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A NEW RATIONAL METHOD FOR CALCULATING THE GSI

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ABSTRACT: In this paper a new approach for a quantitative assessment of the Geological Strength Index (GSI, Hoek et al., 1995) is proposed. In particular, on the basis of the conceptual affinity of the GSI with the Joint Parameter (JP) used in the RMi (Rock Mass index, Palmstrom, 1994), 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 method, mainly based on the fracturing degree of a rock mass. On the basis of such a double-estimation, a definitive "engineering judgement" can be made more rationally. The new approach facilitates as well the implementation, from one side, of the probabilistic approach for managing the inherent uncertainty and variability of rock mass properties and, from the other, of the RMi system as empirical method for tunnel design. Given the complementarities of the two indexes, the proposed approach appears to be very promising. An example application is presented to illustrate the high potentiality of the new method.

1 INTRODUCTION

In the last decades, a general trend towards quantitative tunnel design is observed, in order to guarantee safety and stability of the tunnel at every stage of construction.

This has demanded for a more and more reliable method to quantify the properties of the ground, and as of this the basic decision about the most adequate approach to be used, distinguishing in particular between the discontinuum (DCA) and the equivalent continuum (ECA) approaches often has be made at the early stage of the design. In the former case (DCA), the rock mass is analyzed as a system composed of blocks, each of them interacting with their neighbors through the joints. On the contrary, according to ECA the rock is treated as a continuum medium, with equal-in-all direction geomechanical properties [1].

When, in function of the rock mass structure related to the dimension of the excavation, the ECA approach is reasonably applicable [4,23], the use of the geostructural indexes is rather common to reduce the intact rock properties to that of the in situ conditions.

In particular, for the described application, it is important to refer to the so-called "pure" quality indexes [27,28], which may be representative of the actual geostructural conditions of the rock mass (discontinuity network and relative geotechnical properties). The Geological Strength Index (GSI) [14,17,22,23] and the Jointing Parameter (JP) of the Rock Mass index (RMi) [24,25] are two of the most known and frequently used indexes.

As far as the GSI index is concerned, it is worthwhile observing how the Authors (Hoek et al.) initially indicated a derivation from the "Rock Mass Rating" RMR [6,7,8], as well as from the "Q-system" [2,4], after opportune corrections, to take into consideration only the intrinsic properties 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. 3.5 later) that summarises the qualitative evaluation of the structural, geological characteristics of rock masses and of the relative discontinuity characteristics [12,18,20,23].

Furthermore, Marinos et Hoek [19,21] proposed other two diagrams specifically oriented to the determination of the GSI for heterogeneous (such as a flysch) and for very weak (molasse) rock masses, 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);
  - the evaluation of the "interlockness" degree of the rock blocks;
- a classification method which includes also a wider geological evaluation [22,23].

The evolution of the GSI system in a more qualitative direction has led to a lively discussion at an international level [9, 32].

In effect, a 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 considering 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 cited Authors. 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 cause a change in the assigned GSI rating. For example, a rock mass should be classified as "Blocky" (Fig. 3.5) if it is "very well interlocked, consisting of cubical blocks formed by three orthogonal discontinuity sets". This means that in such a 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 about the excavation behaviour of certain jointed rock masses might have convinced the Authors about this concept, which appears to be a very controversial point, because often the common practice seems to support the opposite opinion and, in addition, it 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 [1, 30 (see Fig.1)];
- the results of laboratory test on samples formed by regular blocks, which have frequently documented the reduction of the geomechanical properties with the reduction of the individual block volume; nevertheless, it should be added that below a certain limit, different mechanisms of failure (in particular, rotational mode) can justify a higher rock mass strength despite the reduction of the unitary block size [3, 5].

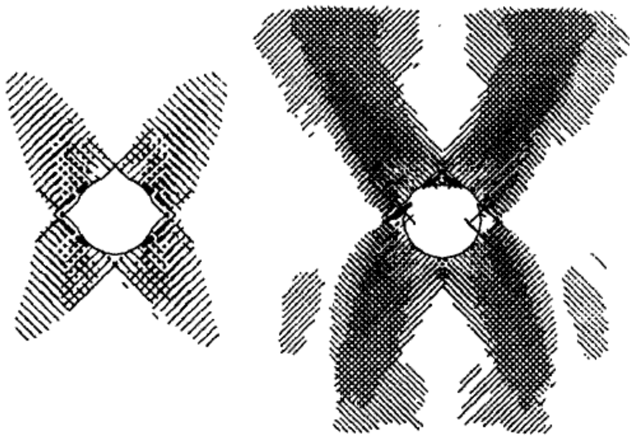

Fig.1: Example of numerical simulation by Distinct Element Method (UDEC) showing the increase of shear zones with the reduction of the unitary block dimension from the left to the right [30].

