RQD: Time to Rest in Peace

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ABSTRACT

Rock Quality Designation (RQD), was introduced by Don Deere in the mid-1960s as a means of using diamond core to classify rock for engineering purposes. Subsequently it was incorporated into the Rock Mass Rating and Q-system classification methods which, world-wide, now play substantial roles in rock mechanics design, whether for tunnels, foundations, rock slopes or rock excavation.

It is shown that a key facet of the definition of RQD is ignored in many parts of the world, and it is noted that there are several inherent limitations to the use of RQD.

Based on mapping of rock formations by seventeen independent professionals at different locations in Australia and South Africa it is shown that differences in assessed RQD values result in significant errors in computed RMR and Q ratings, and also in Geological Strength Index (GSI) and Mining Rock Mass Rating (MRMR).

The introduction of a look-up chart for assessing GSI has effectively removed the need to measure, or estimate, RQD. It has been found that GSI values derived from the look-up chart are as valid as those derived by calculation from the original component parameters, and are satisfactorily consistent between professionals from diverse backgrounds. The look-up charts provide a quick and appropriate means of assessing GSI from exposures. GSI is, in turn a useful rock mass strength index; one new application is presented for assessing potential erosion of unlined spillways in rock.

Incorporation of RQD within the RMR and Q classification systems was a matter of historical development, and its incorporation into rock mass classifications is no longer necessary.

LIST OF NOTATION

GSI	Geological Strength Index
J_a	Joint alteration number, Barton *et a*l. (1974)
J_n	Joint set number, Barton *et al.* (1974)
J_r	Joint roughness number, Barton *et al.* (1974)
J_v	Volumetric joint spacing, Barton *et al.* (1974)
RMR	Rock Mass Rating
RQD	Rock Quality Designation
UCS	Unconfined Compressive Strength
Q	Norwegian rock mass classification index, Barton *et al.* (1974)
Q'	Norwegian rock mass classification index for dry, unstressed rock

Introduction

In mid-2014, two of the authors undertook mapping and classification of rock exposures of unlined spillways in South Africa, in support of an Australian-funded research project (Pells 2015). This work yielded surprising findings in respect to Rock Quality Designation (RQD), which has implications to quantitative rock mass classifications systems. Discussions between all the authors provided confirmation of these findings, creating the impetus for this paper.

Rock Quality Designation (RQD) was devised in 1964 as an index for classifying the relative quality of rock core obtained from small diameter core drilling (about 50 mm) (Deere and Deere 1989). Since such a humble beginning, RQD has been adopted as a fundamental tool in characterising rock masses. It has been used to estimate rock mass shear strength and deformation parameters, bearing capacity of foundations; and most importantly is, "an essential element within the framework of other classification systems" (US Corps of Engineers 1997).

This paper summarises the origins of RQD, and discusses how it has changed to the point that it has substantially different meanings in different parts of the world. The inherent limitations of RQD are summarised, and critical examination is made of its incorporation in Rock Mass Rating (RMR), 'Q-values' and Geological Strength Index (GSI). Results of field work are presented to show the limitations arising from using RQD in the determination of these rock mass classification indices. It is shown that RQD is not required for determining RMR and GSI values.

In core and exposure logging it is better replaced by fracture frequency.

The Genesis and Definition of RQD

In 1964 and 1965, whilst working on sites in granite at the Nevada Test Site for nuclear bombs, Deere and co-workers devised an index, Rock Quality Designation (RQD), to differentiate between relatively good quality rock and poor rock when logging rock core, as an alternative to just judging quality on the basis of core recovery. RQD came to international recognition, and widespread acceptance, through a chapter by Deere in a book edited by Stagg and Zienkiewicz (1968). The 1968 definition of RQD was:

> "RQD is a modified core recovery percentage in which all pieces of sound core over 4 inches long (100mm) are summed and divided by the length of the core run."

A review of 20 years' experience with RQD was given by Deere & Deere (1989) in a report to the US Corps of Engineers. They emphasised three essential features of RQD.

1. It was a means of assessing rock mass quality from nominally 55mm diameter, double-tube core, over a core run.
2. Only sticks of core with lengths greater than 4 inches (100mm) separated by natural mechanical fractures were to be included. Fractures opened up by drilling were to be ignored.
3. "Pieces of core which are not 'hard and sound' (ISRM, 1978) should not be counted for the RQD even though they possess the requisite 4 in, (100mm) length."

RQD was intended as more than an index of fracture spacing. In Deere's words from 1989, *"RQD is an index of rock quality in that problematic rock that is highly weathered, soft, fractured, sheared, and jointed is counted against the rock mass. Thus, it is simply a measurement of the percentage of "good" rock recovered from an interval of a borehole."*

Meaning of "hard and sound"

In the original publications, Deere did not define "sound", but in 1989 Deere & Deere clarified this criterion, and chose to do so with reference to degree of weathering. They concluded:

(i) Highly and Completely Weathered rock and Residual Soil should never be included in RQD, 'highly' being defined following Little (1969) in that 'fairly large pieces can be crumbled in the hands' which agrees with Moye's definition (1955) who originally defined 'highly weathered granite' as where core 54 mm diameter could be 'broken and crumbled by hand'.

(ii) They suggested that Moderately Weathered rock could be included but then the Rock Quality Designation should be marked with an asterix, i.e. RQD*. In the authors' experience this distinction has not been widely adopted in practice.

