RMi - A NEW PRACTICAL CHARACTERIZATION SYSTEM FOR USE IN ROCK ENGINEERING

RMi - et nytt system for å karakterisere bergmasser for bruk i praktisk bergteknikk

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1. INTRODUCTION

> *"Provision of reliable input data for engineering design of structures in rock is one of the most difficult tasks facing engineering geologists and design engineers."*
> Z.T. Bieniawski, 1984

In addition to Bieniawski (1984), several other authors like Hoek and Brown (1980) and Nieto (1983) and have indicated a need for a *strength characterization* of rock masses. The Rock Mass index (RMi) has been worked out to satisfy this need and for improving the methods of rock mass descriptions, including better practical guidelines for obtaining numerical observational data.

Rock masses are composed of rocks penetrated by discontinuities. With great diversity both in the composition of the intact rock and in the nature and extent of the discontinuities, rock masses exhibit an enormous variation range in structure as well as composition. This creates a great challenge when characterizing such complex materials. In addition, as reliable tests of the strength of rock masses are impossible or so difficult to carry out with today's technology, rock engineering is currently based mainly on qualitative, descriptive data found from observations. These descriptive data have to be converted into numerical values to make calculations in rock engineering possible.

2. THE ROCK MASS INDEX (RMi)

Construction materials, such as steel and concrete, commonly used in civil engineering and mining are mostly characterized by their strength properties. This basic property of the material is used in the engineering and design. In rock engineering, no such specific strength characterization of the rock mass is in common use. The Rock Mass index is introduced to characterize the strength of the rock mass to be suitable for application in rock engineering and other types of calculations associated with construction in rock. An important issue has been to use parameters in the RMi which have the greatest significance in engineering. This is described in this section.

2.1 *On the selection of the parameters used in the RMi*

Figure 1 shows the main variables constituting a rock mass. Hoek et al. (1992), are of the opinion that the strength characteristics for jointed rock[1] masses are controlled by the block[2] shape and size as well as the surface characteristics of the block determined by the intersecting joints. They recommend that these parameters be selected to represent the average condition of the rock mass. Also, Tsoutrelis et al. (1990), Matula and Holzer (1978), Patching and Coates(1968) and Milne et al. (1992) have set forth similar ideas. This does not imply that the properties of the intact rock material should be disregarded in the characterization. If joints are widely spaced or if the intact rock is weak, the properties of the intact rock may strongly influence the overall behaviour of the rock mass. The intact rock properties are also important if the joints are discontinuous.[3]

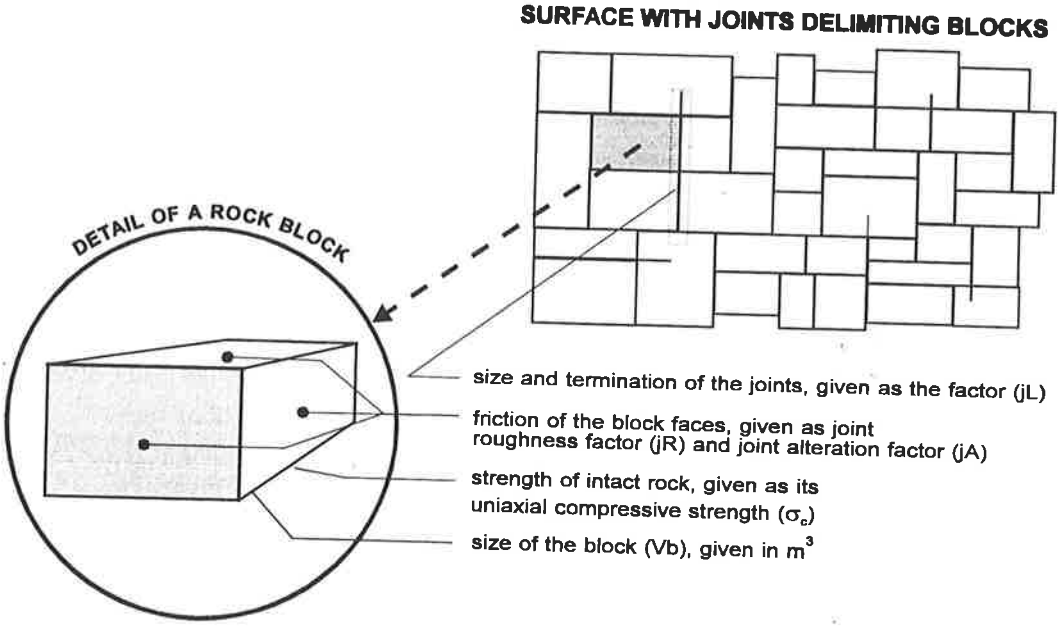

Figure 1 Idealized structure of a typical rock mass and the main parameters which are applied in the RMi. (from Palmström, 1995).

Although rock mass properties in many cases are governed by joints, rocks properties have been a major factor in the formation and development of the actual joints. In this respect petrological data can give useful information on the properties jointing

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[1] The term 'joint' has been used for most natural discontinuities which have thickness smaller than approx. 0.1 m. Thus, joints cover fissures, partings, fractures, natural cracks, as well as many shears and seams.

[2] Joints and other types of discontinuities divide the rocks into blocks.

[3] Discontinuous joints end in massive rock.

(Franklin, 1970; Piteau, 1970). A concise rock description accompanied by jointing observations will, in addition to geology and the type of material at the site, inform the reader of the probable behaviour of the ground.

As indicated in Figure 1, the RMi makes use of the following input parameters:

- compressive strength of intact rock;
- block volume; and
- joint characteristics, as given by its roughness, alteration, and size.

The combination of these parameters, included in the RMi, is shown in Figure 2.
All these are *intrinsic parameters* of the rock mass. The need to use such parameters in characterizing the properties of rock masses has earlier been stressed by Deere et al. (1969) and Patching and Coates (1968).

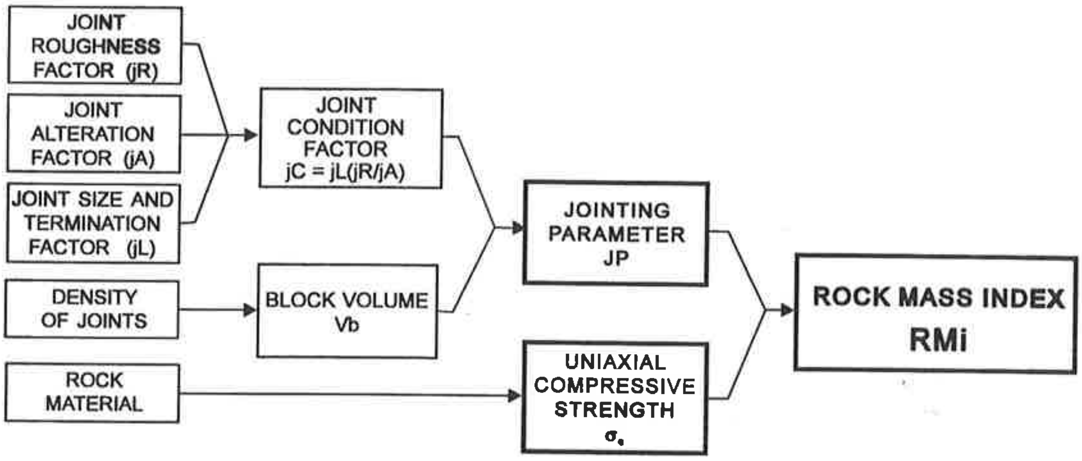

Figure 2   The input parameters to the RMi and their combination (from Palmström, 1995).

