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IMPROVING THE RELIABILITY OF GSI ESTIMATION: THE INTEGRATED GSI-RMI SYSTEM

G. Russo
Geodata SpA, Turin, Italy

ABSTRACT: This paper provides an update on the determination of the Geological Strength Index (GSI, Hoek et al., 1995) by means of a quantitative assessment of the relative input parameters. In particular, an innovative procedure has been found which consists in a rational integration of the GSI with the RMi (Rock Mass index, Palmstrom, 1994). On the base of the conceptual affinity of the GSI with the Joint Parameter (JP), a relationship between the two indexes is derived and exploited in order to obtain a reliable, quantitative assessment of the GSI by means of the basic input parameters for the determination of the RMi (i.e. the elementary block volume and the joint conditions). In this way, the user has the possibility of applying and comparing two truly independent approaches for the determination of the GSI: the traditional qualitative "Hoek's chart", mainly based on the degree of interlocking of rock mass, and the proposed quantitative assessment, mainly based on the fracturing degree of a rock mass. On the basis of such double estimation, a definitive "engineering judgement" can be more rationally expressed. The new approach favourites as well the implementation of the probabilistic approach for managing the inherent uncertainty and variability of rock mass properties. An example of application is presented to illustrate the high potentiality of the method.

1 INTRODUCTION

In current rock engineering practice, it is rather common to use quality indexes for the quantification of the geomechanical parameters, indexes through which the properties of the rock mass are defined, starting from those of the intact rock, taking into consideration the discontinuity network and the relative geotechnical characteristics.

The correct use of such an approach requires in particular:

- a reasonable possibility of assimilation of the rock mass to a "equivalent-continuous" and isotropic geotechnical model;
- reference to "pure" quality indexes that are representative of the geostructural conditions of the in situ rock mass, such as, for example, the "Geological Strength Index" (GSI, Hoek, Kaiser and Bawden, 1995 and following) and the "Joint Parameter" (JP) of the "Rock Mass Index" (RMi, Palmstrom, 1996 and subsequent updates).

As far as the GSI quantification method is concerned, it is worthwhile observing how the Authors initially indicated a derivation from the RMR (Bieniawski, 1973 and following) and Q (Barton, 1974 and following) indexes, after opportune corrections, to take into consideration only the intrinsic characteristics of the rock masses. Later on, however, Hoek progressively abandoned this procedure in favour of a direct determination based only on the use of a diagram ("Hoek's chart", see Fig. 2.5 later) that summarises the qualitative evaluation of the structural geological characteristics of rock masses and of the relative discontinuity characteristics (Hoek, 1997; Hoek and Brown,1997; Hoek ,1998; Hoek and Marinos, 2000; Hoek, 2005: personal communication).

Furthermore, Marinos et Hoek (2000, 2004) proposed other two diagrams specifically oriented to the determination of the GSI for heterogeneous (such as the flysch) and for very weak (molasse) rock mass, respectively.

The logical aspect of such an evolution is probably related to the objective of having:

- a purely "geostructural" index to reduce the intact property: this is particularly relevant in the case where the source is the RMR, as the uniaxial compressive strength of the intact rock (σ_C) is one of the input parameters;
- a qualitative estimation method that is considered the most suitable for:
  - the classification of the most unfavourable geomechanical contexts (according to Hoek, generally for GSI values < 35); incidentally, it can be observed, at the same time, how for very high GSI values (roughly > 75), the use of the index is not recommended for the derivation of the rock mass parameters according to a "equivalent-continuous" model (Hoek , 2005; Diederichs, 2005).
  - the evaluation of the "interlockness" degree of the rock blocks;
- a classification method which includes also a wider geological evaluation (Marinos et al., 2004, 2005).

The Hoek's choice has led to a lively discussion at an international level (see for example Stille and Palmstrom (2003), Bieniawski (2004), etc.).

In effect, the basic problem again crops up that has fundamentally favoured the spread of traditional geomechanical classifications, that is the risk of an excessive subjectivity in the estimation by the users, also taking into consideration their different experiences.

