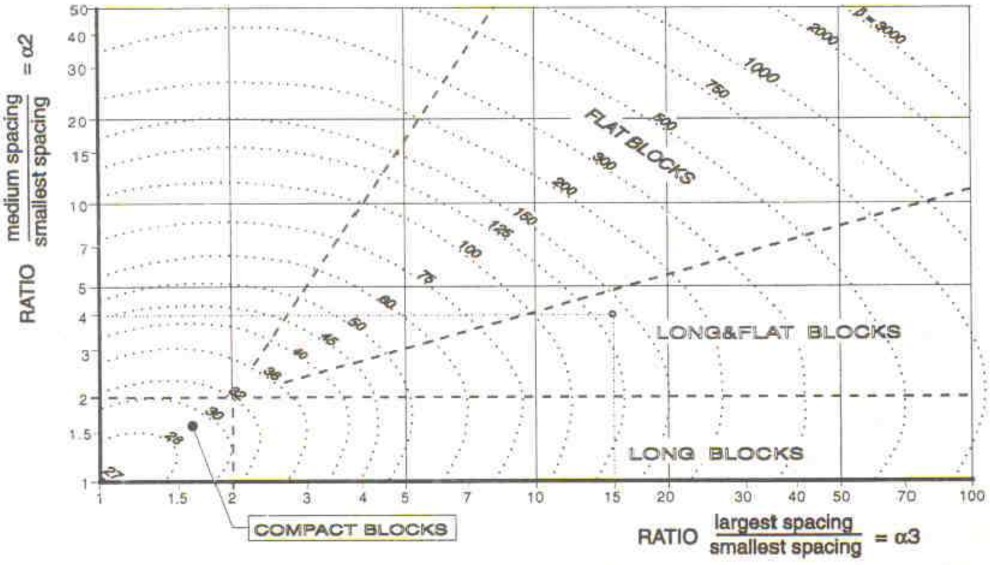

Fig. A.3 Block types characterized by the block shape factor (β) found from the ratio between spacings of the joint sets. The data are based on joint sets intersecing at right angles. Example shown: for $\alpha 2 = 4$ and $\alpha 3 = 15$ $\beta = 135$.

The types of blocks delineated by joints have been characterized in different ways and by different terms. Where relatively regular jointing exists and extensive joint surveys have been carried out, it may be possible to give adequate characterization of the jointing pattern according to the system presented by Dearman (1991). In most cases, however, there is not a regular jointing pattern, therefore a rough characterization of the blocks is generally more practical, for example a division into three main groups only, as presented by Sen and Eissa (1991). The terms applied in this work are shown in Table A4.

TABLE A4 TERMS USED TO CHARACTERIZE THE MAIN TYPES OF BLOCKS

Common terms used for block type	Terms used in this work
Equidimensional, cubical, or blocky blocks	. . . Compact blocks
Elongated, long, columnar, or bar blocks . .	. . . Long blocks
Tabular, platy, or flat blocks	. . . Flat blocks
	. . . 'Long & flat' blocks (a combination of platy and long blocks)

For $\beta = 27 - 32$ the block term 'compact' is introduced; this term has been chosen to include cubical, equidimensional, blocky and other existing terms for blocks not being long or flat. The division chosen for block types is defined in Fig A.3.

The value of β can be found from Fig. A.3 or eq. (A-5) provided that the block is formed by 3 parallel pairs of planes for example 3 joint sets. This requires that all the (three) spacings or the dimensions of the (six) block faces are known. As blocks often have more than six faces or have irregular shape, it can be difficult to find β from eq. (A-6). Therefore, the following simplified method to estimate β has been developed by Palmström (1995), in which the longest and shortest dimension of the block are applied:

$$\beta = 20 + 7\ a3/a1 = 20 + 7\ \alpha 3 \qquad \text{eq. (A-7)}$$

where a3 and a1 are the longest and shortest block dimension.

