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This paper was prepared for presentation at the 47th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, USA June 23-26, 2013

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Quantification of the Geological Strength Index chart

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ABSTRACT:

The original Geological Strength Index chart was developed on the assumption that observations of the rock mass would be made by qualified and experienced geologists or engineering geologists. With the ever increasing use of the GSI chart as the basis for the selection of input parameters for numerical analysis, often by individuals without the strong geologic understanding of rock mass variability necessary to interpret the graphical GSI chart properly, some uniformity and quantification of the chart seems necessary. This paper presents a proposed quantification of the GSI chart on the basis of two well-established parameters - Joint Condition and RQD. Recommendations for future development of more robust scales are presented.

1. INTRODUCTION

The original Geological Strength Index (GSI) chart was developed on the assumption that observations of the rock mass would be made by qualified and experienced geologists or engineering geologists. When such individuals are available, the use of the GSI charts based on the descriptive categories of rock mass structure and discontinuity surface conditions have been found to work well. However, there are many situations where engineering staff rather than geological staff are assigned to collect data, which means that the mapping of rock masses or core is carried out by persons who are less comfortable with these qualitative descriptions.

As part of an ongoing evaluation of the uses and abuses of the Hoek-Brown and Geological Strength Index systems for estimating the mechanical properties of rock masses, the issue of quantifying GSI has been given priority. GSI is the first point of entry into the system and, unless this Index is well understood and applied correctly, the reliability of the estimated properties is open to question.

Figure 1 illustrates the data flow when using the GSI/Hoek-Brown method for estimating the parameters required for a numerical analysis of underground or surface excavations in rock. Depending on whether the users have a geological or an engineering background, there tend to be strongly held opinions on whether the observed geological conditions should be entered either descriptively or quantitatively into the characterization table for GSI. Both of these approaches are catered for in the discussion that follows.

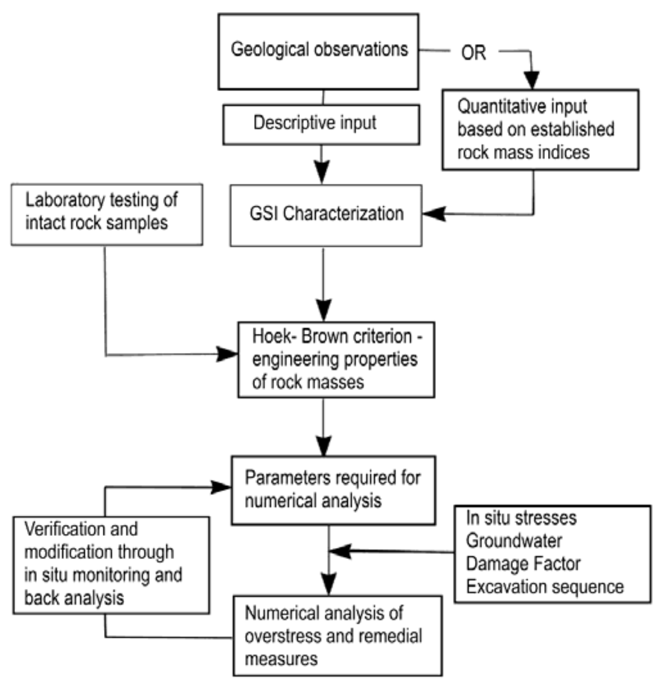

Figure 1: Data entry stream for using the Hoek-Brown system for estimating rock mass parameters for numerical analysis.

2. CONSTRUCTION OF THE BASIC GSI CHART

The GSI chart published by Hoek and Marinos (2000) [1] is reproduced in Figure 2. Scale A has been added to represent the 5 divisions of surface quality with a range of 45 points, defined by the approximate intersection of the GSI = 45 line on the axis. Scale B represents the 5 divisions of the block interlocking scale with a range of 40 points in the zone in which quantification is applied.