Furthermore, the recourse to objective measurements is essential for having a large quantity of data (for example, the borehole core boxes) and to the consequent use of statistical and/or probabilistic analysis. It should be also noted that the evaluation of interlockness degree is often very questionable when examining the core boxes.

On the other side, this last evaluation is probably the most relevant concept introduced by the Author. In fact, it is important to observe that in the Hoek's chart the classification of rock mass structure is not based on the degree of fracturing, but exactly on the interlockness degree of the rock blocks. A practical consequence is that according to the new system the elementary block volume does not necessarily change the assigned GSI rating.

For example, one rock mass should be classified as "Blocky" (Fig. 2.5) if it is "very well interlocked, consisting of cubical blocks formed by three orthogonal discontinuity sets". This means that in such case, if the discontinuity conditions are not changing, one rock mass formed by cubical blocks of 1cm^3 will have the same GSI as the one formed by blocks of 1dm^3, or even of 1m^3. Consequently, for example, a 10m diameter tunnel, subject to a certain stress condition, should exhibit the same excavation behaviour in all these cases.

It is likely to suppose that some practical experiences of excavation behaviour should have convinced the Authors about this concept, which appears to be a very controversial point, because more frequently the common practice seems to support the opposite opinion and, in addition, appears to be in contrast to:

- the most common "pure" indexes for the classification of rock mass quality (RMi, RMR', Q', RQD, ..), in which the fracturing degree is one of the main input parameters;
- the results of numerical simulation for example by Distinct Element Method (for example Shen and Barton, 1997; Barla and Barla, 2000);
- the results of laboratory test on samples formed by cubical blocks, which have frequently documented the reduction of the geomechanical properties with the reduction of the block volume; further, it should be added that Barton and Bandis (1982) pointed out that different mechanisms of failure can justify a higher rock mass strength despite the reduction of the unitary block size.

The argument is evidently "tricky" and perhaps some contrasting experience, when not justifiable by different stress conditions or construction procedure, may simply reflect the limit of the "equivalent- continuum" approach, which disregards the intrinsic discontinuity of the rock mass and the actual degree of freedom of the rock blocks with respect to the excavation surfaces.

Taking into consideration the different elements, in favour and against, an approach that adequately integrates both the qualitative and the quantitative assessment appears to be an optimal choice.

2 QUANTITATIVE INPUT FOR GSI ASSESSMENT

Different authors have proposed a quantification of the input parameters for the determination of the GSI, for example, Sonmez and Ulusay (1999) and Cai et al. (2004). All of them maintained the Hoek's chart as a general reference, finding the input criteria to get the same numerical output as the original diagram.

In particular, as schematically outlined in Fig. 2.1, Cai et al. proposed to use the Unitary Volume of the rock blocks (Vb) and the Joint Condition Factor (JC) as the quantitative input parameters for the determination of the GSI.

As is known, we are dealing with basic parameters for the determination of the RMi index of Palmstrom (1996), even though, in the specific case, the Joint Condition Factor is calculated through the simplified relation of Jc= jW*jS/jA in which jW, jS and jA are the indexes for the quantification of the undulation at a large scale, the roughness and the weathering of the discontinuities, respectively, whose classification points are obtained according to the tables proposed by the Author.