The evaluations made by Palmström show that the shape factor of most types of blocks with (where $\beta < 1000$) can be found from this expression within reasonable accuracy ($\pm$ 25%). For very flat to extremely flat blocks eq. (A-7) should be limited to values of $\beta < 100$.

In Table A5 approximate values of β are correlated to the number of joint sets.

TABLE A5 COMMON CONNECTIONS BETWEEN JOINT SETS, TYPES OF BLOCKS AND VALUES OF β

Number of joint sets	Block shape	Type of blocks	Common range of β
One joint set only One set plus random	very - extremely moderately - very	flat blocks flat blocks	100 - 5000 75 - 300
Two joint sets Two sets plus random	very - extremely moderately - very	long or flat blocks long or flat blocks	75 -500 50 - 200
Three joint sets*) Three sets plus random*)	compact blocks to moderately long or flat blocks		27 - 75
Four or more sets*)			

*) Where there is a significant difference in spacing between the joint sets, very flat and very long blocks can occur also for three or more sets. In these cases the values can be $\beta = 100 - 1000$.

A4 ROCK QUALITY DESIGNATION (RQD)

RQD is perhaps the most commonly used method for characterizing the degree of jointing in borehole cores, although this parameter also may implicitly include other rock mass features like weathering and 'core loss' (Bieniawski, 1984).

This parameter was originally developed to characterize the amount of discontinuities in a drill core. RQD has, however, been chosen as a main input both in the Q and the RMR system. The concequence of this is that where no core drilling has been carried out, the RQD value has to be roughly estimated from surface observations. An approximate transition between surface observations of jointing density and RQD has been presented by Palmström (1974, 1982) shown in Fig. A.4. Hudson and Priest (1983) and Sen and Eissa (1991, 1992) have later developed theoretical analytical approaches to determine RQD from joint spacings.

From its definition - being independent of the length of individual core pieces being longer than 0.1 m - the RQD is a crude measure of the degree of jointing. Also its current use, especially where cores are not available, the quality of this input is relatively poor.

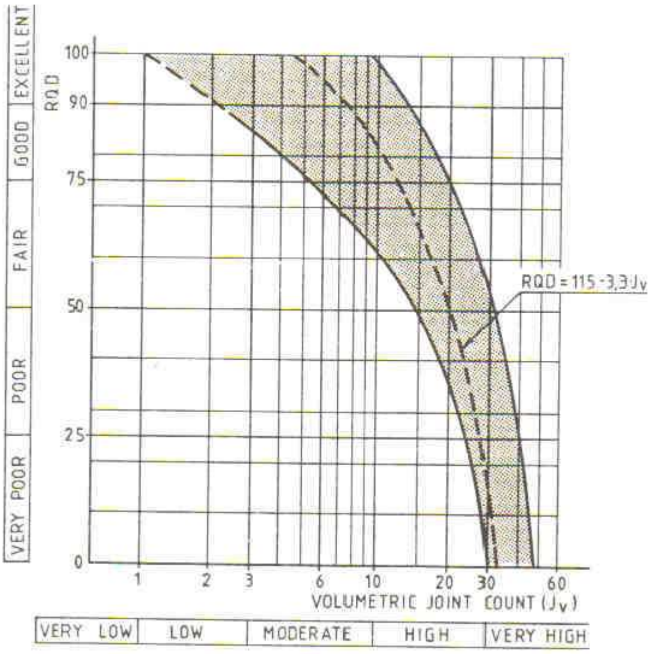

Fig. A.4 Correlation between RQD and Jv (from Palmström, 1982).

4.1 Correlation between RQD and the volumetric joint count (Jv)

It is not possible to obtain good correlations between RQD and Jv or between RQD and other measurements of jointing. This is illustrated in Fig. A.4 where the following expression is given

$$\mathbf{RQD = 115 - 3.3\ Jv} \qquad \text{eq. (A- 8)}$$

(for $Jv > 35$ $RQD = 0$, and for $Jv < 4.5$ $RQD = 100$)

As a consequence of this, especially when many of the core pieces have lengths around 0.1 m, the correlation above must be regarded as being crude. However, where RQD is the only jointing data available, no better transition from RQD via Jv to block volume other than eq. (A-8) has been found.