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 boundaries.

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, and such is the main subject of this paper.

2 PREVIOUS PROPOSALS FOR A QUANTITATIVE ASSESSMENT OF GSI

Different authors have proposed a quantification of the input parameters for the determination of the GSI, for example, Sonmez and Ulusay [31] and Cai et al. [10].

In particular, the former Authors [31], suggest a quantification respectively of the rock mass structure rating by means of the Volumetric Joint Count (Jv), i.e. the number of discontinuities per cubic meter [24], and of discontinuity conditions by a parameter called SRC (Surface Condition Rating) essentially based on the RMR system (Fig.2.1).

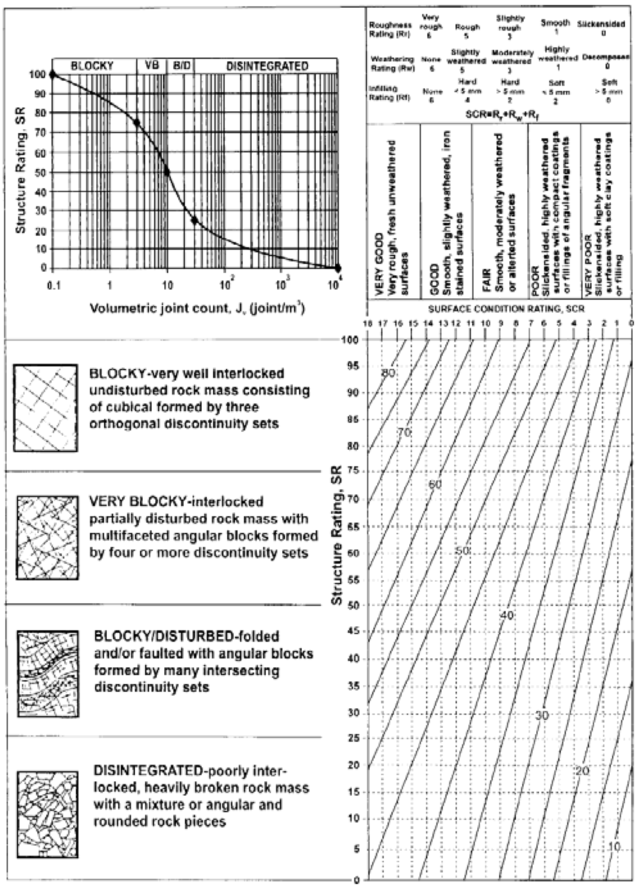

Fig.2.1: Modified Hoek's chart for the determination of the GSI proposed by Sonmez and Ulusay [31].

On the other hand, Cai et al. [10], for the same purposes just described, propose to refer to 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 (Fig.2.2).

As is known, we are dealing with basic parameters for the determination of the RMi index of Palmstrom [24, 25] even though, in the specific case, the Joint Condition Factor is calculated through the simplified relation of Jc= jW*jS/jA, i.e. without including the original Joint Size Factor jL, which takes into account the persistence of discontinuities. 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. The classification ratings for these 3 indexes can be obtained according to the tables proposed by Palmstrom (see the Appendix).

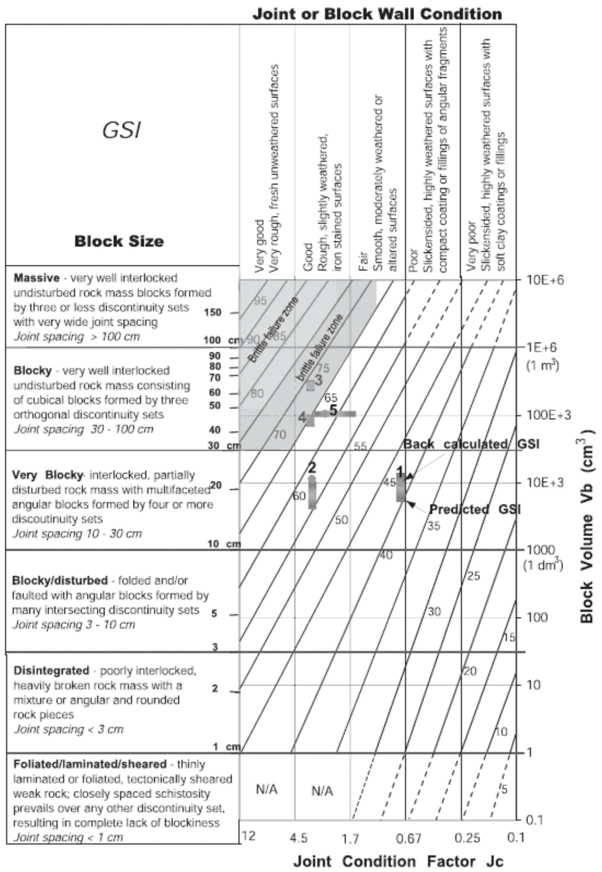

Fig. 2.2 Hoek's chart (1999) for the determination of the GSI modified by Cai et al. [10].