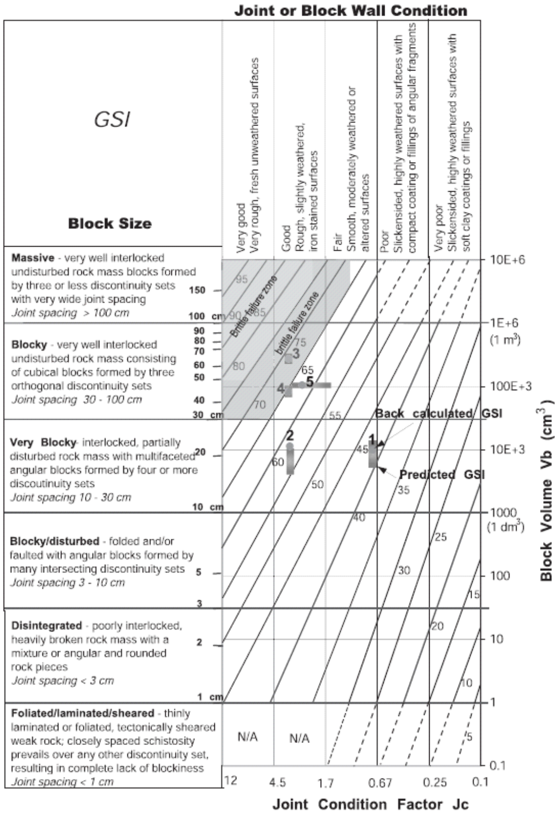


Fig. 2.1 Hoek's chart (1999) for the determination of the GSI modified by Cai, Kaiser et al., 2004.

However, the alternative method of keeping completely independent the two possible assessments of the GSI, is here considered preferable, in order to systematically apply and compare:

- the original “qualitative” approach, fundamentally based on the estimation of the degree of interlockness of the rock blocks through the Hoek's chart;
- an independent “quantitative” approach, described in the next subsection, centred on the measurement of the fracturing degree of the rock mass.

2.1 *The proposed quantitative method: the integrated GSI-RMi system (GRs)*

As already mentioned, the existing alternative proposals for the derivation of the GSI are fundamentally centred on the use of the basic parameters of the RMi system, but with adequate modification of the relative weights in order to maintain unchanged the original output (Hoek's chart).

Nevertheless, given the described conceptual background, and in particular the role of the interlockness degree in such a diagram, this exigency appears to be not fundamental and, on the contrary, an alternative and completely independent method is considered more opportune. Such a method is developed taking into consideration the conceptual equivalence between the GSI and the JP parameter (Jointing Parameter) of the RMi system, considering that both are used to scale down the intact rock strength (σ_c) to rock mass strength (σ_{cm}).

According the two systems, we in fact obtain:

1) RMi: $\sigma_{cm} = \sigma_c * JP$
2) GSI: $\sigma_{cm} = \sigma_c * s^a$ (where s and a are the Hoek & Brown constants)

JP should therefore be numerically equivalent to s^a and given that for undisturbed rock masses (Hoek et al., 2002):

$s = \exp[(GSI-100)/9]$ and $a=(1/2)+(1/6)*[\exp(-GSI/15)-\exp(-20/3)]$

The direct correlation between JP and GSI can be obtained, i.e.:

$JP = [\exp((GSI-100)/9]^{(1/2)+(1/6)*[\exp(-GSI/15)-\exp(-20/3)]}$

For the inverse derivation, the perfect correlation ($R^2 = 0.99995$) can be used with a sigmoidal (logistic) function of the type:

$GSI=(A1-A2)/[1+(JP/X_o)^p]+A2$

with $A1=-12.19835$; $A2=152.96472$; $X_o=0.19081$; $p=0.44318$.

On the basis of this correlation, a quantitative “robust” estimation of the GSI can be assessed, by defining the parameters concurrent to the evaluation of JP, i. e. the block volume (Vb) and the Joint Condition factor (jC). A graphic representation of the described correlation is presented in Fig. 2.2.

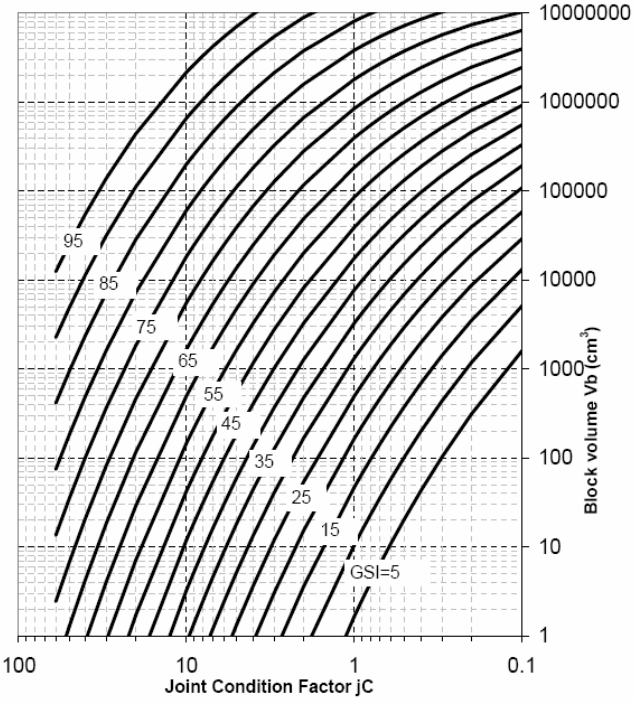


Fig. 2.2: New proposed diagram for the assessment of GSI by means of the RMi parameters jC and Vb.

