CHARACTERIZING THE STRENGTH OF ROCK MASSES FOR USE IN DESIGN OF UNDERGROUND STRUCTURES

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ABSTRACT

A rock mass is a non-homogeneous material built up of smaller and larger blocks of rock. As a great variety exists both in the composition of the rock and in the structure and occurrence of its discontinuities, the rock mass is a material exhibiting a wider range in composition and mechanical properties than most other construction materials. Reliable tests of strength properties of this complex material are impossible, or so difficult to carry out with today's technique, that rock engineering is based mainly on input data determined from observations of the rock mass.

The Rock Mass index (RMi) is providing better input data to design from characterizations based on selected, well defined parameters. Being principally based on the reduction in the strength of a rock mass from discontinuities, RMi is a general characterization of rock masses. It is expressed as $RMi = \sigma_c \cdot JP$; where σ_c is the uniaxial compressive strength of intact rock measured on 50 mm samples, and JP the jointing parameter, i.e. a reduction factor caused by the joints. JP consists of 1) the intensity of jointing, measured as block volume, and 2) the joint characteristics, i.e. joint wall roughness and alteration, and joint size.

Data from 8 large scale tests and 1 back analysis have been used to combine the jointing features into the jointing parameter.

RMi can be applied in various methods in practical rock engineering and design. In addition, some of the parameters in RMi can be used as input to classification systems. As RMi expresses the inherent properties of rock masses, it can be used to compare rock mass features from various locations directly, and thus contribute to improved communication between people involved in rock construction.

1. INTRODUCTION

A rock mass is a material quite different from other structural materials used in civil engineering. It is heterogeneous and quite often discontinuous, but is one of the materials in the earth's crust which is mostly used in man's construction. The complicated structure of the rock mass with its defects and inhomogeneities and the wide range of its applications cause challenges and problems in rock engineering and construction which often involve considerations that are of relatively little or no concern in most other branches of engineering. Therefore, a central role in underground constructions in rock is the use of 'engineering judgement'.

Some of the special features in rock contrary to other construction materials are:

- the *size* or volume of the material involved,
- the variability in *structure* and composition of the material,
- the wide range of its *construction and utilization* purposes, and
- the difficulties in measuring its *quality* and properties.

These factors implies that other methods of data acquisition are used in rock engineering. The properties of rock masses are generally not measured but estimated from descriptions and indirect tests. The stress is not applied by the engineering but is already present.

2. 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 and design for various construction purposes. In rock engineering, no such specific strength characterization of the rock mass is applied. Most engineering is carried out using various descriptions, classifications and unquantified experience. Although the various utilizations of rocks and rock masses have different purposes and are subjected to various problems, the strength properties of the rock mass are generally of main importance. Hoek and Brown (1980), Bieniawski (1984), Nieto (1983) and several other authors have, therefore, indicated the need for a *strength characterization* of rock masses.

The Rock Mass index, RMi, has been developed to characterize the strength of the rock mass as a construction material. There is no single parameter or index which can fully designate the properties of jointed rock mass. Various parameters have different significance and only if combined they can describe a rock mass satisfactorily (Bieniawski, 1984). An important issue has been to apply parameters in RMi which have the greatest significance in engineering.

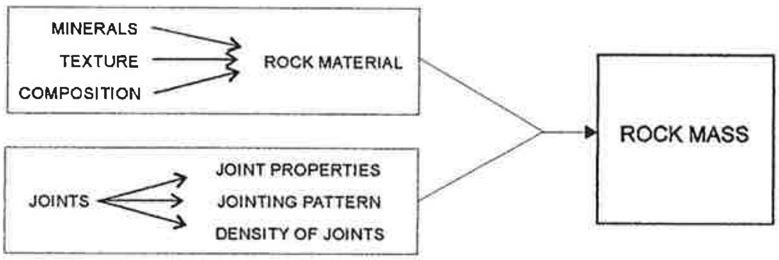

Fig. 1 The main inherent parameters constituting a rock mass

In their presentation of a general classification system Patching and Coates (1968) stressed the importance to select only <u>intrinsic parameters</u> of the rock mass *"which 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."* This has been a main target in working out the RMi system.