Principally, the RMi is based on the reduction in strength of a rock caused by jointing and is expressed as:

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

where σ_c = the uniaxial compressive strength of intact rock measured on 50 mm samples;
JP = the jointing parameter which is a reduction factor representing the block size and the condition of its faces as represented by their friction properties. In addition, a scale factor for the size of the joints have been included, as shown in Figures 1 and 2.

The influence of JP has been found by using calibrations from test results. Because of problems of obtaining compression test results on rock masses at a scale similar to that of typical rock works, it was possible to find appropriate data from only eight large scale tests and one back analysis. Three of these are from Sweden, provided with kind help from Norbert Krauland, Boliden Mines and Bengt Leijon, Conterra AB. These test results have been used to arrive at the following mathematical expression:

$$JP = 0.2\sqrt{jC} \cdot Vb^{D} \qquad \text{eq. (2)}$$

where Vb = the block volume given in m^3,

jC = the joint condition factor is expressed as $jC = jL\ (jR/jA)$ in which jL is the joint length and continuity factor, jR is the joint wall roughness factor [4], and jA is the joint surface alteration factor [2]. Their ratings are shown in Tables 1 to 3,

$D = 0.37\, jC^{-0.2}$ has the following values:

for jC =	0.1	0.25	0.5	0.75	1	1.5	2	2.5	3	4	6	12	16	30
D =	0.586	0.488	0.425	0.392	0.37	0.341	0.322	0.308	0.297	0.28	0.259	0.225	0.213	0.187

The value of JP varies from near 0 for crushed rocks to 1 for intact rock. The exponential form of eq. (2) fits well with the general experience that joint spacings have an exponential statistical distribution as shown by Merritt and Baecher (1981). Most commonly, the joint condition factor $jC = 1$ to 2; thus, the jointing parameter will vary between $JP = 0.2\ Vb^{0.37}$ and $JP = 0.28\ Vb^{0.32}$. For $jC = 1.75$ the jointing parameter and the Rock Mass index can simply be expressed as

$$JP = 0.25\ \sqrt[3]{Vb} \quad \text{and} \quad RMi = 0.25\ \sigma_c\ \sqrt[3]{Vb} \qquad \text{eq. (3a) and eq. (3b)}$$

Significant *scale effects* are generally involved when the tested rock volume is enlarged from laboratory size to field size. From the calibration described above, the RMi is tied to large samples where the scale effect has be included in JP. For massive rock masses, however, the scale effect for the uniaxial compressive strength (σ_c) has not been accounted for, as σ_c is related to 50 mm sample size. Barton (1990) suggests from data presented by Hoek and Brown (1980) and Wagner (1987), that the actual compressive strength for large, massive 'field samples' may be determined from

$$\sigma_{cm} = \sigma_c 50\ (0.05/Db)^{0.2} \qquad \text{eq. (4)}$$

where $\sigma_c 50$ = the uniaxial compressive strength for 50 mm sample size

Db = block diameter measured in metre, which may be found from $Db = \sqrt[3]{Vb}$ or, in cases where a pronounced joint set occurs, from $Db = S$, where S is the spacing of this set. If the block shape factor (β) is known (see Appendix [5], Section A6) the equivalent block diameter is

$$Db = \frac{\beta_o}{\beta}\sqrt[3]{Vb} = \frac{27}{\beta}\sqrt[3]{Vb} \qquad \text{eq. (5)}$$

The expression $(0.05/Db)^{0.2} = f_\sigma$ in eq. (4) is the scale factor for compressive strength.

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[4] The factors jR and jA are similar to the joint roughness number (Jr) and the joint alteration number (Ja) in the Q-system (Barton et al., 1974). The symbols Jr and Ja have been changed into jR and jA because some minor modifications have been made in their definitions.

[5] In addition to the block shape factor mentioned above, the Appendix describes various types of measurements which can be used to estimate the block volume.

Eq. (4) is valid for sample diameters up to some metres, and may, therefore, be applied for massive rock masses.

TABLE 1 THE RATINGS OF THE JOINT ROUGHNESS FACTOR (jR) FOUND FROM SMOOTHNESS AND WAVINESS (From Palmström, 1995)
(The ratings of jR are similar to Jr in the Q-system)

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 filled joints: jR = 1		For irregular joints a rating of jR = 5 is suggested		

*) For slickensided joints the value of jR depends on the presence and appearance of the striations; the highest value is used for marked striations.

TABLE 2 CHARACTERIZATION AND RATING OF THE JOINT ALTERATION FACTOR (jA).
(from Palmström (1995)
(jA is similar to Ja in the Q-system, except for the grade of alteration)

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 for staining	1
-Alteration of joint wall:		
· 1 grade more altered	- The joint surface exhibits one class higher alteration than the rock	2
· 2 grades more altered	- The joint surface shows two classes higher alteration than the 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 WITH PARTIAL OR NO CONTACT BETWEEN THE ROCK WALL SURFACES

TYPE OF FILLING MATERIAL	**DESCRIPTION**	**Partial wall contact** thin fillings (< 5 mm*)) **jA**	**No wall contact** thick filling or gouge **jA**
-Sand, silt, calcite etc.	- Filling of friction materials without clay	4	8
-Compacted clay materials	- "Hard" filling of softening and cohesive materials	6	10
-Soft clay materials	- Medium to low over-consolidation of filling	8	12
-Swelling clay materials	- Filling material exhibits clear swelling properties	8 - 12	12 - 20

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

TABLE 3 THE JOINT SIZE AND CONTINUITY FACTOR (jL) (from Palmström, 1995).