It should be noted that here the Joint Condition Factor (jC) is of course the original one proposed by Palmstrom, i.e. including the jL factor that expresses the persistence of the discontinuities: $jC_{(Palmstrom)}=jR*jL/jA$ where $jR=jW*jS$. For example, the case jL=1 corresponds to an average joint length of 1÷10m.

As indicated for example in Fig. 2.3, Palmstrom developed different methods for the derivation of the Unitary Volume of the Blocks (Vb) on the basis of statistical analyses and illustrated correlations with the different joint indexes of the rock masses (RQD, number of discontinuities per linear, squared or cubic metre (Jv), weighted density of the discontinuities (wJd, Fig. 2.4), etc.).

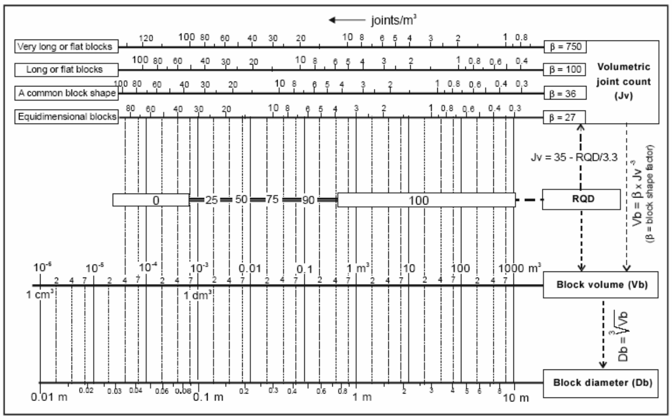
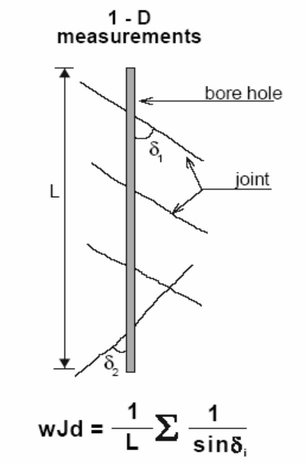


Fig. 2.3 Different fracturing indexes and their reciprocal correlations (Palmstrom, 2000)



$$wJd = \frac{1}{L}\sum\frac{1}{\sin\delta_i}$$

The evaluation of the Vb is also improved through the estimation of the shape factor of the rock blocks (β), on the basis of which, for example, the relations $Vb=\beta*Jv^{-3}=\beta*wJd^{-3}$ are proposed, given that, according to the Author, wJd≈Jv.

Furthermore, the Jointing Parameter is calculated by means of the equation $JP=0.2*jC^{0.5}*Vb^{D}$ in which $D=0.37*jC^{-0.2}$.

Fig. 2.4: Calculation of the wJd from scanline (Palmstrom, 2000)

A complete treatment of the RMi method can be found on A. Palmstrom’s web site www.rockmass.net.