From the volumetric joint count the block volume can be found provided input of the block shape factor (β), see eq. (A-5a) and (A-5b). Where β is not known, it is recommended to use a 'common' value of $\beta = 40$.

A5 JOINT FREQUENCY MEASUREMENTS

When the frequency is given for each joint set, it is possible to establish a correlation between joint frequencies and block volume. In other cases, when an 'average frequency' is given, it is uncertain whether this frequency value refers to one-, two- or three-dimensional measurements; hence no accurate correlation can be presented.

A5.1 2-D joint frequency in an area or surface

The 2-D joint frequency is the number of joints measured in an area. The length of the joints compared to the size of the area will, however, influence on the frequency observed. Thus, some sort of adjustments have to be made to estimate the block volume from this type of measurement. Fig. A.5 shows three different observation areas for which the joints are larger than the dimension of the area.

In the table below the density of joints per square metre and per metre are given. As seen, the latter method gives a constant number of the joint frequency (Na), given as the density of joints per metre. If the shorter joints occur, a higher amount of joints may be observed within the area, as shown in the right diagram of Fig. A.5.

size of area A .	**number of joints** na	**joints/m^2** $Na = na/A$	**joints/m** $Na = na/\sqrt{A}$
4 m^2	4	1	2
20 m^2	10	0.5	2.2
63 m^2	17	0.27	2.1

The joint frequency (Na) should, therefore, be adjusted for the lengths of the joints if they are shorter than the length of the observation plane, expressed as

$$\mathbf{Na = \Sigma(na_i \cdot L_i / \sqrt{A})} \qquad \text{eq. (A-9)}$$

where na = the number of joints with length L and
A = the area of the observation plane.

Na varies with the orientation of the observation plane and with respect to the attitude of the joints. Recording of Na in several surfaces of various orientation gives a more accurate measure of the jointing. Being an average measurement, Na should be measured in selected areas with the same type of jointing. A larger area should be divided into smaller, representative areas containing similar jointing, and the variation in jointing for the whole area calculated from these registrations.

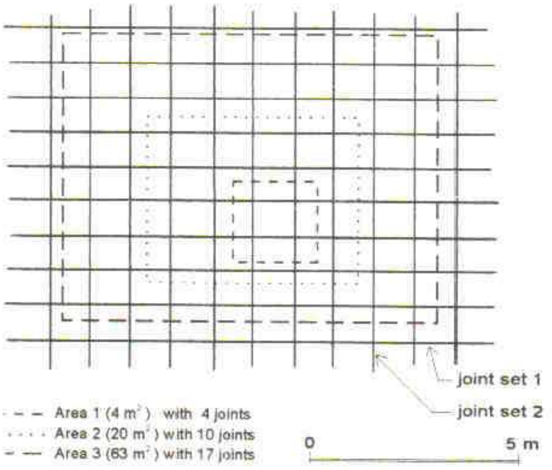

Fig. A.5 Various sizes of the observation area and the number of joints observed. All joints are longer than the dimension of the area.

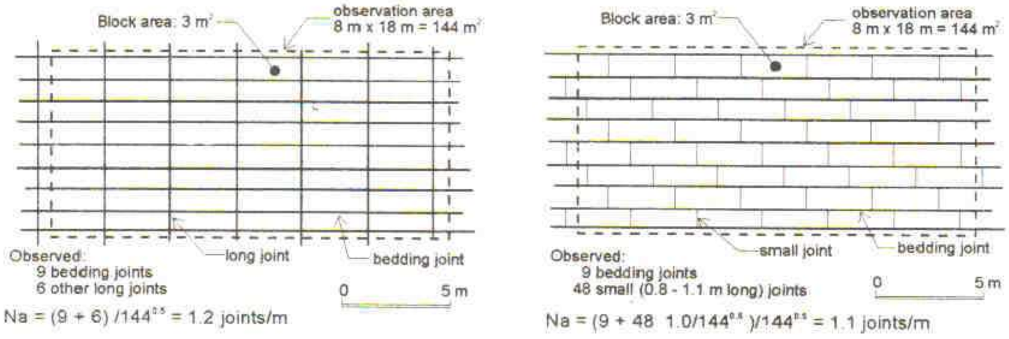

Fig. A.6 Two 'exposures' of joints with different jointing pattern. The blocks in both have the same size. A higher amount of joints is recorded in the lower figure where the cross joints are short. Applying Na = na /$\sqrt{A}$ the same value of Na is found for both exposures.