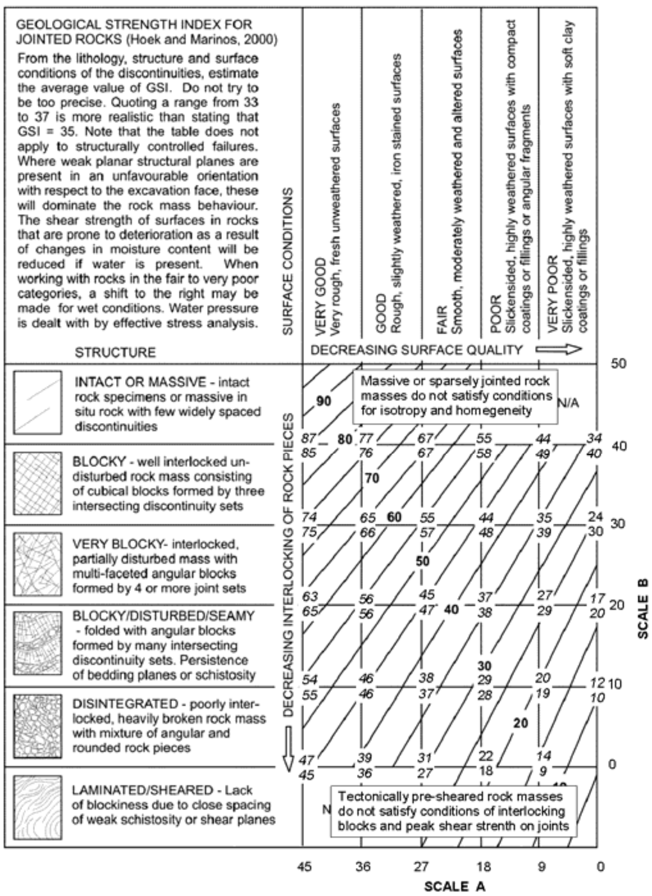

Figure 2: The basic structure of the Hoek and Marinos (2000) GSI chart and possibilities for quantification.

At each intersection of the A and B scales the value of GSI has been estimated from the GSI lines on the chart. These values are shown as the upper italicized number at the intersection point. At the same intersection points the lower italicized number equals the sum of the A and B values. The two numbers at each intersection point are then plotted against each other in Figure 3.

This plot demonstrates that there is a high potential for quantifying GSI by means of two linear scales representing the discontinuity surface conditions (scale A) and the interlocking of the rock blocks defined by these intersecting discontinuities (scale B).

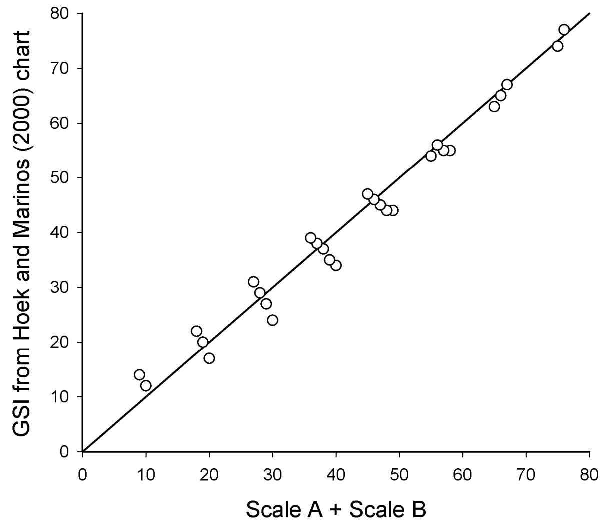

Figure 3: Plot of GSI estimated from the basic GSI chart against the sum of the A and B values.

Figure 3 also shows that there is a systematic trend in each group of plotted points and, from an examination of the chart in Figure 2, it is obvious that this trend is due to the fact that the original GSI lines, which were hand drawn, are neither parallel nor equally spaced.

With a modest correction to the original GSI lines to make them parallel and equally spaced, the error trends in Figure 3 can be eliminated completely. This correction has been applied to Figure 5.

Note that the correction of the GSI lines and the addition of the A and B scales do not change the chart's original function of estimating GSI from field observations of blockiness and joint condition, characterized in terms of the descriptive axis title blocks. Hence the chart shown in Figure 5 has the potential for satisfying both the descriptive and quantitative user camps.