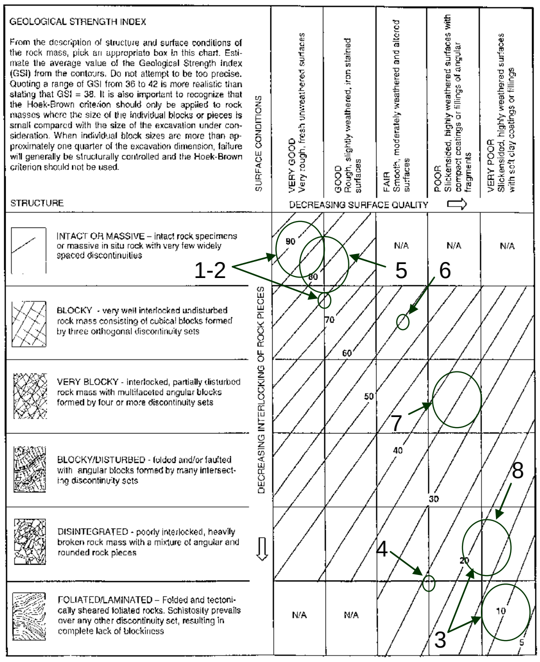
Just as an example of application, in Figs. 2.5 (a,b), some case histories reported by Hoek in different papers have been processed for determining the GSI by means of the proposed quantitative approach and compared with the original classification furnished by the Author (Fig. 2.6).

The link between the considered example and the reference paper is highlighted in the bibliography section by the relative number in square brackets (e.g.: [→*3*]).

Evidently, this attempt of comparison may be just indicative and in general the evaluation of the discontinuity condition have not been changed from the original in order to focus better on the rock mass structure assessments.

In the diagram of Fig. 2.6, other direct applications of the two methods to some representative rock outcrops in the Alpine domain have been added for enriching the comparison.

As one can see in such figure, as expectable, a certain difference between the two determinations of the GSI are observed, mainly in the central part of the graph, where probably the influence of the block size rating determines the highest scatter respect the traditional approach.



GEOLOGICAL STRENGTH INDEX

From the description of structure and surface conditions of the rock mass, pick an appropriate box in this chart. Estimate the average value of the Geological Strength Index (GSI) from the contours. Do not attempt to be too precise. Quoting a range of GSI from 36 to 42 is more realistic than stating that GSI = 38. It is also important to recognize that the Hoek-Brown criterion should only be applied to rock masses where the size of the individual blocks or pieces is small compared with the size of the excavation under consideration. When individual block sizes are more than approximately one quarter of the excavation dimension, failure will generally be structurally controlled and the Hoek-Brown criterion should not be used.

INTACT OR MASSIVE – intact rock specimens or massive in situ rock with very few widely spaced discontinuities

BLOCKY - very well interlocked undisturbed rock mass consisting of cubical blocks formed by three orthogonal discontinuity sets

VERY BLOCKY - interlocked, partially disturbed rock mass with multifaceted angular blocks formed by four or more discontinuity sets

BLOCKY/DISTURBED - folded and/or faulted with angular blocks formed by many intersecting discontinuity sets

DISINTEGRATED - poorly interlocked, heavily broken rock mass with a mixture of angular and rounded rock pieces

FOLIATED/LAMINATED – Folded and tectonically sheared foliated rocks. Schistosity prevails over any other discontinuity set, resulting in complete lack of blockiness

Fig. 2.5 (a): Some GSI values from different case histories reported in Hoek's papers.

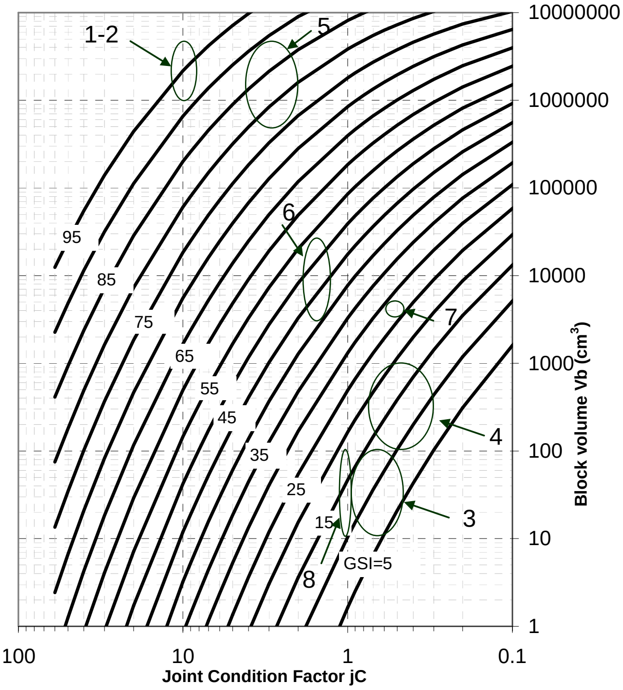


Fig. 2.5 (b): GSI values obtained for the same case histories as those in Fig.2.5(a)

A comparison between the method proposed by Cai et al. and the new system is shown in the next subsection, by means the application of a probabilistic approach.