The correlation between 2-D registrations of the joint density in a rock surface and 3-D frequency values (given as Jv) can be done using the empirical expression

$$\mathbf{Jv = Na \cdot ka} \qquad \text{eq. (A-10)}$$

where Na = number of joints per metre measured in a surface, and
ka = correlation factor shown in Fig. A.7.

Fig. A.7 shows that ka varies mainly between 1 and 2.5 with an average value ka = 1.5. It has its highest value where the observation plane is parallel to the main joint set.

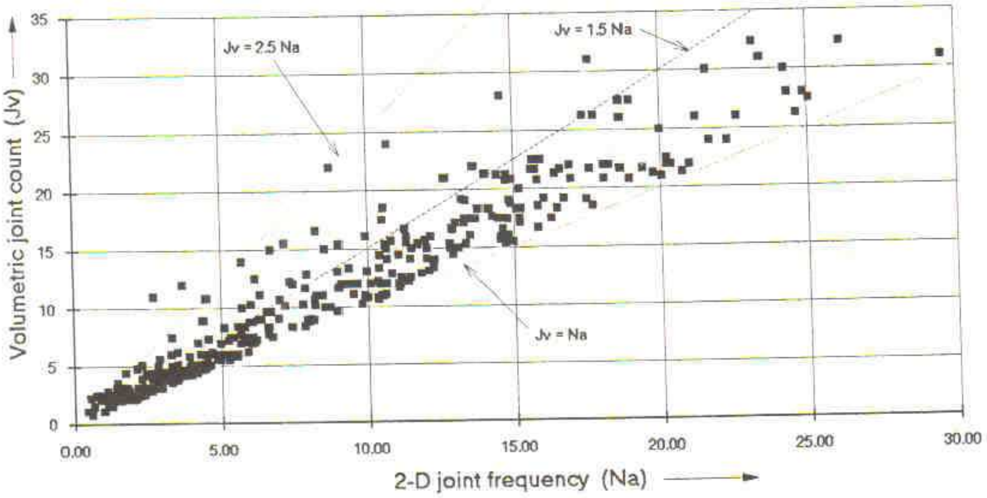

Fig. A.7. The connection between 2-D joint observations in a surface and the volumetric joint count (Jv) for various jointing patterns and orientations of the observation plane (from Palmström, 1995a).

5.2 1-D jointing frequency measurements along a scanline or drill core

This is a record of joint frequency along a borehole or a scanline given as the number of joints intersecting a certain length. This 1-D joint frequency is an average measure along the selected length of the core. As in other core logging methods and in surface observations it is important to select a section of the line or core length which shows similar jointing frequency. At the start of the logging it is rational to divide the length into such sections of uniform or similar frequency.

The 'joint frequency' can, as mentioned, be inaccurate if it is not strictly defined what is included in the measurement; it should therefore be accompanied by additional information on how it has been measured.

The correlation between 1-D joint frequency registrations in drill holes or along scanlines and volumetric 3-D frequency (Jv) can be done using a similar expression as eq. (A-10)

$$\mathbf{Jv = Nl \cdot kl} \qquad \text{eq. (A-11)}$$

where Nl = 1-D joint frequency, i.e. the number of joints per metre along a core or line, and

kl = correlation factor shown in Fig. A.8 with an average value kl = 2. As expected there is a rather poor correlation between kl and Jv .

The joint spacing registrations presented in the following are similar to the joint frequency measurements.