Before proceeding any further with this discussion it is necessary to define a number of conditions and limitations of the proposed quantitative GSI chart.

1. The addition of quantitative scales to the GSI chart should not limit the use for which it was originally designed – the estimation of GSI values from direct visual observations of the rock conditions in the field.

2. A fundamental assumption of the Hoek-Brown criterion for the estimation of the mechanical properties of rock masses is that the deformation and the peak strength are controlled by sliding and rotation of intact blocks of rock defined by intersecting discontinuity systems. It is assumed that there are several discontinuity sets and that they are sufficiently closely spaced, relative to the size of the structure under consideration, that the rock mass can be considered homogeneous and isotropic. These concepts are illustrated diagrammatically in Figure 4.

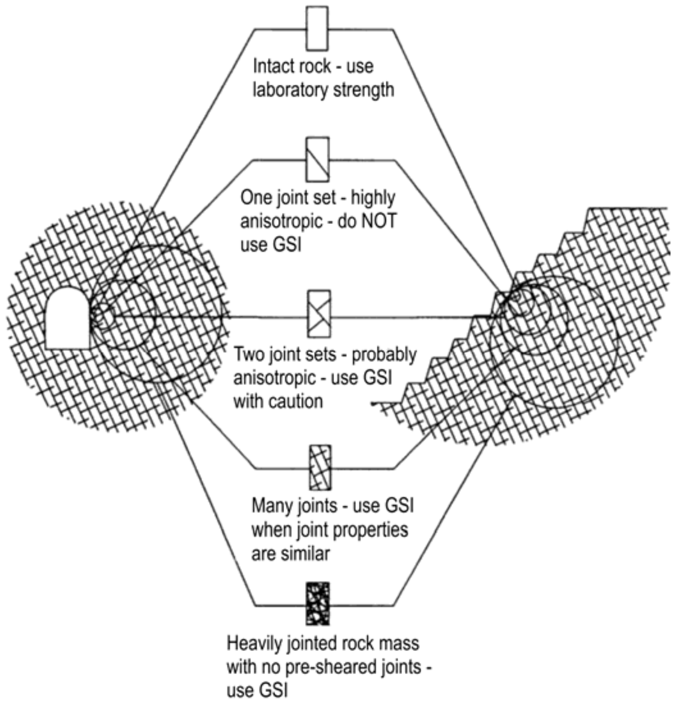

Figure 4: Limitations on the use of GSI depending on scale.

3. For intact massive or very sparsely joined rock, the GSI chart should not be used for input into the Hoek-Brown criterion as shown in Figure 1. This is because there are insufficient pre-existing joints to satisfy the conditions of homogeneity and isotropy described above. Hence, in order to avoid confusion, the upper row of the chart shown in Figure 2 has been removed in the development of the quantified GSI chart. Brittle failure processes such as rockbursts and spalling are specifically excluded from the section of the quantified GSI chart since these processes do not involve the rotation and translation of interlocking blocks of rock as defined in 2 above. Similarly, structurally controlled failure in sparsely jointed rock does not fall within the definition of homogeneity inherent in the definition of GSI.

4. The lower row of the original 2000 GSI chart has also been removed since this represents previously sheared or transported or heavily altered materials to which the conditions defined in item 2 above also do not apply. A second GSI chart for heterogeneous, pre-sheared materials such as flysch has been published by Marinos and Hoek (2002) [2] and Marinos et al (2007) [3]. Where applicable this flysch chart could be used or a similar site specific chart could be developed for rock masses that fall below the last row of the chart given in Figure 5.

Some approaches for tackling both ends of the rockmass competency scale addressed in paragraphs (3) and (4) are suggested by Carter et al, 2008, [4].

5. In order to quantify GSI using the chart, the quantities used to construct the A and B scales have to be practical ratings that are familiar to engineering geologists and geotechnical engineers operating in the field. They should also be well established in the literature as reliable indices for characterizing rock masses intersecting discontinuity systems. It is assumed that there are a sufficient number of discontinuities and that they are sufficiently closely spaced, relative to the size of the structure under consideration, that the rock mass can be considered homogeneous and isotropic.