Another main principle in RMi is the effect from the joints in a rock mass to reduce the strength of the intact rock, expresses as $RMi = \sigma_c \cdot JP$ eq. (1)

σ_c = the uniaxial compressive strength of the intact rock material, and

JP = the jointing parameter, see Fig. 2. It is a reduction factor representing the block size and the condition of its faces represented by their friction properties and the size of the joints. The value of JP varies from almost 0 for crushed rocks to 1 for intact rock. Its value is found by combining the block size, and the joint conditions as shown in the next section.

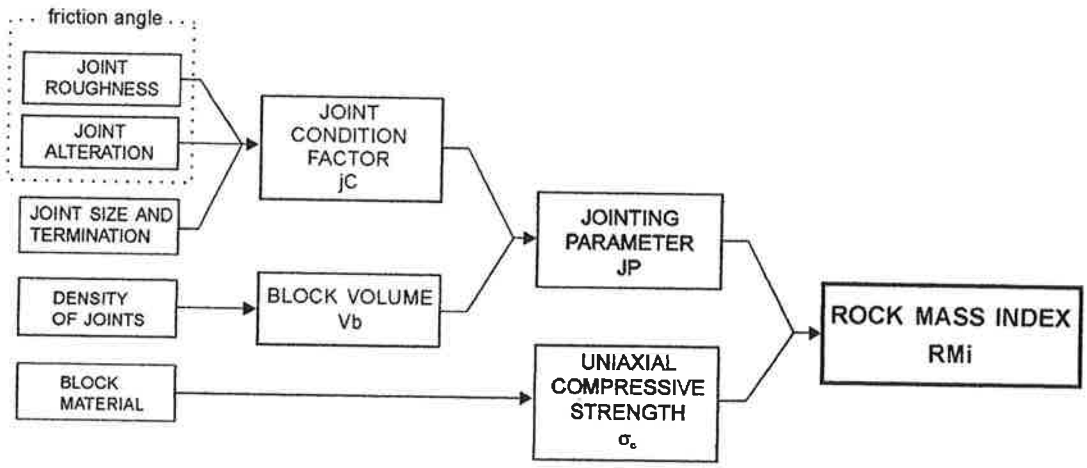

Fig. 2 The combination of the parameters used in RMi.

3. CALIBRATION OF RMi FROM KNOWN ROCK MASS STRENGTH DATA

It is practically impossible to carry out triaxial or shear tests on rock masses at a scale which is of the same size as that of underground excavations (Hoek and Brown, 1988). As the rock mass index, RMi, is meant to express the compressive strength of a rock mass, a calibration of it is necessary.

The uniaxial compressive strength of intact rock, σ_c is defined and can be determined within a reasonable accuracy. The jointing parameter (JP), however, is a combined parameter made up of several features:

- the block volume, Vb, which can be found from field measurements, and
- the joint condition factor, jC, which is the result of three independent joint parameters (roughness, alteration and size).

Results from large scale tests and field measurements of rock mass strengths have been used to determine how Vb and jC can be combined to express the jointing parameter, JP. The calibration has been performed using known test results of the uniaxial compressive strength and the inherent parameters of the rock mass. The values for Vb and jC have been plotted in Fig. 3 and the lines representing jC have been drawn.

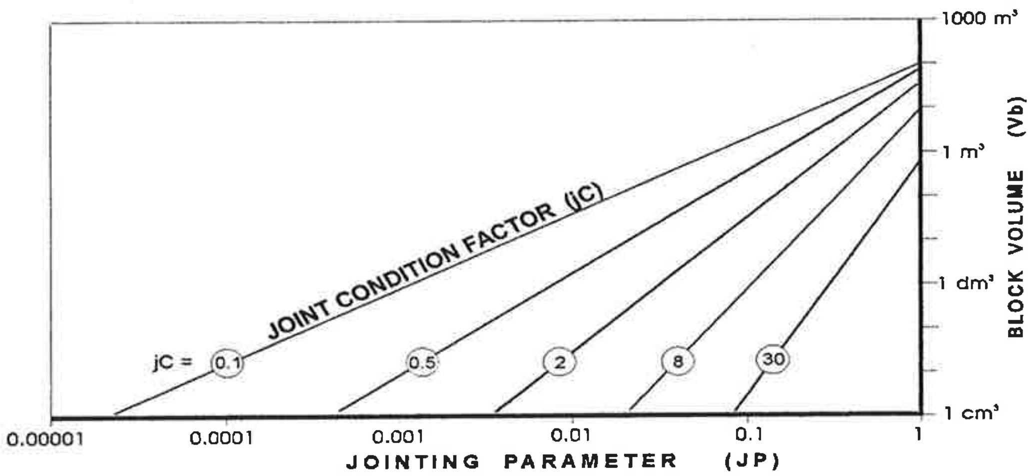

Fig. 3 The graphical combination of block volume (Vb), joint condition factor (jC) and jointing parameter (JP).