JOINT LENGTH	TERM	TYPE	jL continuous joints	jL 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 occurs as a single discontinuity, and should in these cases be treated separately. **) Discontinuous joints end in massive rock

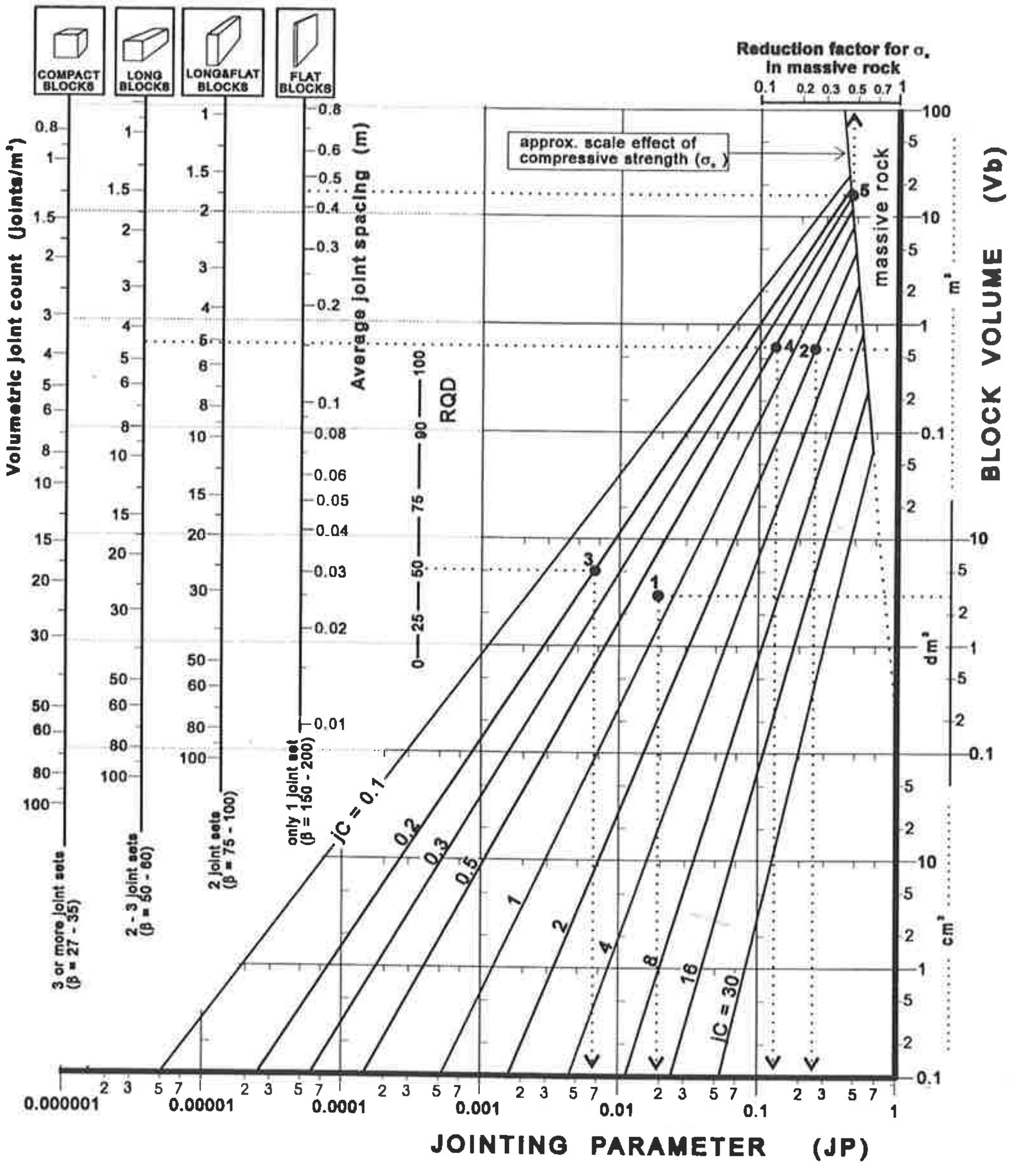

Figure 3 *The jointing parameter (JP) found from the joint condition factor (jC) and various measurements of jointing intensity (Vb, Jv, RQD). The determination of JP from Vb (or RQD or Jv) in the examples shown in Section 3 are indicated (from Palmström, 1996a).*

From Figure 3 the jointing parameter (JP) can be found using the block volume (Vb) and the joint condition factor (jC). As shown in the upper left part of the diagram, the volumetric joint count (Jv) for various joint sets (and/or block shapes) can be used instead of the block volume. This is based on the correlations given in the Appendix. Also, the RQD can be used, but its inability to characterise massive rock or highly jointed rock masses leads to a reduced quality of the JP.

The classification of RMi is presented in Table 4. 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.

TABLE 4 CLASSIFICATION OF RMi. (from Palmström, 1995)

TERM		RMi value
for RMi	**related to rock mass strength**	
Extremely low	Extremely weak	< 0.001
Very low	Very weak	0.001 - 0.01
Low	Weak	0.01 - 0.1
Moderate	Medium	0.1 - 1
High	Strong	1 - 10
Very high	Very strong	10 - 100
Extremely high	Extremely strong	> 100

The RMi can be applied in various types of rock engineering with adjustment for features related to the particular project or utilisation of the rock. These applications are briefly described in Section 4.3.

3. EXAMPLES

The values of the jointing parameter (JP) found in the following examples are shown in Figure 3.

Example 1

The block volume has been measured as Vb = 0.003 m^3 (= 3 dm^3). As given in Tables 1 to 3, the joint condition factor jC = 0.75 is determined from:

- the rough joint surfaces and small undulations of the joint wall which gives jR = 3;
- the clay coated joints, i.e. jA = 4; and
- the 3 - 10 m long, continuous joints, which gives jL = 1.

Applying the values for Vb and jC in Figure 3, a value of JP = 0.02 is found.[6)] With a compressive strength of the rock σ_c = 50 MPa, the value of RMi = 0.02 · 150 = 3 (high)

[6)] Using eq. (2) a value of JP = 0.018 is found

Example 2
The block volume is $Vb = 0.6\ m^3$. The joint condition factor $jC = 2$ is determined from Tables 1 to 3, based on:

-smooth joint surfaces and planar joint walls which gives $jR = 1$;

-fresh joints, $jA = 1$; and 1 to 10 m long discontinuous joints, i.e. $jL = 2$.

From Figure 3 the value $JP = 0.25$ is found. [7] With a compressive strength $\sigma_c = 50$ MPa of the rock, the value of RMi = 12.5 (very high).

Example 3
Values of RQD = 50 and $jC = 0.2$ give $JP = 0.007$

Example 4
Two joint sets with average spacings 0.3 m and 1 m, and some random joints occur in an area. The volumetric joint count is $Jv = 1/0.3 + 1/1 + 0.5$ [8] $= 4.5$
With a joint condition factor $jC = 0.5$ the jointing parameter $JP = 0.12$ (by using the column for 2 to 3 joint sets in Figure 3).

Example 5
The following jointing features are measured: only one joint set with average spacing $S = 0.45$ m, and a joint condition factor $jC = 8$. For this massive rock it is seen in Figure 3 that the value of JP is determined from the scale factor for compressive strength $f_\sigma = 0.45$. For a rock with $\sigma_c = 130$ MPa the value of RMi = 59.6 (very high).

4. DISCUSSION

The RMi can be applied in various types of rock engineering with adjustment for features related to the particular project or utilisation of the rock These applications are briefly mentioned in Section 4.3.