It is possible to observe that both of the described methods are maintaining Hoek's chart as the general reference, finding some adequate input criteria to get the same numerical output as obtainable from the original diagram.

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.

3 THE NEW PROPOSED QUANTITATIVE METHOD

As already mentioned previously , the existing alternative methods for the derivation of the GSI are mainly centred on the use of some parameters used in 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, such objective appears to be not fundamental and, on the contrary, an alternative and completely independent method is considered more opportune [29]. Such a new method ("GRs") 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 with 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)

Therefore, JP should be numerically equivalent to s^a, and given that for undisturbed rock masses [15]:

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

Then, a direct correlation between JP and GSI can be obtained (Fig.3.1a), i.e.:

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

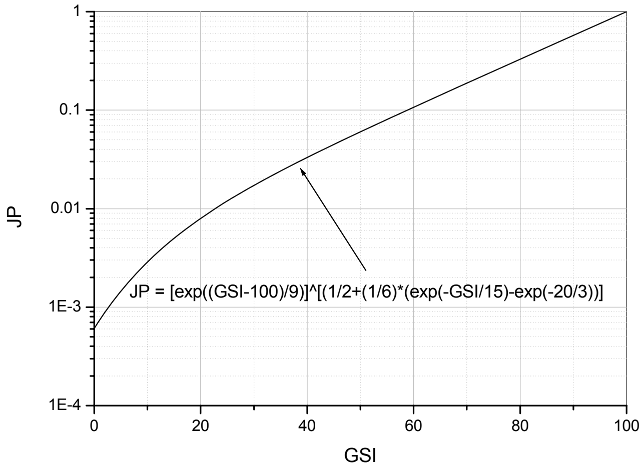

Fig. 3.1(a): Relationship between GSI and JP.

Note: in line with Hoek et al. indications [20], a minimum GSI value of 5 is suggested for practical purpose.

For the inverse derivation, the perfect correlation (R^2 = 0.99995) can be used with a sigmoidal (logistic) function of the type shown in Fig. 3.1b, which presents just some negligible differences only for very low values (GSI<5):

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

with A1=-12.198; A2=152.965; X_o=0.191; p=0.443. Then: $GSI \approx 153-165/[1+(JP/0.19)^{0.44}]$

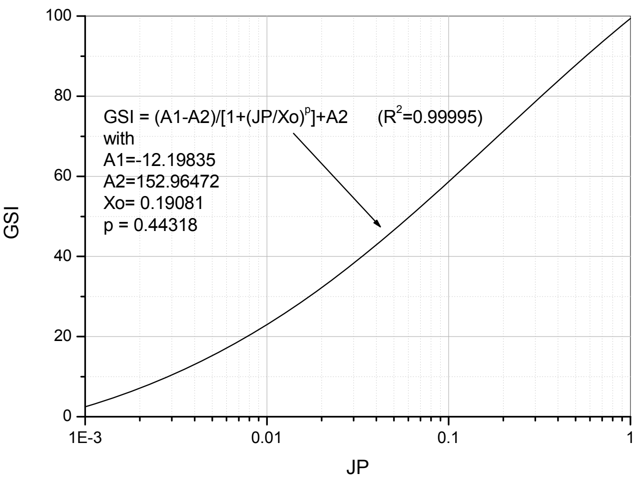

Fig. 3.1(b): Sigmoidal correlation between JP and GSI.

Note: in agreement with the comment to the Fig.3.1(a), a minimum GSI of 5 is suggested for practical purpose.

On the basis of the above correlations, a quantitative “robust” estimation of the GSI can be made, 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 found relationship is presented in Fig. 3.2. 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: $jC_{(Palmstrom)}=jR*jL/jA$ where $jR=jW*jS$. For example, the case jL=1 corresponds to an average joint length of 1÷10m.