3. ESTIMATION OF GSI IN TERMS OF RQD AND JOINT CONDITION

Scale A in Figure 2 represents discontinuity surface conditions while Scale B represents the blockiness of the rock mass. Prime candidates for these scales are the Joint Condition ($JCond_{89}$) rating defined by Bieniawski (1989) [5] and the Rock Quality Designation (RQD) defined by Deere (1963) [6]. These ratings are given in Appendix 1.

The $JCond_{89}$ rating corresponds well with the surface conditions defined in the text boxes of the x axis of the GSI chart in Figure 5. This rating parameter has been in use for many years and users have found it to be both simple and reliable to apply in the field.

The RQD rating has been in use for 50 years and some users have defined it as boringly reliable. Hence these two ratings appear to be ideal for use as the A and B scales for the quantification of GSI.

Figure 5 shows a chart in which the A scale is defined by 1.5 $JCond_{89}$ while the B scale is defined as RQD/2. The value of GSI is given by the sum of these scales which results in the relationship:

$$GSI = 1.5\ JCond_{89} + RQD/2 \qquad (1)$$

4. CHECK OF QUANTIFIED GSI AGAINST MAPPED GSI

In order to check whether or not the proposed quantification of GSI works it is necessary to check the values of GSI predicted from equation 1 against field mapped GSI values. At the time of writing only one set of reliable field data, from a drill and blast tunnel, is available to the authors. The GSI values calculated from $JCond_{89}$ and RQD are plotted against mapped GSI values in Figure 6. This plot shows that the correlation between the calculated and mapped GSI values is reasonably close to the ideal 1:1 relationship for a perfect fit. This suggests that, once additional field data are obtained, the application of this quantification of GSI may justify the transition from proposed to recommended.

It is possible that some adjustments in the positions of the $JCond_{89}$ and RQD scales in Figure 5 may be required as more mapped GSI data becomes available and as experience is gained in using this quantification.