Mathematically these lines are expressed as

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

where Vb is given in m³, and $D = 0.37 \cdot jC^{-0.2}$ has following values:

for jC =	0.1	0.25	0.5	0.75	1	1.5	2	2.5	3	4	6	9	12	16	20
D =	0.586	0.488	0.425	0.392	0.37	0.341	0.322	0.308	0.297	0.28	0.259	0.238	0.225	0.213	0.203

The joint condition factor is expressed as jC = jL (jR/jA) where jL, jR and jA are factors for joint length and continuity, joint wall roughness, and joint surface alteration. Their ratings are shown in Tables 1 - 3.

Most commonly the joint condition factor jC = 1 - 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 can simply be expressed as $JP = 0.25\ \sqrt[3]{Vb}$; and for jC = 1: $JP = 0.2\ Vb^{0.37}$

Significant *scale effects* are generally involved when a 'sample' is enlarged from laboratory size to field size. From the calibration described above, RMi is tied to large samples where the scale effect has be included in JP. The joint size factor (jL) is also a scale variable. For massive rock masses, however, where the jointing parameter JP ≈ 1 the scale effect for the uniaxial compressive strength (σ_c) must be 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 'field samples' with diameter (d, measured in mm) may be determined from $\sigma_{cf} = \sigma_{c50}\ (50/d)^{0.2} = \sigma_{c50}\ (0.05/Db)^{0.2} = \sigma_{c50} \cdot f_\sigma$ eq. (3)
where σ_{c50} is the uniaxial compressive strength for 50 mm sample size.

Eq. (3) is valid for sample diameter up to some metres, and may, therefore, be applied for massive rock masses as indicated in Fig. 5. ($f_\sigma = (0.05/Db)^{0.2}$ is the scale factor for compressive strength). The approximate block diameter in eq. (3) may be found from $Db = \sqrt[3]{Vb}$, or, where a pronounced joint set occurs, simply by applying the spacing of this set.

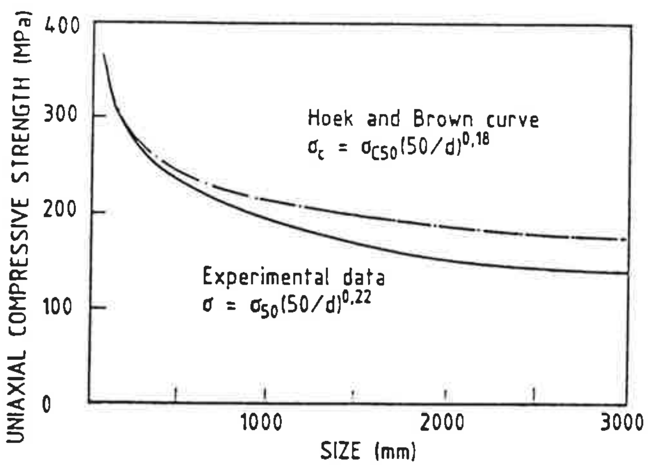

Fig. 4 Empirical equations for the scale effect of uniaxial compressive strength (from Barton (1990), based on data from Hoek and Brown, 1980 and Wagner, 1987).

Fig. 5 shows the same diagram as Fig. 3 where also other measurements than block volume can be applied to determine jC. These are showns in the upper left part in the diagram. Here, the volumetric joint count (Jv) for various joint sets (and/or block shapes) can be used instead of the block volume. Also, RQD can be used, but its inability to characterize massive rock and highly jointed rock masses leads to reduced quality of JP.

The classification of RMi is presented in Table 4.

TABLE 1 THE JOINT ROUGHNESS FACTOR (jR) FOUND FROM SMOOTHNESS AND WAVINESS
(The ratings of jR are similar to Jr in the Q-system, see Barton et al., 1974)

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 value of jR depends on the presence and outlook of the striations; the highest value is used for marked striations.