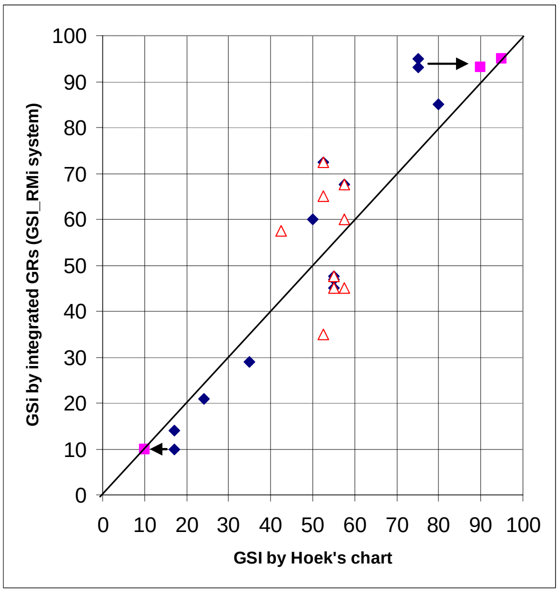


Fig. 2.6: Correlation between the GSI mean values in Fig. 2.5 (a,b) and between other practical applications described in the text (triangular symbols). The two arrows in the figure highlight also the effect of some modifications to the original GSI values that appear more consistent with the approximate re-interpretation of the examined data.

2.2 *Probabilistic implementation of the "quantitative" approach*

As already experimented in several practical cases, the application of the described quantitative methods with a probabilistic type of approach is considered to be particularly interesting and of great potential (Russo and Grasso, 2006). This approach allows the variability and/or uncertainty of the available data to be adequately taken into account. In particular, when the latter are statistically significant (in quantitative and qualitative terms), the frequency histograms and/or the density functions that best describe the data distribution are used as input. At the same manner, in cases of great uncertainty and lack of data, the probabilistic approach allows the assumed parametric variability field to be considered on the basis of expert estimates.

Figures 2.7 and 2.8(a,b) show an input/output of the probabilistic analysis example conducted applying the MonteCarlo method (500 simulations with Latin-Hypercube sampling) for the probabilistic derivation of Vb and jC, and therefore of the GSI, by the two previously described “quantitative” methods.

In order to favour a comparison between these two methods, a unitary value of the parameter jL is assumed so that Jc $_{\text{(Cai et al.)}}$ = jc $_{\text{(Palmstrom)}}$. The analysis examined some surveys performed in calcareous-dolomite rocks and did not consider the fault and/or intense fractured zones, which were studied separately. The results can therefore be considered, in this case, representative of the “ordinary” conditions of the rock mass.

In short, the analysis of the available data led to the quantification of the input parameters with the distributions indicated in Fig. 2.7 from each of them, at each simulation, a value is sampled and concur to the assessment of a single GSI value. The GSI values obtained from the analysis are explained in the two diagrams shown in Fig. 2.8 (a,b): each point highlighted by a circle represents a possible result, which is the fruit of the probabilistic combination of the input parameters. For comparison purposes, the graphs also report some deterministic evaluations of the GSI conducted on rock outcrops of the same lithology (cross symbols).