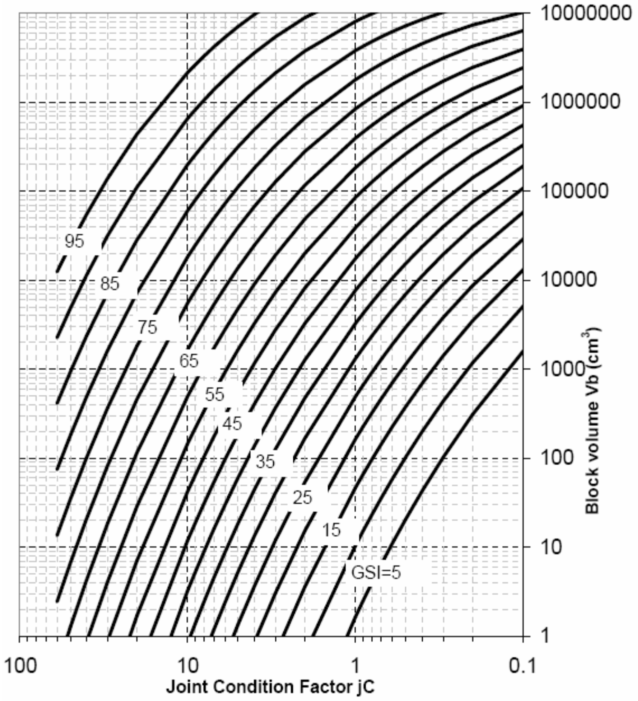

Fig. 3.2: New proposed diagram for the assessment of GSI by means of the RMi parameters jC (see in Appendix) and Vb.

Note: as previously described about the minimum GSI value, the value GSI=5 should be assigned to the cases falling in the low right corner of the graph.

As indicated for example in Fig. 3.3, Palmstrom [24,25] 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 for the rock masses (RQD, number of discontinuities per linear, squared or cubic metre (Jv), weighted density of the discontinuities (wJd, Fig. 3.4), etc.).

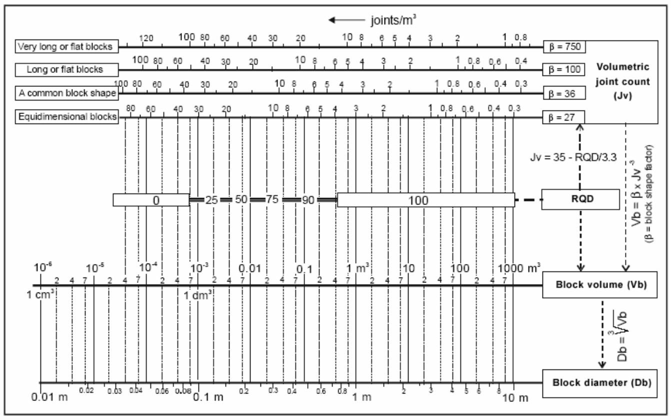

Fig. 3.3 Different fracturing indexes and their reciprocal correlations [24].

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 $D=0.37*jC^{-0.2}$.

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

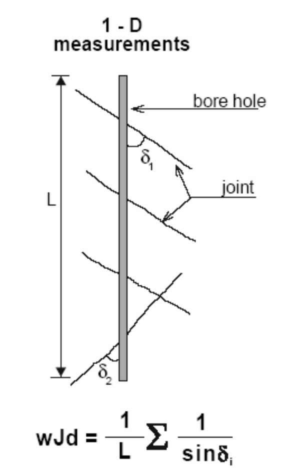

Fig. 3.4: Calculation of the wJd from scanline [24]

Just as an example of application, in Figs. 3.5 (a,b), some case histories reported by Hoek and his collaborators in different papers have been processed for determining the GSI by means of the new proposed quantitative method.

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

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

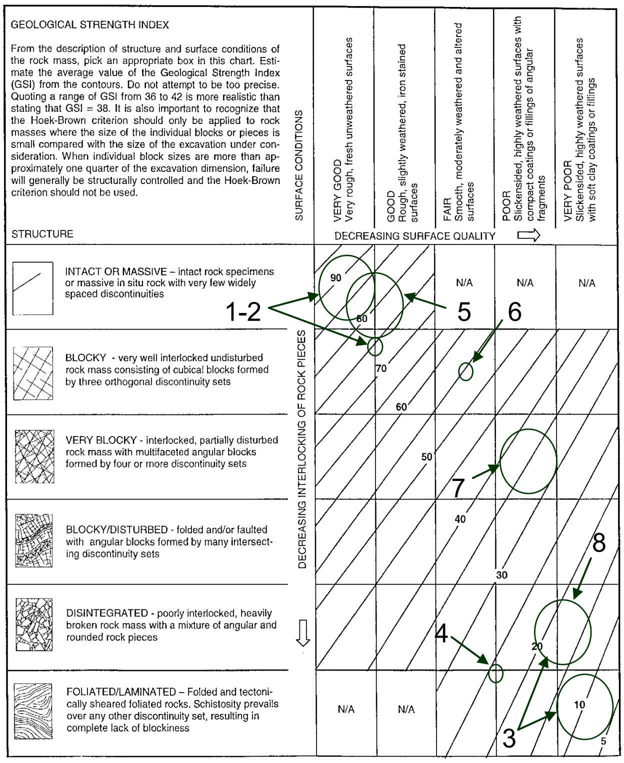

Fig. 3.5 (a): Some GSI values from different case histories reported in Hoek's papers.