4.1 Benefits - limitations of the RMi

Some of the benefits of the RMi system are:

- *The RMi will give significant improvements in the use of geological input data.* This is mainly achieved by its systematic use of well defined parameters in which the three-dimensional character of rock masses is represented by the block volume.
- *The RMi can easily be used for rough estimates when limited information is available on the ground conditions.* For example, in early stages of a project where rough estimates are sufficient, eq. (3b) can be applied.

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7) JP = 0.24 is found using eq. (2)

8) The assumed value for the random joints.

- *The RMi is well suited for comparisons and exchange of knowledge between different locations.*
  In this way it may contribute to improved communication between people involved in rock engineering and design.
- *The RMi offers a platform suitable for engineering judgement.*
  RMi is a general parameter which characterizes the inherent strength of rock masses, and may be applied in engineering as a quality indicator for this construction material. As RMi is composed of real block volumes and common joint parameters for rock masses, it should easily be related to the field conditions. This is important in application of engineering judgement.
- *The RMi system covers a wide spectrum of rock mass variations.*
  It therefore has possibilities for wider applications than the existing rock mass classification and characterization systems of today.

Any attempt to mathematically express the variable structure and properties of jointed rock masses in a general failure criterion, may result in complex expressions. By restricting the RMi to uniaxial compressive strength only, it has been possible to arrive at the relatively simple expressions in eqs. (1) and (2). Because simplicity has been preferred in the structure as well as in the selection of parameters in RMi, it is clear that such an index may result in inaccuracy and limitations, of which the main are connected to:

- *The range and types of rock masses covered by the RMi.*
  Both the intact rock materials as well as the joints exhibit great directional variations in composition and structure which may result in a large range in compositions and properties of rock masses. It is, therefore, not possible to characterize all these combinations in one, single number. Nevertheless, the RMi probably characterizes a wider range of materials than most classification systems.
- *The accuracy in the expression of 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) used in obtaining JP and the relatively small size of some of the samples tested, may be sources of error in the expression for JP. The value of RMi found may therefore be approximate. In some cases, however, errors in the various parameters may partly have neutralized each other.
- *The effect of combining parameters that vary in range.*
  The parameters used to calculate the RMi will in general express a certain range of values. As with any classification system, combination of such variables may cause errors. In some cases the result is that the RMi may be inaccurate. For these reasons, the RMi may best be considered as a *relative* index in its characterization of the rock mass strength.

4.2 Other similar rock mass characterization methods

A similar approach to a strength characterization of rock masses has been proposed by Hansagi (1965a, 1965b), who introduced a reduction factor (C_g) comparable to the jointing parameter (JP) to arrive at an expression for the *compressive strength* of the rock mass, expressed as

$$\sigma_{cm} = \sigma_c \cdot C_g \qquad \text{eq. (6)}$$

Hansagi named C_g as a '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.

In its original form the Hoek-Brown criterion is expressed in terms of the major and the minor principal stresses at failure as

$$\sigma_1' = \sigma_3' + (m \cdot \sigma_c \cdot \sigma_3' + s \cdot \sigma_c^{\,2})^{1/2} \qquad \text{eq. (7)}$$

where σ_1' = is the major principal effective stress at failure.
σ_3' = is the minor principal effective stress.
σ_c = is the uniaxial compressive strength of the intact rock material from which the rock mass is composed.
s and m are empirical constants representing inherent properties of jointing conditions and rock characteristics.

For $\sigma_3' = 0$, eq. (7) expresses the unconfined *compressive strength* of a rock mass

$$\sigma_{cm} = \sigma_c \cdot s^{1/2} \qquad \text{eq. (8)}$$

This expression is similar in structure to the expression $\text{RMi} = \sigma_c \cdot \text{JP}$

4.3 Possible applications of the RMi

The main purpose during development of the RMi has been to work out a practical system to characterize rock masses which can be used in rock engineering and design. When applied, the RMi-value or its parameters are adjusted for local features of importance for the engineering purpose, as indicated in Figure 4.

Figure 5 shows the main areas for application of RMi together with the influence of its parameters in different fields. The RMi-value can seldom be used directly in classification systems as many of them are systems made for a particular purpose. Some of the input parameters included in the RMi are sometimes similar to those used in the classifications and may then be applied more or less directly.

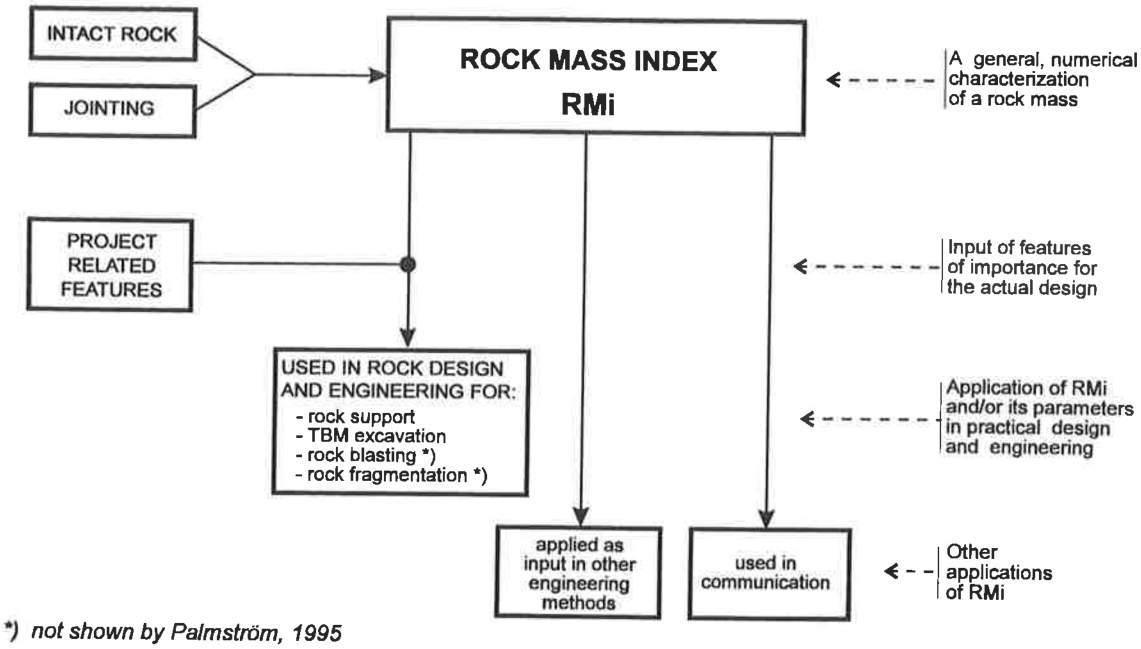

Figure 4 The principle application of RMi in rock engineering (from Palmström, 1995)