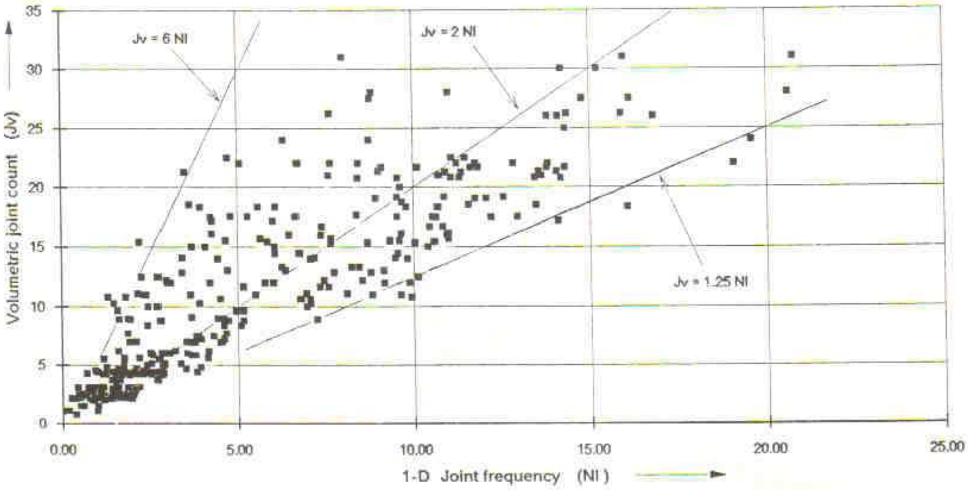

Fig. A.8. The connection between 1-D joint observations in drill cores or along a scanline and the volumetric joint count (Jv) for various jointing patterns and orientations of the borehole (or scanline) (from Palmström, 1995a).

6 JOINT SPACING REGISTRATIONS

The terms *joint spacing* and *average joint spacing* are often used in the description of rock masses. Joint spacing is the distance between individual joints within a joint set. Where more than one set occurs, this measurement for surface observations is often the average of the spacings for these sets.

However, when the recordings are made on drill cores the spacing is often the average length of core bits.[5] Thus, the spacings or frequencies are not true recordings as joints of different sets are included in the measurement. In addition, random joints which do not necessarily belong to any joint set, influence. As the term 'joint spacing' does not indicate what is included, it is frequently difficult to determine whether a 'joint spacing' referred to in the literature represents the true joint spacing. Thus, there is often much confusion related to joint spacing recordings.

As joint spacing (S) is the inverse of joint frequency, the correlation factor between joint spacing and the volumetric joint count is:

for 2-D observations in rock surfaces $\mathbf{ca = 1/ka}$ (average $ca = 0.67$)
for 1-D observations of scanlines or boreholes $\mathbf{cl = 1/kl}$ (average $cl = 0.5$)

Deere et al. (1969) have experienced that where several joint sets occur, the resulting average 'volumetric spacing' is generally 2/3 to 1/3 of the average joint spacing of any of the joint sets. For correlation purposes they consider it sufficiently accurate to use a ratio of 1/2. This is the same average value as has been found for cl. It must

---

Joint or fracture intercept is the appropriate term for measurement of the distance between joints a line or borehole.

be realized, however, that this ratio may vary. If, for example, only one dominant joint set occurs, the ratio would be closer to unity. The ratio also depends on the orientation of the borehole or observation surface relative to the attitude of the joints.

Franklin et al. (1971) have suggested to record a direct measure of joint spacing by using the *fracture spacing index* (I_f), which refers to the average size of cored material. When few joints are present in the core, I_f is the unit length divided by the number of fractures within the unit. If the core is very broken, I_f is the average diameter of a number of separate rock fragments. The latter can be compared with direct estimates of block volume made on small fragments in drill cores which has been mentioned in Section A1.1. Franklin et al. (1971) and Hudson and Priest (1983) recommend two or more inclined boreholes in different directions to obtain an accurate estimation of the fracture spacing index.