TABLE 2 CHARACTERIZATION AND RATING OF THE JOINT ALTERATION FACTOR (jA).
(jA is similar to Ja in the Q-system, except for the alteration, see Barton et al., 1974)

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	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 PARTLY OR NO CONTACT BETWEEN THE ROCK WALL SURFACES

TYPE OF FILLING MATERIAL	DESCRIPTION	Partly 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).

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

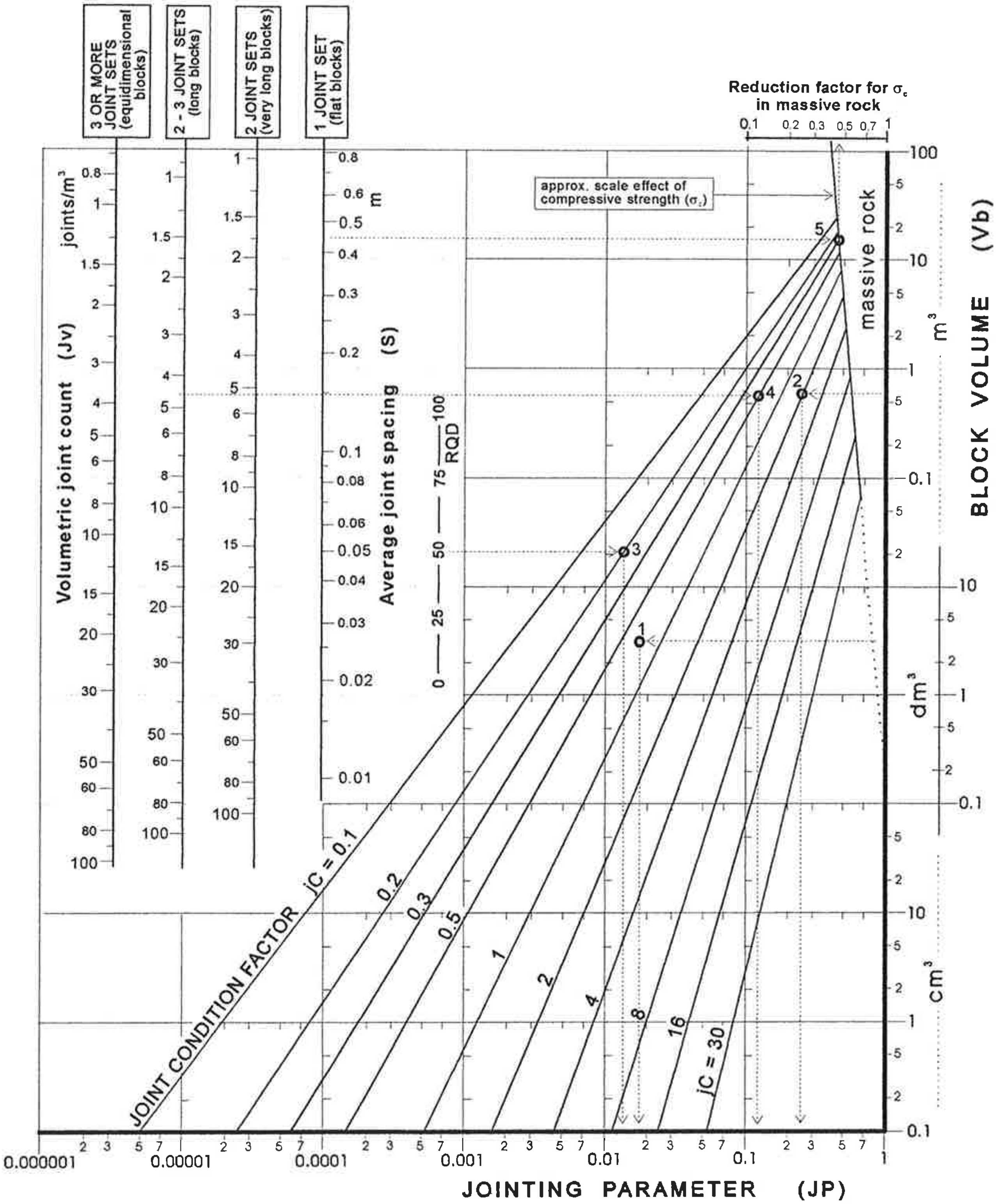

Fig. 5 The jointing parameter (JP) found from the joint condition factor (jC) and various measurements of jointing intensity (Vb, Jv, RQD). The determination of JP from Vb (or RQD or Jv) in the examples are indicated.