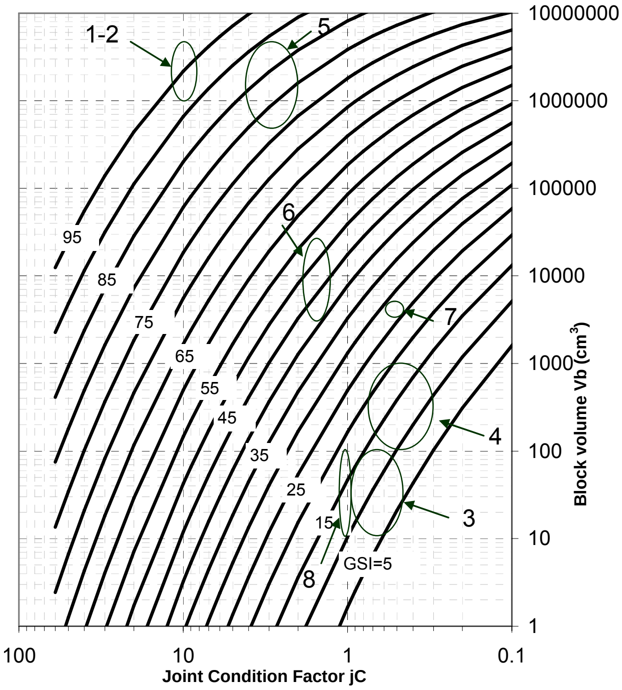

Fig. 3.5 (b): GSI values obtained for the same case histories as those in Fig.2.5(a)

In Fig. 3.6(a) the comparison of the two approaches is more clearly represented, both for the above examples and, in addition, for n.97 geostructural surveys realized on different representative rock outcrops in the Alpine structural domain.

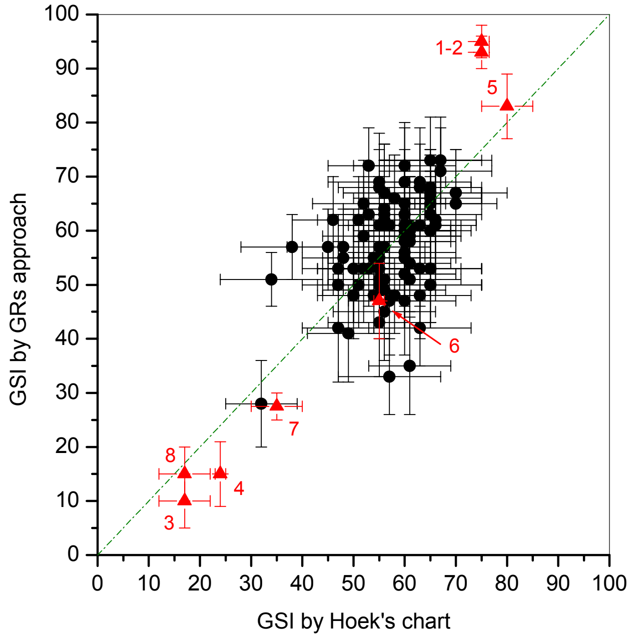

Fig. 3.6: Comparison between the GSI values in Figs. 3.5 (triangular symbols, references in Bibliography), as well as between the results of n.97 geostructural surveys (black circles) in the Alpine structural domain. For the new quantitative approach ("GRs"), the probabilistic method has been implemented, as further described in the Section 4, and the error bars in the figure correspond to two times the standard deviation.

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 greatest scatter respect the traditional approach, or, more simply, the density of the available data is higher.

The scatter of the results in the central part of the graph appears rather symmetrical with respect to the perfect correlation and determines the similarity of statistics reported in Fig. 3.6 (b).

A certain tendency to derive by the GRs method lower and higher values than the traditional approach, it is observed in the lowest (~GSI<25) and highest (~GSI>75) zones of the graph of Fig. 3.6(a), respectively.