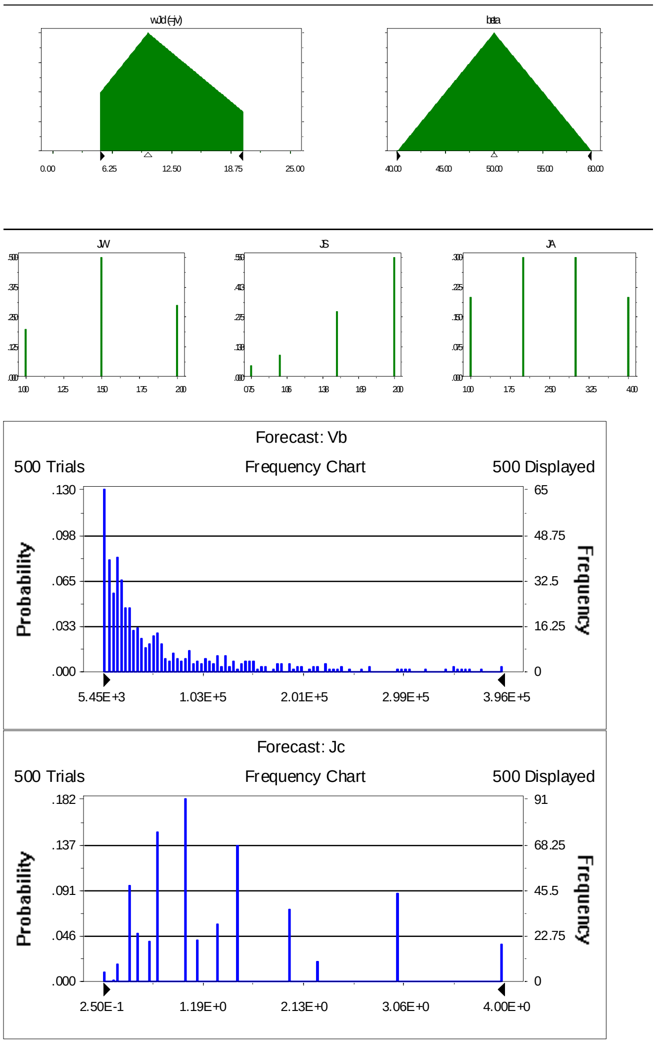


Fig.2.7: Example of probabilistic quantitative assessment of GSI. Above: input parameters [wJd(≈Jv),β,jW,jS,jA]; below: calculated parameters [(Vb,Jc)]. The derived GSI distributions for both the applied methods are compared in Fig. 2.9.

Looking at Table 2.1 et Fig. 2.9, it can be seen that, in the case under examination, the use of the two approaches give rather comparable results for the central part of the frequency distributions. The "GRs" approach, however, yields a relatively wider spread in the tails of the distributions, marked by a difference between the two extreme percentiles of 44 points, against the 33 obtained with the Cai method. The simplifying assumption, on one hand, of jL = 1 and therefore Jc = jC should however be recalled and on the other hand, more generally, much more marked differences can be associated to the analysis of more unfavourable geotechnical contexts. It can be seen, for example, how an examination of a hypothetical condition of jC=Jc=1 e Vb=10cm^3 would lead to GSI values equal to about 30 with the Cai method and only about 10 with the GRs.

As commented in section 1, it is interesting to observe that the use of the Hoek's chart might lead to very high GSI values also in such highly fractured conditions of the rock mass, if, for example, the "Blocky" structure would be recognised.

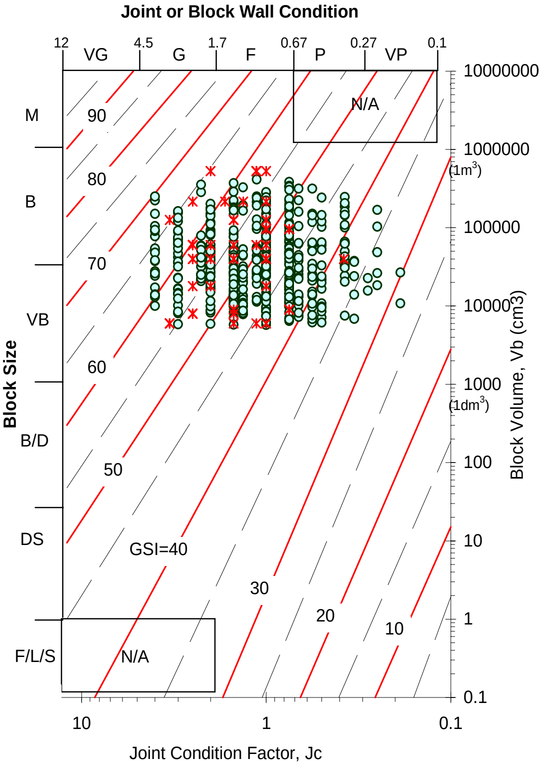


Fig. 2.8(a): Results of the probabilistic calculation using the Cai et al. method