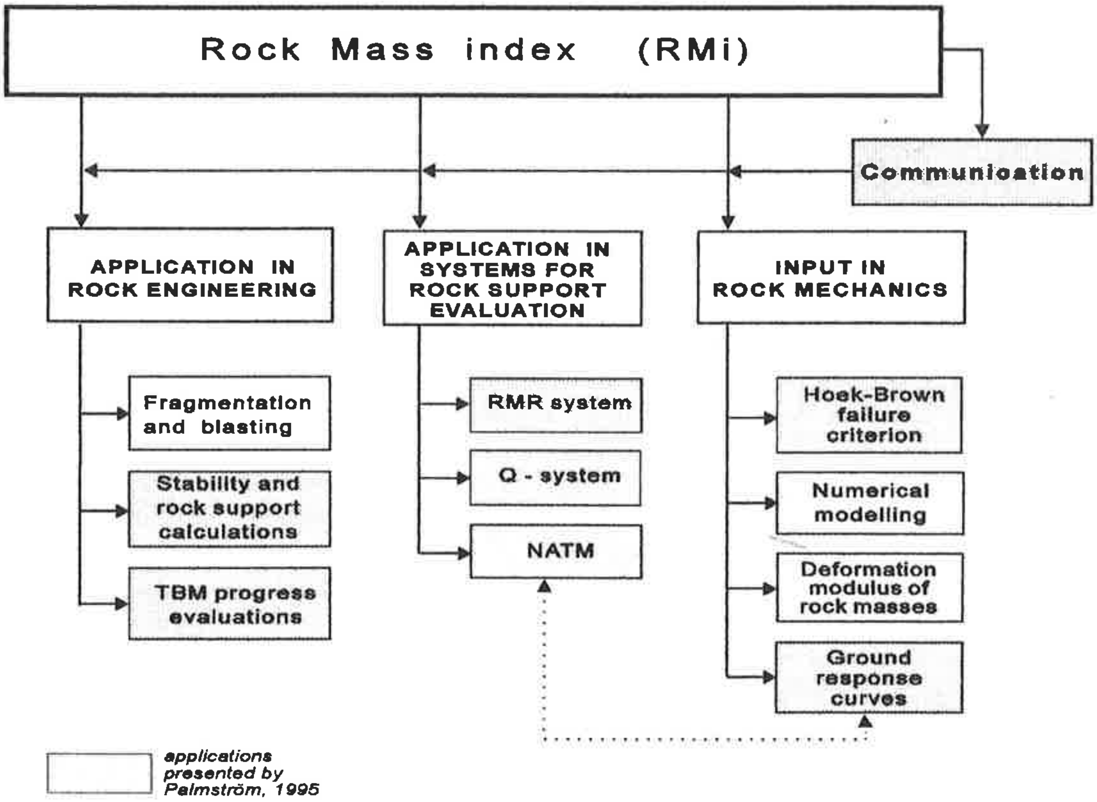

Figure 5 The main applications of RMi in rock mechanics and rock engineering (from Palmström, 1995).

According to Hoek and Brown (1980) the constants m and s in the Hoek-Brown failure criterion for rock masses[9)] depend on the properties of the rock and the extent to which it has been broken before being subjected to the [failure] stresses. Both constants are dimensionless.

The value of s ranges from 0 for jointed rock masses to 1 for intact rock. It is found using the RMR or the Q classification system as described by Hoek (1983), Hoek and Brown (1980, 1988), and Wood (1991). As seen in eq. (8) the value of $s = \text{JP}^2$ can be found directly by applying the RMi system.

The constant m varies with the jointing. In the later publication on the Hoek-Brown failure criterion it has been replaced by m_b. Palmström (1995) has shown that based on data from Wood (1990) and Hoek et al.(1992) it can be mathematically expressed:

- for undisturbed rock masses as $m_b = m_i \cdot \text{JP}^{0.64}$ eq. (9)
- for disturbed rock masses as $m_b = m_i \cdot \text{JP}^{0.857}$ eq. (10)

where m_i = values for intact rocks given in Table 5.

TABLE 5 VALUES FOR THE m_i FACTOR IN THE HOEK-BROWN FAILURE CRITERION (from Palmström, 1995a, based on Wood, 1990 and Hoek et al., 1992).

Sedimentary rocks	Rating of the factor m_i [1)]	**Igneous rocks**	Rating of the factor m_i [1)]	**Metamorphic rocks**	Rating of the factor m_i [1)]
Anhydrite	13.2	Andesite	18.9	Amphibolite	31.2
Claystone	3.4	Basalt	(17)	Amphibolitic gneiss	31 ?
Conglomerate	(20)	Diabase (dolerite)	15.2	Augen gneiss	30 ?
Coral chalk	7.2	Diorite	27 ?	Granite gneiss	30 ?
Dolomite	10.1	Gabbro	25.8	Gneiss	29.2
Limestone	8.4	Granite	32.7	Gneiss granite	30 ?
Sandstone	18.8	Granodiorite	20 ?	Greenstone	20 ?
Siltstone	9.6	Monzonite	30 ?	Marble	9.3
		Norite	21.7	Mica gneiss	30 ?
		Rhyolite	(20)	Mica quartzite	25 ?
		Syenite	30?	Mica schist	15 ?
				Phyllite	13 ?
				Quartzite	23.7
				Slate	11.4
				Talc schist	10 ?

1) Values in parenthesis have been estimated by Hoek et al (1992); some others with question mark have been assumed by Palmström (1995a)

Thus, RMi introduces an easier and more direct method to find the values of both constants s and m, as JP involves only inherent features which have a direct impact on the behaviour of the rock mass. In this way, RMi may contribute to a future improvement of the Hoek Brown failure criterion.

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9) 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 and crushed rock masses.

A system for application of RMi in rock support evaluations in underground excavations have been presented by Palmström (1995a). It is based on two main groups of ground; the continuous and the discontinuous rock masses determined by the ratio between block diameter and the tunnel diameter. For each group a chart has been presented, see Palmström (1995a or 1996a). In addition to the parameters involved in the RMi, the joint orientation, the rock stress level in the excavation, and the number of joint sets are used. For weakness zones additional information on the thickness of the zone and the quality of the adjacent rock masses are used. Thus the RMi method for rock support evaluation contains more information on the ground conditions than other similar classification systems for rock support determination.

For estimates of the penetration rate of full face tunnelling machines (TBM) a system applying JP and σ_c in addition to specification of the TBM has been presented by Palmström (1995a).

Finally, the system for characterizing block geometry (volume, shape factor, angles) in the RMi system may be of use in numerical models.

ABSTRACT

The Rock Mass index, RMi, has been developed to satisfy a need for a strength characterization of rock masses for use in rock engineering and design. The method gives a measure of the reduction of intact rock strength caused by joints given by $RMi = \sigma_c \cdot JP$ Here σ_c is the uniaxial compressive strength of the intact rock measured on 50 mm diameter samples, and JP is the jointing parameter which is a combined measure of block size (or intensity of jointing) and joint characteristics as measured by joint roughness, alteration and size.

This paper describes the method of determining the RMi for a rock mass using various common field observations. The determination of a meaningful equivalent block size is a key issue which is described in detail.