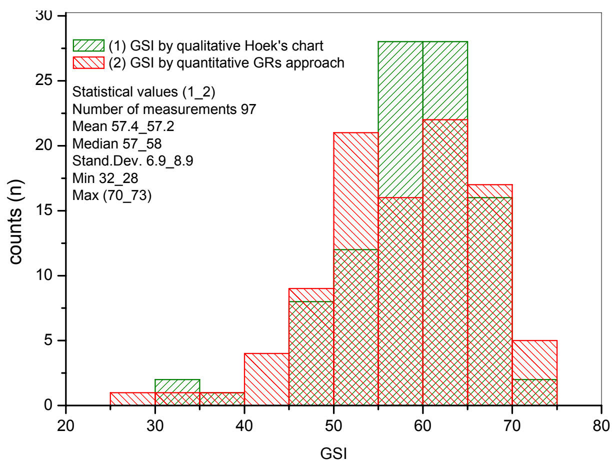

Fig. 3.6 (b): Comparison of the histograms and statistical values of the GSI for the n. 97 geostructural surveys realized.

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

4 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 [28].

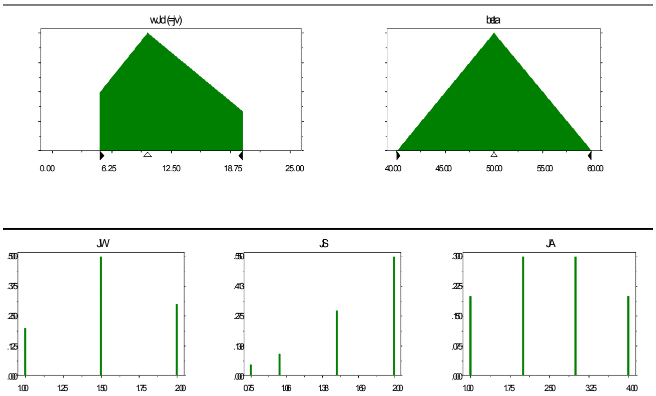

Fig. 4.1 (a): Example of probabilistic, quantitative assessment of GSI. Input parameters (from left to right)→ above: wJd(≈Jv), β; below: jW , jS and jA

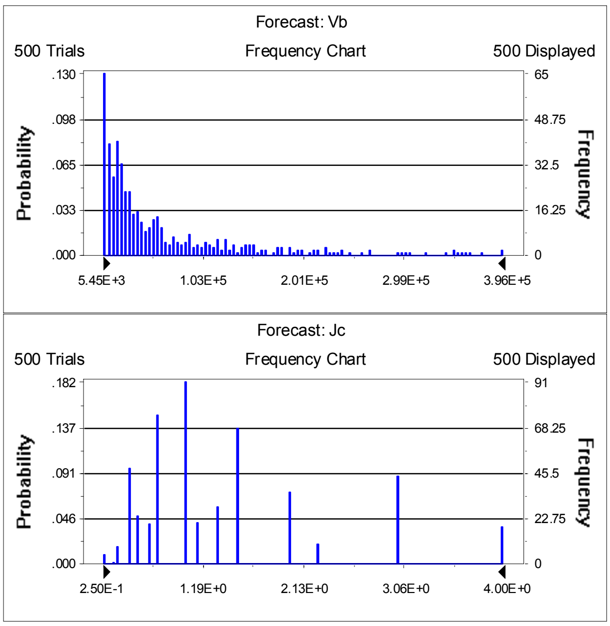

Fig. 4.1 (b) : Example of probabilistic quantitative assessment of GSI. Calculated parameters (Vb,Jc). The derived GSI distributions for both the applied methods are reported in Fig. 4.2 (a,b) and compared in Fig.4.4 and Tab.4.1.

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. In 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 4.1(a,b) and 4.2(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 facilitate 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 boreholes 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. 4.1(a) 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 Figs. 4.2 (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).

It can be seen from Table 4.1 et Fig. 4.4 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 new “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.

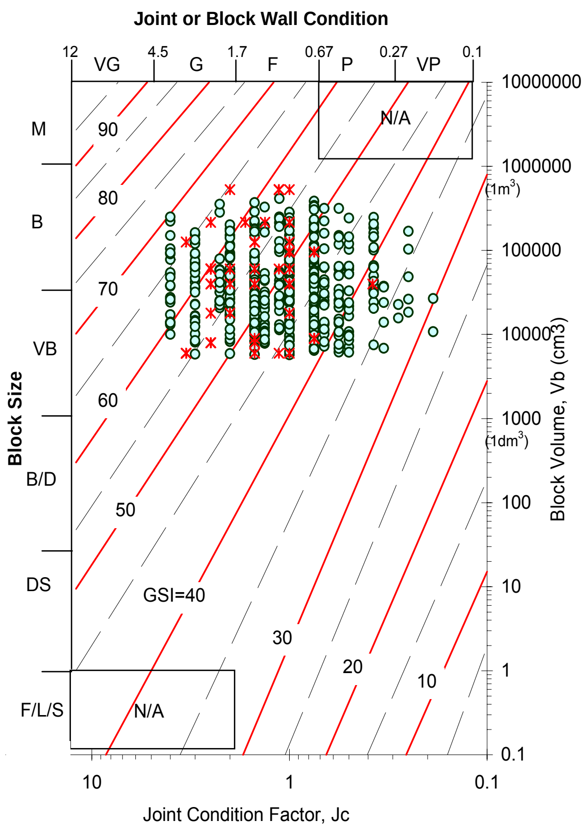

Fig.4.2(a): Results of the probabilistic analysis with the method of Cai et al.