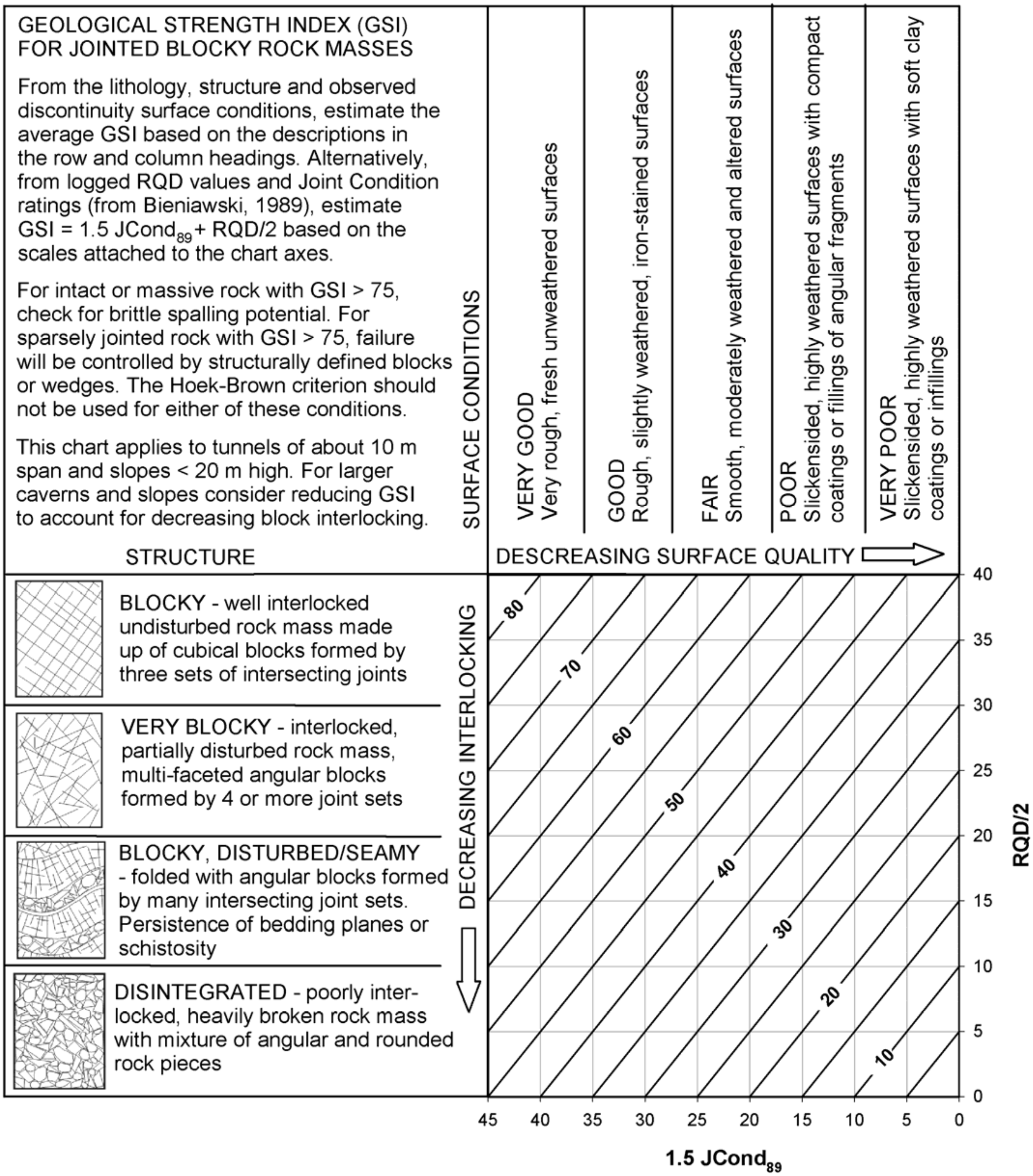

Figure 5: Quantification of GSI by Joint Condition and RQD.

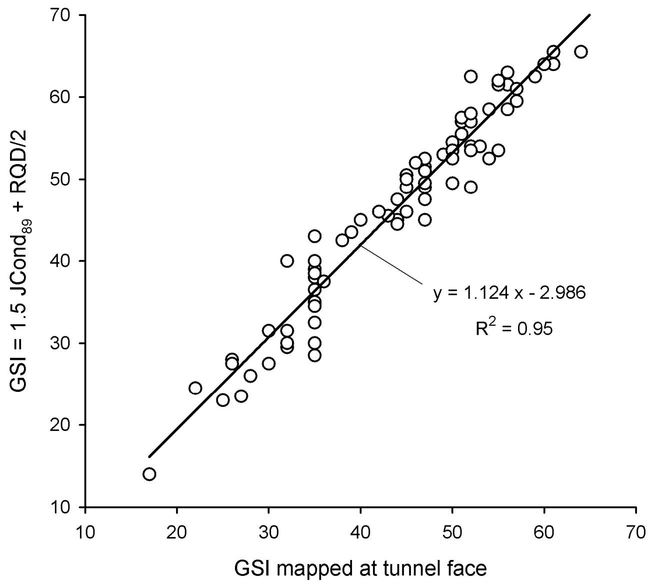

Figure 6: Comparison between mapped GSI and GSI predicted from $JCond_{89}$ and RQD.