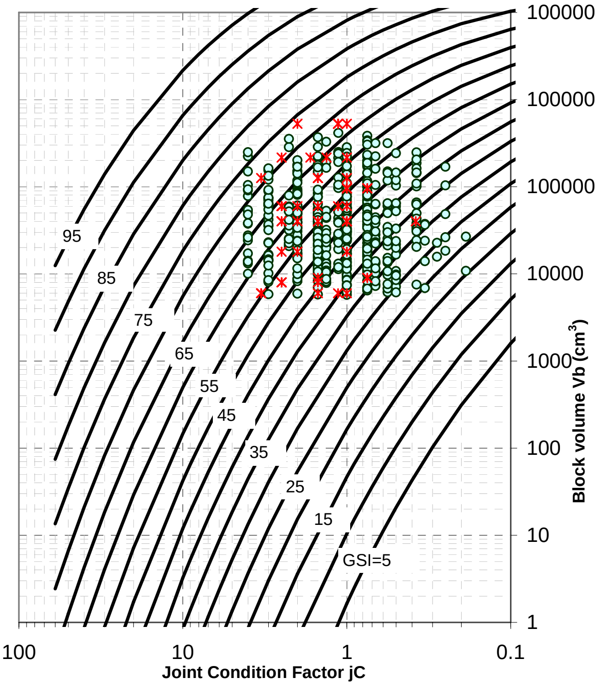


Fig. 2.8 (b): Results of the probabilistic calculation using the new "GRs" approach

fractile	GSI	
	Cai et al.	GRs approach
0.01	33	28
0.25	44	44
0.50	48	50
0.75	54	58
0.99	66	72

Table 2.1 Results of the probabilistic analysis reported in Figs. 2.8 (a,b).

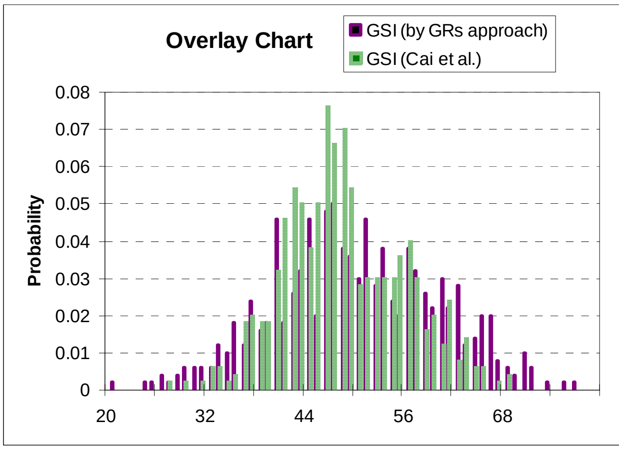


Fig. 2.9: Overlay chart for the comparison of the results of the probabilistic simulation by the GRs and the Cai et al. approach.

3 CONCLUSIVE REMARKS

A new method for the GSI estimation has been proposed, mainly based on the quantitative assessment of the same parameters concurring to the calculation of the Jointing Parameter (JP) used for the determination of the RMi.

The approach is not intended to substitute the "qualitative" approach centred on the use of the Hoek's chart, but more properly to integrate it by a completely independent system.

In such a way, the final engineering judgement can be assessed on the basis of both the traditional method, essentially based on the degree of interlocking of rock masses, and the new system, mainly based on the measured state of fracturing.

Furthermore, the new approach is not covering special cases of complex and/or weak rock, in which the cited specific charts proposed by Hoek and Marinos appear to be more adequate, if the basic conditions of applicability of the GSI are satisfied.

Finally, as further important step, it is important underline that the proposed approach favourites as well the concurrent calculation of the RMi and consequently the possibility of application of the empirical method for tunnel design developed by Arild Palmstrom.

Given the complementarities, the proposed integrated system appears to be very promising.

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