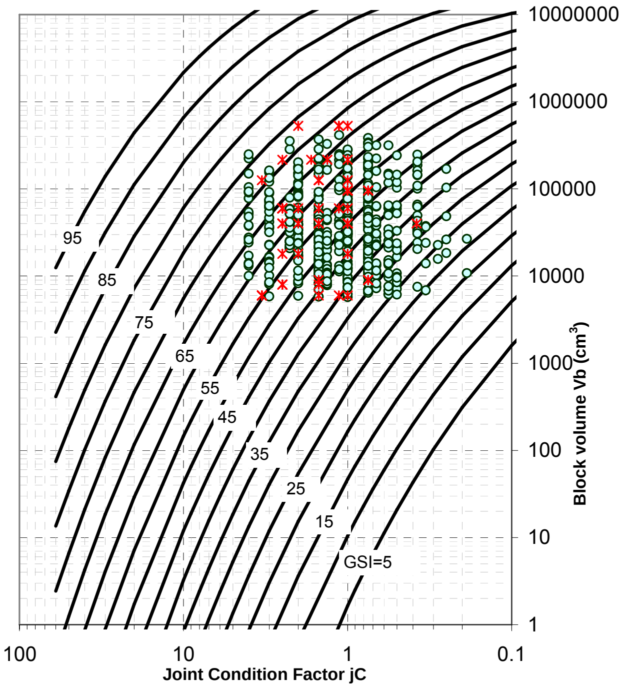

Fig.4.2(b): Results of probabilistic analysis with the GRs approach

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 and Vb=1000cm^3 would lead to GSI values equal to about 39 with the Cai method and about 28 with the GRs. This result is confirming that the unitary rock block volume appears to play a more relevant role in the GSI determination for the GRs approach than for the Cai approach (Fig. 4.3).

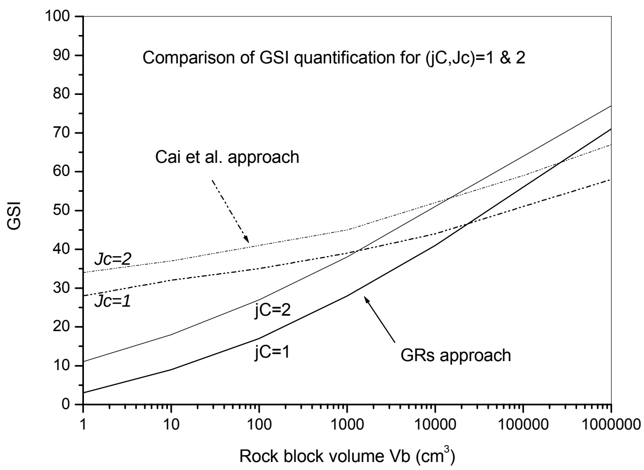

Fig.4.3:Comparison between the Cai et al. approach and the GRs approach for jC,Jc=1-2.

Note: It must be observed that the lines are only theoretical ones for low Vb values, given the very remote possibility of combination with the considered joint conditions. Furthermore, the simplified assumption jL=1 is not realistic for such cases.

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 4.1: Results of the probabilistic analysis reported in Figs. 4.2 (a,b).

Furthermore, as already commented in Section 1, it is interesting to observe that the use of the Hoek's chart alone 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.

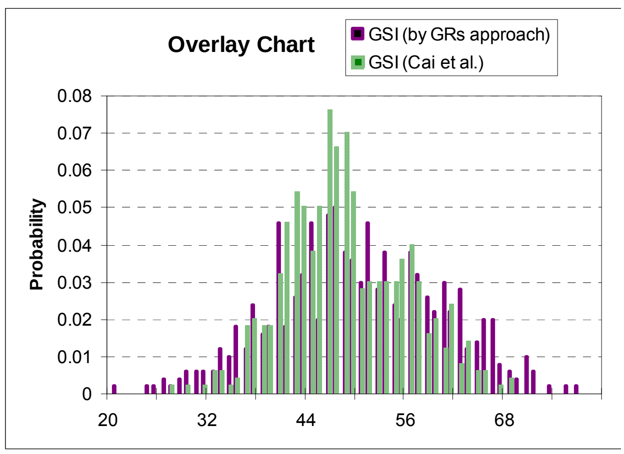

Fig. 4.4: Overlay chart for the comparison of the results of the probabilistic simulation by the GRs and the Cai et al. approach.