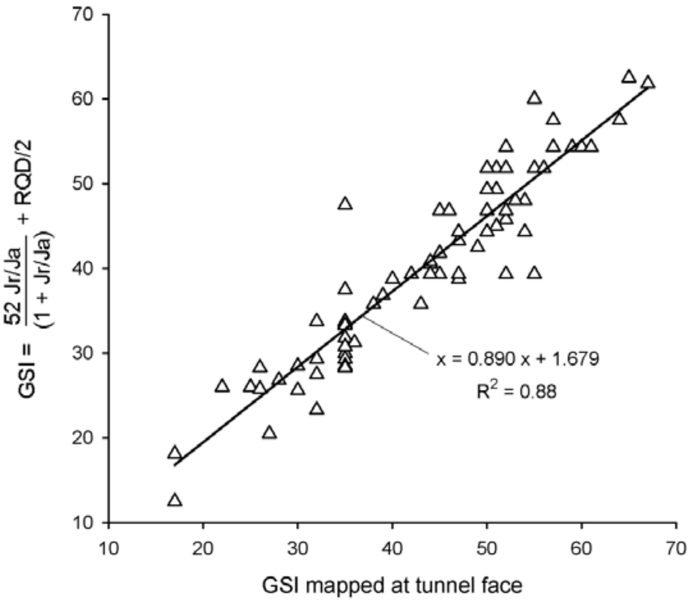

Figure 7: Comparison between mapped GSI and GSI predicted from Jr/Ja and RQD.

5. ALTERNATIVE JOINT CONDITION SCALE

In recognition of the fact that values of $JCond_{89}$ are not always available in data from field mapping, the authors have examined two options for alternative scales for the surface quality axis in Figure 5.

The first candidate is the version of Joint Condition rating ($JCond_{76}$) included in the paper by Bieniawski (1976) [7] (see Appendix 1). Regression analysis of a plot of individual values assigned to $JCond_{76}$ and $JCond_{89}$ gives $JCond_{89} = 1.3\ JCond_{76}$ which, when substituted into equation 1, gives

$$GSI = 2\ JCond_{76} + RQD/2 \qquad (2)$$

A second candidate is the quotient Jr/Ja, included in the Tunnelling Quality Index (Q) of Barton et al (1974) [8]. This quotient (Jr/Ja) represents the roughness and frictional characteristics of the joint walls or fillings.

Comparing the ratings for $JCond_{89}$ with those allocated to Jr and Ja by Barton et al (1974) [7] (see Appendix 1) gives the relationship $JCond_{89} = 35\ Jr/Ja/(1 + Jr/Ja)$. Substitution of this relationship into equation 1 yields:

$$GSI = \frac{52\ Jr/Ja}{(1 + Jr/Ja)} + RQD/2 \qquad (3)$$

For the same data set used in the preparation of Figure 6, the predicted values of GSI are plotted against field mapped values of GSI in Figure 7. While the results for a linear regression analysis are not as good as those obtained for equation 1, the fit is an acceptable approximation for engineering applications.

6. RQD DETERMINED FROM FACE MAPS

When no core is available and RQD has to be determined from the mapping of tunnel faces, tunnel walls or slope faces, three methods are available.

The first involves a simple physical measuring rod or tape held against or in front of the face. The length of intact rock segments greater than 10cm falling between natural fractures intersecting the rod or tape are summed in a fashion similar to core-based RQD. This procedure is described in Hutchinson and Diederichs (1996) [9]. A virtual version of this approach can be carried out on high quality face photos or Lidar scans.

Priest and Hudson (1976) [10] found that a reasonable estimate of RQD could be obtained from discontinuity spacing measurements made on core or from an exposure by use of the equation:

$$RQD = 100\ e^{0.1\lambda}\ (0.1\lambda + 1) \qquad (4)$$

where λ is the average number of discontinuities per meter.

Palmström (1982) [11], also studied RQD but in relation to the Volumetric Joint Count, Jv, a measure of the number of joints crossing a cubic meter of rock. Based on mapping of exposures or on orthogonal scanline mapping underground, the following expression was derived:

$$RQD = 115 - 3.3\ Jv \qquad (5)$$

More recently, Palmström (2005) [12] extended his analysis by including computer generated blocks of different sizes and shapes. A new correlation between RQD and Jv was found to give somewhat better results that the commonly used RQD = 115 – 3.3Jv. He suggested that this relationship (equation 5) given in his 1982 paper should be modified to:

$$RQD = 110 - 2.5\ Jv \qquad (6)$$

7. CONCLUSION AND RECOMMENDATIONS

With some minor modifications to the GSI chart published by Hoek and Marinos (2000) [1] it has been found that two simple linear scales, $JCond_{89}$ and RQD, can be used to represent the discontinuity surface conditions and the blockiness of the rock mass. These ratings are well established in engineering geology practice, are simple to measure or estimate in the field and are possibly the ratings that give the highest degree of consistency between different geologists working on a single project. Most importantly, in a direct check between GSI estimated from the sum of these ratings and GSI obtained by direct tunnel face mapping, the agreement is acceptable for the characterization of jointed rock masses in order to obtain properties for input for numerical models.