TABLE 4 CLASSIFICATION OF RMi

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

4. ON THE SELECTION OF THE PARAMETERS USED IN RMi

For jointed rock masses, Hoek et al. (1992) is 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 joints[1]. They recommend that these parameters are selected to represent the average condition of the rock mass. Similar ideas have been set forth by Tsoutrelis et al. (1990), Matula and Holzer (1978), Coates and Patching (1968) and Milne and Potvin (1992). This does not mean, that the properties of the intact rock material should be disregarded in the characterization. After all, if joints are widely spaced or if the intact rock is weak, the properties of the intact rock may strongly influence the gross behaviour of the rock mass. The rock material is also important if the joints are discontinuous. In addition, the rock description will inform the reader on the geology and the type of material at the site. Although rock properties in many cases are overruled by joints, it should be brought in mind that the properties of rocks highly determine the formation and development of joints. Petrological data can make an important contribution towards the prediction of mechanical performance, provided that one looks beyond the rock names at the observations on which they are based (Franklin, 1970). It is, therefore, important to retain the names for the different rock types, for these in themselves give relative indications of their inherent properties (Piteau, 1970).

These considerations and study of more than 15 different classification systems have been used in the selection of the input parameters to RMi:

- the size of the blocks delineated by joints, - measured as block volume, Vb;
- the strength of the block material, - measured as uniaxial compressive strength, σ_c;
- the shear strength of the block faces, - characterized by factors for the joint characteristics, jR and jA; and
- the size and termination of the joints, - given as their length and continuity factor, jL.

4. EXAMPLES

Example 1

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

rough joint surfaces and small undulations of the joint wall which gives jR = 3;

clay coated joints, i.e. jA= 4; and 3 - 10 m long, continuous joints gives jL = 1.

Applying the values for Vb and jC in Fig. 5, a value of JP = 0.02 [*)] is found. With a compressive strength of the rock σ_c = 150 MPa, the value of RMi = 3 (high).

[*)] using eq. (2) a value of JP = 0.018 is found

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

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

smooth joint surfaces and planar joint walls which gives jR = 4;
fresh joints, jA= 1; and 1 - 3 m long discontinuous joints, i.e. jL = 3.

From Fig. 5 the value JP = 0.25 *) is found. With a compressive strength σ_c = 50 MPa, the value of RMi = 12.5 (very strong).
*) JP = 0.24 is found using eq. (2)

Example 3
Values of RQD = 50 and jC = 0.2 give JP = 0.015 as shown in Fig. 5.

Example 4
Two joint sets spaced 0.3 m and 1 m and some random joints have been measured. The volumetric joint count Jv = 1/0.3 + 1/1 + 0.5**) = 4.5
With a joint condition factor jC = 0.5 the jointing parameter JP = 0.12 (using the column for 2 - 3 joint sets in Fig. 5)
**) *assumed influence from the random joints*

Example 5
Jointing characteristics: one joint set with spacing S = 0.45 m and jC = 8.
For this massive rock; the value of JP is determined from the reduction factor for compressive strength f_σ = 0.45. For a rock with σ_c = 130 MPa the value of RMi = 59.6 (very strong).

5. POSSIBLE APPLICATIONS OF RMi

Fig. 6 shows the main areas for application of RMi together with the influence of its parameters in different fields. The RMi-value can not be used directly in classification systems as many of them are composed of systems of their own. Some of the input parameters in RMi are sometimes similar to those used in the classifications and may then be applied more or less directly.

The jointing parameter (JP) in RMi is similar to the constant s (= JP^2) in the Hoek-Brown failure criterion for rock masses. RMi may, therefore, contribute in a future improvement of this criterion. The rock mass strength characteristics found from RMi can also be further applied in a numerical characterization in the NATM as well as for input to ground response curves.