5 CONCLUSIVE REMARKS

A new hybrid method for the estimation of the GSI value of a rock mass 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 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 a rock mass, and the new system, mainly based on the observed state of fracturing. However, it is here important to note that even in the latter case, the influence of rock mass interlockness is not excluded by the system, but mainly covered by the roughness parameter jR [26].

The new approach is not covering special cases of complex and/or weak rocks, in which the cited specific charts proposed by Hoek and Marinos may be more adequate. More in general, independent from the method used, it is in any case important that the basic condition of applicability of the GSI, i.e. the possible reference to an equivalent continuum model, is reasonably justified for the examined cases. In particular, the cited Authors have recommended that the GSI system should not be applied to those rock masses in which there is a clearly defined dominant structural orientation, as well as in the presence of strong hard rock with a few discontinuities spaced at distances of similar magnitude to the dimensions of the tunnel [23].

Furthermore, for very high GSI values (roughly >70, i.e. in the domain of the so-called "brittle failure zone"), the use of the index is also not recommended for the derivation of rock mass parameters according to the equivalent continuum approach [10,11,12].

As for the original RMi system, a particular care should be adopted in evaluating the correct jC rating for extremely fractured rock mass. In such a context, it is the current author's opinion that the Joint Size Factor (jL) may play an important role in avoiding too cautious assumption about jC and then low excessively the GSI values.

Finally, as a further important step, it is useful to underline that the described new approach can facilitates, as well, the concurrent calculation of the RMi and consequently offer the possibility to apply empirical methods to tunnel design based on such a quality index.

Given such complementarities, an “integrated” GSI-RMi system appears to be very promising for the future.

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APPENDIX

TABLES WITH RATINGS FOR SOME INPUT PARAMETERS TO THE ASSESSMENT OF RMi

[original version from A.Palmstrom's web site http://www.rockmass.net (May, 2007)]

TABLE 1 THE JOINT ROUGHNESS FACTOR (jR) (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	Slighty undulating	Undulating	Strongly undulating	Stepped or Interlocking (large scale)
Irregular or stepped (small scale)	3	4.5	6	9	12
Very rough	2	3	4	6	8
Rough	1.5	2	3	4.5	6
Smooth	1	1.5	2	3	4
Polished or slickensided *)	0.5 - 1	1	1.5	2	3
For filled joints jR = 1					

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

TABLE 2 THE JOINT ALTERATION FACTOR (jA) (the ratings of jA are similar to Ja in the Q-system)

A. CONTACT BETWEEN THE TWO JOINT WALLS			
Joint wall character		**Description**	Rating of jA
CLEAN JOINTS:	Healed or welded joints	Non-softening, impermeable filling (quartz, epidote, etc.)	0.75
	Fresh joint walls	No coating or filling in joint, except from staining (rust)	1
	Altered joint walls	One grade higher alteration than the rock in the block	2
		Two grades higher alteration than the rock in the block	4
COATING OR	Friction materials	Materials of sand, silt calcite, etc. without content of clay	3
THIN FILLING OF:	Cohesive materials	Materials of clay, chlorite, talc, etc.	4

B. FILLED JOINTS WITH PARTLY OR NO JOINT WALL CONTACT		*Partly wall contact*	*No wall contact*
Type of filling	**Description**	Thin filling (< approx. 5mm)	Thick filling or gouge
Friction materials	Sand, silt calcite, etc. without content of clay	4	8
Hard cohesive materials	Compacted filling of clay, chlorite, talc, etc.	6	10
Soft cohesive materials	Medium to low overconsolidated clay, chlorite, talc, etc.	8	12
Swelling clay materials	Filling material exhibits swelling properties	8 - 12	12 - 20

TABLE 3 THE JOINT SIZE FACTOR (jL)

Joint length	**Type**		Continuous joints*)	Discontinuous joints
< 0.5m	Crack		4	8
< 1m	Bedding or foliation parting		3	6
0.1 - 1m	Joint	(small)	2	4
1 - 10m	Joint	(medium)	1	2
10 - 30m	Joint	(long or large)	0.75	1.5
> 30m	(Filled) joint, seam or shear **)		0.5	1

**) Often a singlular discontinuity with significant impact and should in these cases be evaluated separately

*) Discontinuous joints end i massive rock