In recognition of the fact that values of $JCond_{89}$ are not always available in data from field mapping, two alternative scales for the surface quality axis have been investigated. One of these is a relationship between $JCond_{89}$ and the $JCond_{76}$ version of this parameter, used in older data sets, which can be used as a direct replacement of $JCond_{89}$. The second alternative is the quotient Jr/Ja that gives a relationship to $JCond_{89}$ which provides an acceptable approximation for engineering applications.

The goal of this paper was to construct a practical set of scales for the GSI chart, based on existing and well established scales used in either the RMR or Q classifications. Cai et al (2004) [13], Somnez and Ulusay (1999) [14] and Russo (2007, 2009) [15, 16] have published quantified GSI charts which incorporate joint surface and rock structure scales based on parameters related to those used by the authors in constructing Figure 5. All of these quantified GSI charts, including that proposed in Figure 5 of this paper, have advantages and disadvantages. However, they all suffer from two significant shortcomings.

Firstly, the parameters used to specify the joint surface conditions (the equivalent of Scale A in Figure 5) are all based on ratings of joint roughness, joint alteration and joint waviness. These ratings, with the exception of joint waviness, are based upon assessment of the degree of surface roughness and alteration rather than on any physical measurements of the shear strength of the surfaces themselves. It is this shear strength that is a controlling parameter in the behavior of the jointed rock mass and it is questionable whether the somewhat arbitrary nature of the roughness and alteration ratings can provide a reliable assessment of this shear strength.

Secondly, the use of RQD by the authors or some variation of the volumetric joint count Jv or the block volume Vb, by the other authors, limits the definition of rock structure to the dimension of the blocks. This takes no account of the ratio of block size to the size of the tunnel or slope which, as shown in Figure 4, has a significant influence on the application of the GSI chart for characterizing the rock mass.

Direct measurement of physical properties and numerical modeling of the progressive failure and deformation of the rock mass, while not devoid of challenges and abuses by over-enthusiastic users, offer the potential for resolving some of these deficiencies.

Measurement of the frictional strength of sawn or ground surfaces of small specimens is simple enough in a field laboratory with basic equipment. Similarly, measurement of small and large scale surface undulations, at a scale relevant to the problem under consideration, and combining these measurements with the basic friction angle of the rock surface is a well-established procedure described by Barton and Choubey (1977) [17].

Numerical techniques such as the Synthetic Rock Mass model (Mas Ivars et al. (2011) [18]) provide the means of incorporating the joint fabric of a rock mass at different scales. In the long run these methods have the potential to allow direct three-dimensional modeling of all of the physical components of a rock mass and provide a much more rigorous alternative to the empirical characterization and rockmass parameter estimation approach using the GSI chart. In the short term, numerical modeling techniques can be used to develop rock structure scales which incorporate both the scale of the rock blocks and the scale of the engineering structure in which they exist.

Rating-based rock mass characterization scales, such as those used in this paper, have played a critical role in the development of practical design tools for rock engineering. However, while practitioners may continue to apply these methods for some time, researchers should turn their attention to the actual physical properties of rock joints and numerical modeling of rock fracture networks to develop and apply a better understanding of jointed rock mass behavior.

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9. ACKNOWLEDGMENTS

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10. APPENDIX 1 –PARAMETER DEFINITION

The Rock Quality Designation (RQD) was developed by Deere (1963) [6]. The index was developed to provide a quantitative estimate of rock mass quality from drill core logs. RQD is defined as the percentage of intact core pieces longer than 100 mm (4 inches) in the total length of core. The core should be at least NW size (54.7 mm or 2.15 inches in diameter) and should be drilled with at least a double-tube core barrel. The correct procedures for measurement of the length of core pieces and the calculation of RQD are summarized in Figure 8.