SAMMENDRAG

RMi (Rock Mass index) som er et nytt system for karakterisering av bergmasser, tilbyr bedre kvalitet ved bruk av geologiske data i bergteknikk. Det er basert på parametre for bergart (trykkfasthet) og oppsprekning (mengde av sprekker uttrykt ved blokkvolum, ruhet og karakter av sprekkeflater, samt lengde av sprekkene). For å kunne kombiner alle disse parametrene i et uttrykk for en bergmasses fasthet, er det benyttet kalibrering mot 7 kjente tester av bergmasser og en 'back analysis'. Ved å karakterisere bergmassers styrke, er RMi godt egnet for å kunne benyttes som basis inngangsparameter i ulike bergtekniske beregninger, som for eksempel stabilitet- og sikringsbestemmelser, inndrift ved fullprofilboring, og Hoek-Brown bruddkriterium for bergmasser. Blokkstørrelsen er viktigste inngangsparameter i systemet. Måter å måle denne på er derfor viet stor plass i artikkelen.

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APPENDIX

METHODS AND CORRELATIONS TO DETERMINE THE BLOCK VOLUME

> *"The success of the 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

A1 INTRODUCTION

In most cases the block size is the most important factor in the RMi. Block size is also used in some of the applications of RMi in engineering, especially for design of rock support. Consequently, the accuracy of this parameter has a significant impact on the quality of the RMi and hence of the calculations performed. This appendix presents methods to determine the block volume from various types of jointing observations and measurements.

The block dimensions are determined by joint spacings and the number of joint sets. Individual or random joints and possibly other planes of weakness may further influence the size and shape of blocks. Impact from rock blasting may also influence. As the joint spacings generally vary greatly, the difference in size between the smaller and the larger blocks can be significant. Therefore, the characterization of block volume should be given rather as an interval than as a single value.

If less than 3 joint sets occur, defined blocks may not be found. However, in many cases the presence of random joints or other weakness planes may contribute to defining blocks. 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. Thus, from time to time the block size and shape therefore have to be determined using a simplification where an *equivalent block volume* is used, as is described in Section A8.

The correlations between various joint measurements are shown in Figure A1. 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 preferred, as is presented in this Appendix.

A2 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. For small blocks or fragments having volumes in dm^3 size or less, this method of block volume measurement is often beneficial as it is much easier to estimate the volume of a block compared to all the measurements which have to be made to include all joints. Block volume can also be measured in drill cores where small fragments occur for example in faulted or crushed zones.

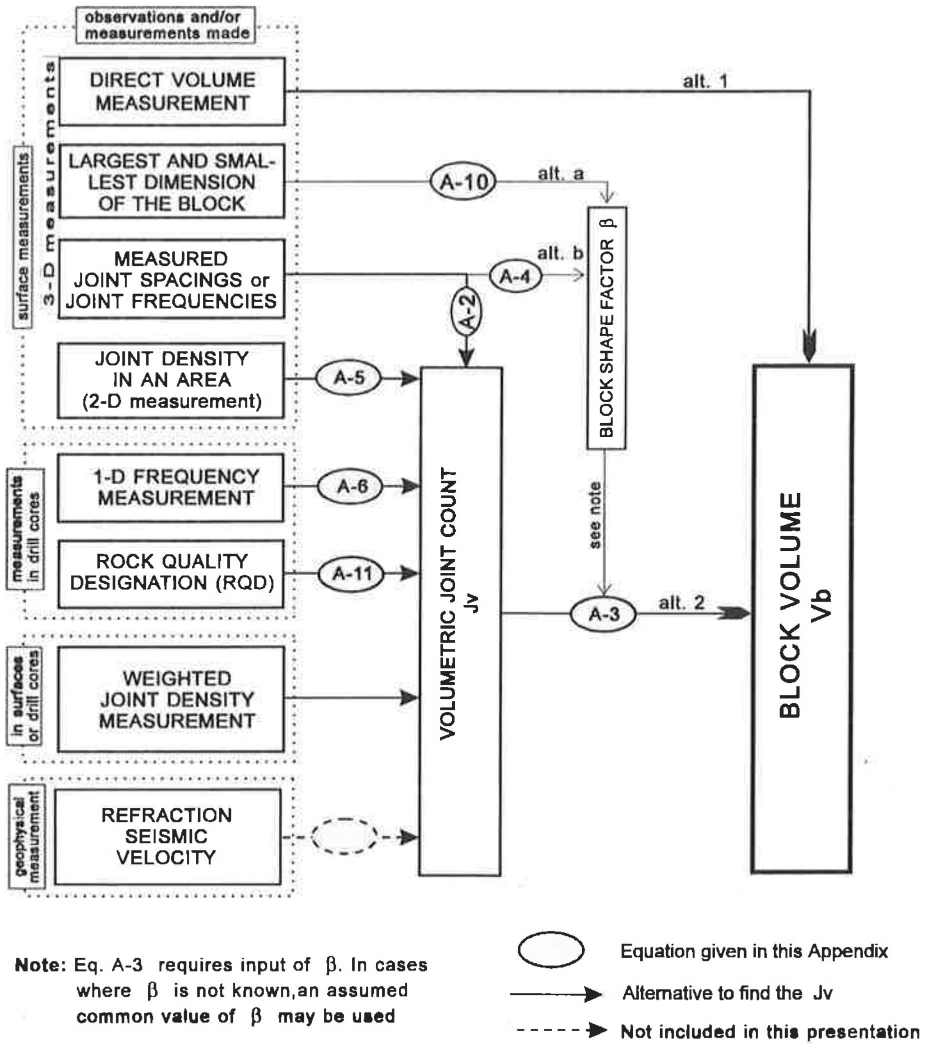

Fig. A1 The principles in estimating the block volume from various types of joint density measurements. (Revised from Palmström, 1995a)

A3 BLOCK VOLUME FOUND FROM JOINT SPACINGS

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 is, in the case of surface observations, often given as the average of the spacings for these sets. There is often some uncertainty as to how this average value is found. For instance, the average spacing for

3 joint sets having spacings: S1 = 1 m, S2 = 0.5 m, and S3 = 0.2 m is Sa = 0.125 m, and not 0.85 m which initially may seem appropriate.[10)]

When logging drill cores the average length of core pieces[11)] or frequencies are seldom true spacings, as joints of different sets probably are included in the measurement. In addition, random joints which do not necessarily belong to any joint set, have an influence.

As the term 'joint spacing' does not indicate what it includes, 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.

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 as is mentioned in Section 3.

Where three regular joint sets occur, the block volume can be found from the joint spacings as

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

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 block volume in cases where joints intersect at right angles.

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

A4 BLOCK VOLUME FOUND FROM JOINT FREQUENCY MEASUREMENTS

A4.1 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 of the number of joints within a unit volume of rock mass, defined by

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10) The average spacing is found from 1/Sa = 1/S1 + 1/S2 + 1/S3 and not from Sa = (S1 + S2 + S3)/3 which often seems to be applied.

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

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

where S_i = the joint spacing in metres for the each joint set *i*.

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

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

where Nr = the number of random joints. A more accurate method to determine Nr has been described by Palmström (1995a or 1995d).