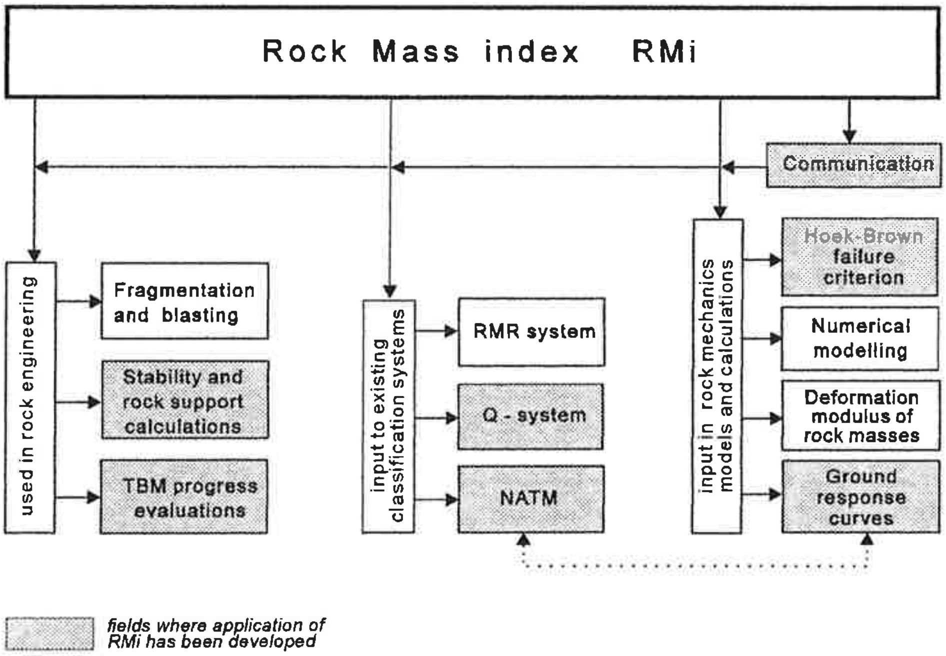

Fig. 6 The main applications of RMi in rock mechanics and rock engineering.

6. BENEFITS - LIMITATIONS

Some of the benefits using the RMi system in rock mechanics and rock engineering are:

- RMi will give significant improvements of the input of geological data applied in rock engineering by its systematic use of well defined input from rock mass characterizations.
- RMi can easily be used for rough estimates when limited information on the ground conditions is available, for example in early stages of a project where rough estimates are sufficient.
- RMi is well suited for comparisons and exchange of knowledge between different locations, as well as in general communication.
- RMi offers a stepwise system suitable for engineering judgement.
- It is easier and more accurate to find the values of s $(= JP^2)$ using the RMi system than the methods outlined by Hoek and Brown (1980) which incorporate use of the RMR or Q system.
- The RMi system covers a wide spectrum of rock mass variations and therefore has possibilities for wider applications than other rock mass classification and characterization systems.
- The use of parameters in RMi can improve input in other rock mass classification systems and in NATM

As RMi is restricted to express only the compressive strength of rock masses, 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 selection of parameters in RMi, it is clear that such an index may result in inaccuracy and limitations; the main are connected to:

- *The range and types of rock masses covered by 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 in compositions and properties of rock masses. It is, therefore, not possible to characterize all these combinations in one, single number. However, it should be added here that RMi probably may characterize a wider range of materials than most other 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) in JP and the size of the samples tested, which in some of the cases had insufficient amount of blocks, cause that there may be errors connected to the expression for JP. The value of RMi found can, therefore, turn out to be approximate. In some cases, however, the errors in the various parameters may partly neutralize each other.
- *The effect of combining parameters that vary in range.*
  The input parameters to RMi express generally a certain range of variation related to changes in the actual representative volume of a rock mass. Combination of these variables in RMi (and any other classification system) may cause errors.

The result of the foregoing is that RMi in many cases will be inaccurate in characterizing the strength of such a complex assemblage of different materials and defects that a rock mass is. For these reasons, RMi is regarded as a *relative* expression of the rock mass strength.

Acknowledgement

This paper is part of a Ph.D thesis titled 'A system for rock mass characterization useful in practical rock engineering' which has been carried out at the University of Oslo, Norway. The funding by the Royal Norwegian Council for Scientific and Industrial Research (NTNF) - from 1.1.93 Norway Research Council (NFR) - has made this work possible.
I am most grateful for all support from the Norwegian Geotechnical Institute during the development of this contribution.

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