The use of *weighted joint density measurements* will generally improve the characterization of block size, also where only results from a single borehole is available. This method may positively reduce the amount of drill holes in a site where measurement of joint density or block size is a main reason in the investigation.

A7 WEIGHTED JOINT DENSITY MEASUREMENTS (wJd)

R. Terzaghi (1965) points out that the accuracy of jointing measurement can be increased by replacing the number of joints measured in a surface or borehole (N_α) intersected at an angle α, by a value N_{90}. N_{90} represents the number of joints with the same orientation which would have been observed at an intersection angle of 90°. This is expressed as

$$\mathbf{N_{90} = N_\alpha/\sin\alpha} \qquad \text{eq. (A-12)}$$

Terzaghi stresses the problem connected to small values of α, because, in these cases, the number of intersections will be significantly affected by local variations in spacing and continuity. *"Further, no correction whatsoever can be applied if α is zero. Hence N_{90} would fail to correctly indicate the abundance of horizontal and gently dipping joints in a horizontal observation surface."*

The method for weighted joint density measurement presented in the following is based on measuring the angle between each joint and the observation surface or borehole. To solve the problem of small intersection angles and to simplify the observations, the angles have been divided into intervals as shown in Table A6. For 2-D measurements (surface observations) the weighted joint density is defined as

$$\mathbf{wJd = \Sigma(1/\sin\delta_i)\ /A = \Sigma(f_i)\ /A} \qquad \text{eq. (A-13)}$$

and, similarly, for 1-D registrations along a scan line or in drill cores

$$\mathbf{wJd = \Sigma(1/\sin\delta_i)\ /L = \Sigma(f_i)\ /\ L} \qquad \text{eq. (A-14)}$$

where δ_i = the angle between the observation plane (surface) and the individual joint.
A = the size of the area in m^2, see Fig. A.9.
L = the length of the measured section along core or line.
f_i = the interval factor given in Table A6; its ratings have been determined by Palmström (1995) from trial and error of various angles and joint spacings.

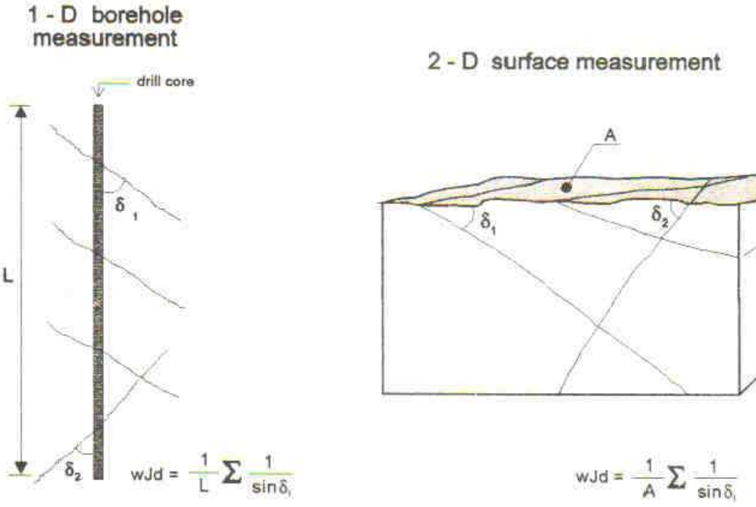

Fig. A.9. The intersection between joints and a drill core hole (left) and a surface (right) (from Palmström, 1995).

TABLE A6 SELECTED INTERVALS OF THE ANGLE (δ_i) AND THE CORRESPONDING FACTOR ($f_i = 1/\sin\delta_i$).

angle δ_i	factor f_i
> 60°	1
31 - 60°	1.5
16 - 30°	3.5
< 16°	6

In practice, each joint is multiplied by the value of (f_i) for the actual angle interval. It should be possible to quickly determine the intervals in Table A6 for the angle δ_i through observations after some training. The intervals chosen discards as mentioned the strong influence of the smallest angles, i.e. angles parallel or nearly parallel to the observation plane or borehole.