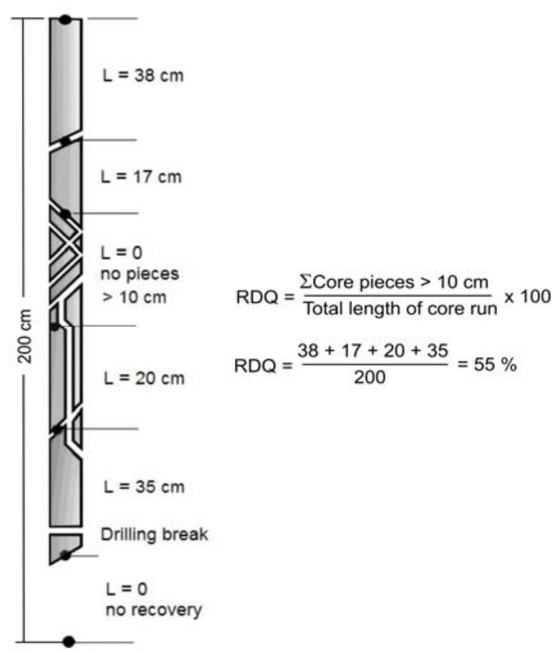

Figure 8: Definition of RQD, after Deere (1963) [6].

The definition of $JCond_{89}$ in Table 1 is reproduced directly from Bieniawski (1989) [5] while $JCond_{76}$, from Bieniawski (1976) [7], is defined in Table 2.

The parameters Jr and Ja, for rock wall contact, from Barton et al (1974) [8], are defined in Table 3

Table 1: Definition of $JCond_{89}$, after Bieniawski (1989) [5].

Condition of discontinuities	Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1 – 5 mm Continuous	Soft gouge > 5 mm thick or Separation > 5 mm Continuous
Rating	30	25	20	10	0

Guidelines for classification of discontinuity conditions

Discontinuity length (persistence) Rating	< 1 m 6	1 to 3 m 4	3 to10 m 2	10 to 20 m 1	More than 20 m 0
Separation (aperture) Rating	None 6	< 0.1 mm 5	0.1 – 1.0 mm 4	1 – 5 mm 1	More than 5 mm 0
Roughness Rating	Very rough 6	Rough 5	Slightly rough 3	Smooth 1	Slickensided 0
Infilling (gouge) Rating	None 6	Hard infilling < 5 mm 4	Hard filling > 5 mm 2	Soft infilling < 5 mm 2	Soft infilling > 5 mm 0
Weathering Rating	Unweathered 6	Slightly weathered 5	Moderate weathering 3	Highly weathered 1	Decomposed 0

Table 2: Definition of $JCond_{76}$, after Bieniawski (1976) [7]

Condition of discontinuities	Very rough surfaces Not continuous No separation Hard joint wall rock	Slightly rough surfaces Separation < 1 mm Hard joint wall rock	Slightly rough surfaces Separation < 1 mm Soft joint wall rock	Slickensided surfaces or Gouge < 5 mm thick or Joints open 1 – 5 mm Continuous joints	Soft gouge > 5 mm thick or Joints open > 5 mm Continuous joints
Rating	25	20	12	6	0

Table 3: Definition of Jr and Ja for rock wall contact (no pre-shearing), after Barton et al (1974) [8].

JOINT ROUGHNESS NUMBER Jr	Rating	JOINT ALTERATION NUMBER Ja	Rating
Discontinuous joints	4	Tightly healed, hard, non-softening, impermeable filling	0.75
Rough and irregular, undulating	3	Unaltered joint walls, surface staining only	1.0
Smooth, undulating	2	Slightly altered joint walls, non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc	2.0
Slickensided, undulating	1.5	Silty-, or sandy-clay coatings, small clay fraction (non-softening)	3.0
Rough or irregular planar	1.5	Softening or low friction clay, mineral coatings, i.e. kaolinite, mica. Also chlorite, talc, gypsum and graphite etc., and small quantities of swelling clays. (Discontinuous coatings, 1 – 2 mm or less in thickness)	4.0
Smooth, planar	1.0		
Slickensided, planar	0.5		