Jv can easily be calculated from joint observations, since it is based on 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 as described by Palmström (1995a or 1995d).

A4.2 The correlation between block volume (Vb) and 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 is a correlation between them (Palmström, 1982). Jv varies with the joint spacings, while the block size also depends on the type of block. A correlation between the two parameters has therefore to be adjusted or corrected for the block shape and the angle between the joint sets, given as

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

For cases where all angles between the block faces are 90°, the block volume is

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

The factor $\beta = \dfrac{(\alpha 2 + \alpha 2 \cdot \alpha 3 + \alpha 3)^3}{(\alpha 2 \cdot \alpha 3)^2}$ eq. (A-4)

(where $\alpha 2$ = S2/S1 and $\alpha 3$ = S3/S1) depends mainly on the differences between the joint set spacings. It has therefore been named the *block shape factor*. It is further described in Section A8.

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 joint frequency measurements and block volume estimates (Palmström, 1982). Important here is the block shape factor β which is included in all equations to estimate the block volume, see Figure A1.

When the frequency is given for each joint set, it is, as mentioned, possible to determine the block volume directly. In other cases, when an 'average frequency' is given, it is as for joint spacings, uncertain whether this frequency value refers to one-, two- or three-dimensional measurements; hence no accurate general correlation can be presented. The use of joint frequency measurements presented in the following paragraph are similar to the joint spacing measurements shown in Section A3.

A4.3 Block volume found from 2-D joint frequency measurements on an area or surface

The 2-D joint frequency is the number of joints measured in an area. A simple correlation between 2-D and 3-D frequency (Jv) values can be done using the empirical expression

$$Jv = Na \cdot ka \qquad \text{eq. (A-5)}$$

where ka = correlation factor. It varies mainly between 1 and 2.5 with an average value $ka = 1.5$. The factor has its highest value where the observation plane is parallel to the main joint set.

The joint frequency (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 measure, Na should be measured in selected areas showing the same type and density of jointing. Thus, a large area should be divided into smaller, representative areas containing similar jointing, and the variation in jointing for the whole area calculated based on these observations.

As the length of the joints compared to the size of the area will influence on the frequency observed, some sort of adjustments should be made where more accurate estimates are required.

A4.4 From 1-D jointing frequency measurements along a scanline or drill core

This is a record of the 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 a selected length of the core. As in other core logging methods, it is important to measure the joints in sections along the line or core which shows a similar joint frequency. At the start of the logging it is rational to divide the length of the borehole/scanline into such sections.

The correlation between 1-D joint frequency observations in drill holes (or scanlines) and volumetric 3-D frequency (Jv) can be done using an expression similar to eq. (A-5). The joint frequency, given as the number of joints per metre, can be expressed as:

$$Jv = Nl \cdot kl \quad \text{eq. (A-6)}$$

where kl = correlation factor, which varies between 1.25 and 6, with an average value $kl = 2$. There is generally a rather poor correlation between Jv and Nl.

A5 WEIGHTED JOINT DENSITY MEASUREMENTS (wJd)

R. Terzaghi (1965) points out that the accuracy of jointing measurements can be increased by replacing the number of joints measured on a surface or in a bore hole (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

$$N_{90} = N_\alpha / \sin\alpha \quad \text{eq. (A-7)}$$

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. *"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 weighted joint density method is based on measuring the intersection 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 A1.

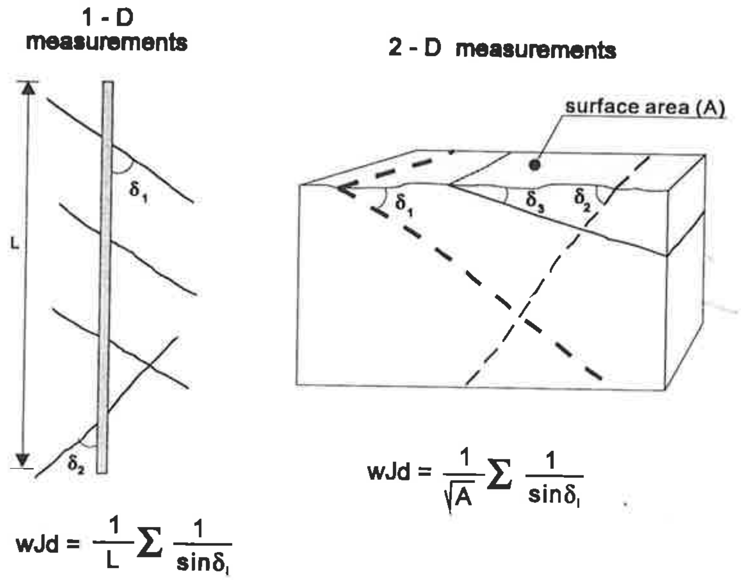

Fig. A2. The intersection between joints and a drill core hole (left) and a surface (right) (from Palmström, 1995).

For 2-D measurements (surface observations) the weighted joint density is defined as

$$wJd = (1/\sqrt{A})\,\Sigma(1/\sin\delta_i) = (1/\sqrt{A})\,\Sigma(f_i) \qquad \text{eq. (A-8)}$$

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

$$wJd = (1/L)\,\Sigma(1/\sin\delta_i) = (1/L)\,\Sigma(f_i) \qquad \text{eq. (A-9)}$$

where δ_i = the angle between the observation plane (surface) and the individual joint.
A = the size of the area in m^2, see Figure A2.
L = the length of the measured section along core or line.
f_i = the interval factor given in Table A1; its ratings have been determined by Palmström (1995a) from trial and error of various angles and joint densities.

In practice, each joint is multiplied by the value of (f_i) for the actual angle interval. After some training it should be possible to quickly determine the intervals in Table A1 for the angle δ_i. By applying these intervals the strong influence of the smallest angles, i.e. angles parallel or nearly parallel to the observation plane or bore hole, are removed

TABLE A1 SELECTED INTERVALS OF THE ANGLE (δ_i) AND THE CORRESPONDING FACTOR (f_i) (from Palmström, 1995)

angle δ_i	**factor f_i** (= $1/\sin\delta_i$)
> 60°	1
31 - 60°	1.5
16 - 30°	3.5
< 16°	6

As the weighted joint density method reduces the inaccuracy caused by the orientation of the observation surface or bore hole, it leads to a better characterization of the rock mass, which in turn may result in a reduced amount of bore holes required in an investigation.

The weighted joint density is approximately equal to the volumetric joint count, i.e. $Jv \approx wJd$.

A6 BLOCK TYPES AND SHAPES

Methods to determine the block shape factor β given in eq. (A-4) and its characterization are described in this section. The *type and shape* of blocks are determined by:

- the number of joint sets;
- the differences 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 in Figure A3. The types of blocks delineated by joints have in the literature been characterized in different ways and by different terms. Where relatively regular jointing exists, 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 no regular jointing pattern; a rough characterization of the blocks is therefore generally more practical, for example a division into three main groups only, as presented by Sen and Eissa (1991). The terms applied by Palmström (1995a) are shown in Figure A3. For β = 27 to 32 the block term 'compact' has been introduced to include cubical, equidimensional, blocky and other existing terms for blocks not being long or flat.