The weighted joint density method reduces the inaccuracy caused by the orientation of the observation surface or borehole. Hence it leads to a better characterization of the density of joints, which in turn may result in reduced amount of boreholes in an investigation.

Correlation between wJd and Jv

The weighted joint density is approximately equal to the volumetric joint count

$$Jv = wJd$$

8 METHODS TO FIND THE EQUIVALENT BLOCK VOLUME WHERE JOINTS DO NOT DELIMIT BLOCKS

As mentioned in Section A1 a minimum of three joint sets in different directions are theoreticially necessary to delimit blocks in a rock mass. There are, however, cases with irregular jointing where blocks are formed mainly from random joints, and other cases where the blocks are delimited by one or two joint sets and additional random joints.

Where the jointing is composed of one or two joint sets with no or few random joints, the joints do not define individual blocks. In such cases an *equivalent block volume* is applied in the calculations. Such block volume may be found from the following methods:

1. Where only one joint set occurs the equivalent block volume may be considered similar to the area of the joint plane (i.e. $L1^2$) multiplied by the joint spacing (S1) (Example: For foliation partings with lengths L1 = 0.5 - 2 m and joint spacing S1 = 0.2 m, the equivalent block volume is between
   $Vb = 0.2 \cdot 0.5^2 = 0.05 \text{ m}^3$ and $Vb = 0.2 \cdot 2^2 = 0.8 \text{ m}^3$.)

2. For two joint sets the spacing for the two sets (S1 and S2) and the length (L) of the joints can be applied: $Vb = S1 \cdot S2 \cdot L$

3. The equivalent block volume can be found from eq. (A-5b): $Vb = \beta \cdot Jv^{-3}$ which requires input from the block shape factor (β), which can be estimated from eq. (A-7)[6] $\beta = 20 + 7\ a3/a1$
   where a1 and a3 are the shortest and longest dimension of the block. A method to arrive at a better estimate of β using the length and spacing of the joints, is outlined in the following:

   Eq. (A-7) is developed for three joint sets. Where less than three sets occur, it can be adjusted by a factor n_j representing the rating for joint sets to characterize an *equivalent* block shape factor:

   $$\boldsymbol{\beta = 20 + 7\ (S_{max}/S_{min})(3/n_j) = 20 + 21(S_{max}/S_{min} \cdot n_j)} \qquad \text{eq.(A-15a)}$$

   or a more accurate expression developed by Palmström (1995) can be applied:

   $$\boldsymbol{\beta = 20 + (21/n_j)\ (S_{max}/S_{min})^{(1 + 0.1 \log (Smax / Smin))}} \qquad \text{eq. (A-15b)}$$

   The ratings of n_j are given as:

3 joint sets + random	$n_j = 3.5$
3 joint sets	3
2 joint sets + random joints	2.5
2 joint sets	2
1 joint set + random joints	1.5
1 joint set only	1

As the volumetric joint count can be measured also where joints do not delimit defined blocks, h can be applied where few joints sets are found.

4. For fissures, partings and small joints where their lengths can often be found or easily estimated, the length and spacing of the joints correspond to the longest and shortest block dimension, hence the ratio length/spacing = L/S can be applied in eq. (A-15a):

   $$\boldsymbol{\beta = 20 + 21\, L/(S \cdot n_j)} \qquad \text{eq. (A-15c)}$$

   For long joints it is sufficiently accurate to use a length $L = 4$ m.

Example

For one joint set ($n_j = 1$) spaced $S1 = 0.2$ m having average joint length
$L1 = 2$ m the block shape factor according to eq. (A-15a) is

$\beta = 20 + 21\ L1/(S1 \cdot n_j) = 230$.

The volumetric joint count for this set is $Jv = 1/S1 = 5$ This gives

$Vb = \beta \cdot Jv^{-3} = 1.84\ m^3$

(For a defined block limited by 3 joints sets with spacings S1, L1, and L1 the volume is: $Vb = 0.2 \cdot 2 \cdot 2 = 0.8\ m^3$)