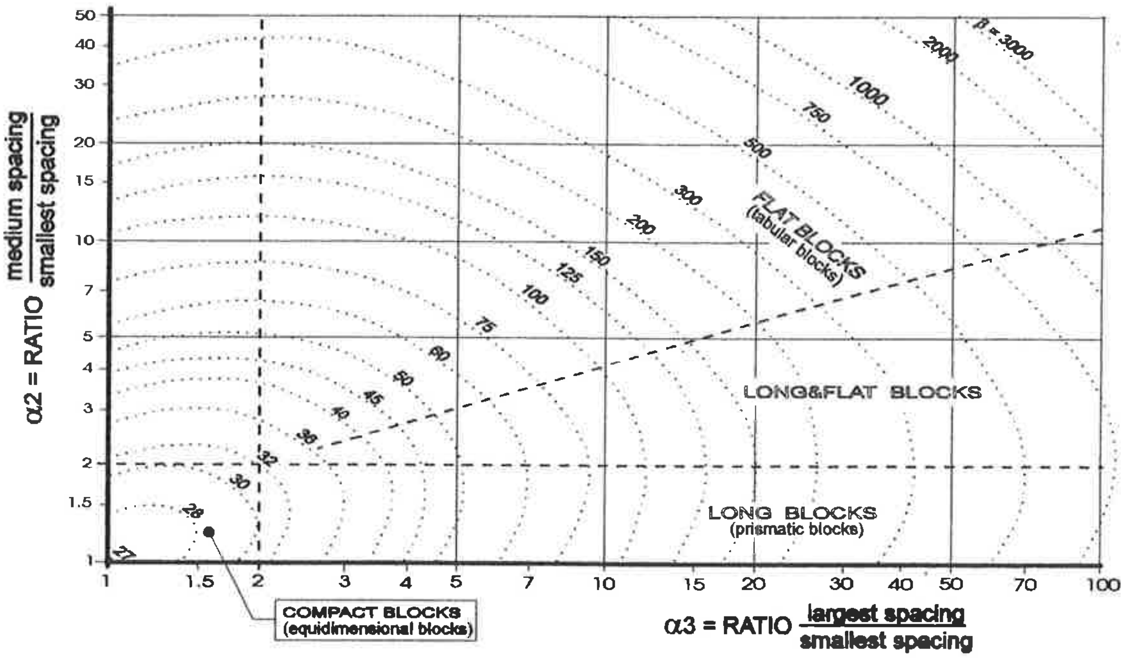

Fig. A3 Block types characterized by the block shape factor (β) found from the ratio between spacings of the joint sets. The data are based on 3 joint sets intersecting at right angles (from Palmström, 1995a). Example: For $\alpha 2 = 4$ and $\alpha 3 = 15$, $\beta = 135$.

The use of Figure A3 requires 3 joint sets. As blocks often have more than six faces or have irregular shape, it can be difficult to estimate β. Therefore, the following simplified method to estimate β has been developed by Palmström (1995a), in which the longest and shortest dimension of the block are applied:

$$\beta = 20 + 7\, a3/a1 = 20 + 7\, \alpha 3 \qquad \text{eq. (A-10)}$$

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

The evaluations made by Palmström (1995a) have shown that eq. (A-10) covers most types of blocks (where $\beta < 1000$) within reasonable accuracy ($\pm$ 25%). For very flat to extremely flat blocks (see Figure A3) eq. (A-9) has limited accuracy.

Where β is not known, it is recommended to use a 'common' value of $\beta = 40$.

A7 CORRELATION BETWEEN THE 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. Palmström (1982) presented the following simple expression:

$$Jv = 35 - 0.3\ RQD \qquad \text{eq. (A- 11)}$$

Especially where many of the core pieces have lengths around 0.1 m, the correlation above may inaccurate. However, when RQD is the only joint data available, eq. (A-11) has been found to be the best simple transition from RQD via Jv to block volume.

The block volume (Vb) can be found from the volumetric joint count (Jv) using input of the block shape factor (β) (see eqs. (A-3a) and (A-3b)).

A8 METHODS TO FIND AN EQUIVALENT BLOCK VOLUME WHERE JOINTS DO NOT DELIMIT BLOCKS

As mentioned in Section A1 a minimum of three joint sets in different directions are theoretically 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. In cases 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 used in the calculations of RMi. Such block volume may be found from one of the following methods:

1. Where only *one joint set* occurs, the equivalent block volume may be considered to be similar to the area of the joint plane[12] multiplied by distance between the two joints: $Vb = L^2 \cdot S$ Here L is the joint length and S is the spacing between the joints. [Example: For foliation partings with lengths L = 0.5 m to 2 m and average joint spacing S = 0.2 m, the equivalent block volume will vary between $Vb = S \cdot L^2 = 0.2 \cdot 0.5^2 = 0.05\ m^3$ and $Vb = 0.2 \cdot 2^2 = 0.8\ m^3$]

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. For most cases the equivalent block volume can be found from eq. (A-3b) [$Vb = \beta \cdot Jv^{-3}$] which requires input from the block shape factor (β). β can be estimated from eq. (A-10)[13] [$\beta = 20 + 7\ a3/a1$]

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[12] Here is assumed that the joint plane is circular, i.e. $A = \pi \cdot L^2/4 \approx L^2$

A method to arrive at a better estimate of β using the length and spacing of the joints, is given in the following:

Eq. (A-4) was developed for defined blocks formed by three joint sets. Where less than three sets occur, β can be adjusted by a factor n_j, which represents a rating for the actual number of joint sets, to characterize an *equivalent* block shape factor:

$$\beta = 20 + 7\,(S_{max}/S_{min})(3/n_j) = 20 + 21 S_{max}/(S_{min} \cdot n_j) \qquad \text{eq. (A-12)}$$

The ratings of n_j are given as:

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

4. For small discontinuities (fissures, partings and small joints) for which the lengths can be measured 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 replace S_{max}/S_{min} in eq. (A-12): $\beta = 20 + 21\,L/(S \cdot n_j)$ eq. (A-13)

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

A8.1 Example

For one joint set (n_j = 1) spaced at S1 = 0.2 m with an average joint length L1 = 2 m, the block shape factor according to eq. (A-13) is $\beta = 20 + 21\,L1/(S1 \cdot n_j) = 230$.
The volumetric joint count for this set is Jv = 1/S1 = 5 which gives
$Vb = \beta \cdot Jv^{-3} = 1.84\ m^3$.
[For a defined block limited by 3 joints sets crossing at right angles with spacings S1, L1, L1, the volume is $Vb = 0.2 \cdot 2 \cdot 2 = 0.8\ m^3$]

[13] As the volumetric joint count can be measured also where joints do not delimit defined blocks, this approach may be applied where few joints sets are found.