Deere and Deere (1989) emphasised that the "*purpose of the soundness requirement is to downgrade the rock quality where the rock has been altered and weakened either by agents of surface weathering or by hydrothermal activity. Obviously, in many instances, a judgment decision must be made as to whether or not the degree of chemical alteration is sufficient to reject the core piece".* ASTM D 6032-02 defined 'sound' core (only sound rock to be included in RQD) as: *'sound core' is any core which is fresh to moderately weathered and which has sufficient strength to resist hand breakage.*

Uncertainties, confusion and errors

As discussed as early as 1978 by Deere's co-workers (Cording and Mahar 1978) there can be several causes for low quality of core *"and they need to be determined when using RQD"*. These included; improper handling, drilling parallel to and intersecting a joint, separation on bedding and foliation surfaces that are not open in the field, and core discing. There are other long-recognised problems with measurement and use of RQD (see Foster 2015), including:

- measurements are usually taken post-boxing, rather than upon exposure in the core barrel splits, leading to incipient fractures opening up and lower RQD being logged than characteristic of the ground *in situ*
- typical standard practice is to retain the original prescription and measure RQD by core run, although Deere and Deere (1989) do suggest logging by lithology as being appropriate,
- directional bias means that where the geology is dominated by joints near-parallel to the borehole, those defects are under-sampled,
- confusion exists in respect to the definition of 'natural mechanical fractures' within certain rock types like schists, phyllite and shales, and
- confusion in dealing with well-defined incipient discontinuities that have tensile strength; in fact these should be ignored when calculating RQD.

However, the greatest source of differences in core-logged RQD values arises from professionals in certain parts of the world ignoring the "hard and sound" criterion in the definition.

The current situation in the United Kingdom (Hencher 2008), and much of the rest of Europe, is to ignore the requirement for "hard and sound" rock (British Standard BS5930, since 1999). All cored "rock" counts in the RQD assessment, with 'rock' being defined as having substance strength of greater than 0.6MPa (BS EN ISO 14688-2:2004). The criterion of 'sound' is similarly ignored by many other authors including Palmstrȍm (2005).

Material of substance strength >0.6MPa does not comply with Deere's definition of "hard and sound" and its inclusion results in logged RQD values much higher than computed on the basis of the original definition (see Figure 1). The consequences are potentially dangerous, such as when designing support measures in weak rock masses on the basis of RMR and Q charts which assume RQD data determined using the proper Deere definition (Hencher 2015).

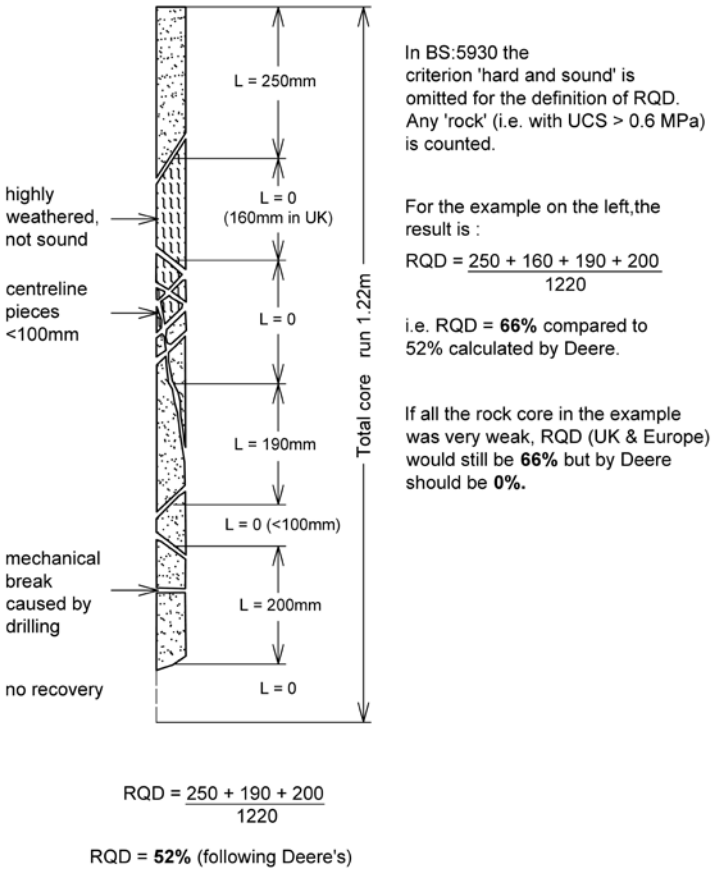

Figure 1 - RQD determination as per Deere & Deere (1989), and compared to current UK and European practice.

A further substantial issue is the practical necessity where, in many situations, cored borehole data are not available and RQD is estimated from exposures, or RADAR, or photographs; despite this contradicting the original definition and intent. Such estimation invokes consideration of 'sound rock', the difficulty of establishing that a discontinuity has zero tensile strength and would cause a break in core, and directional bias (Hencher 2014).

In addition the process may lead the geologist or engineer to adopt a relationship between RQD and volumetric joint spacing (J_v), such as that of Palmstrȍm (2005):

$$RQD = 110 - 2.5J_v \text{ (for } J_v = 4 \text{ to } 44) \quad (1)$$

or between defect frequency and RQD, such as per Priest and Hudson (1976), namely:

$$RQD = 110.4 - 3.8/\dot{x} \quad (2)$$

where $\dot{x}$ = mean spacing of defects assuming an exponential distribution.

The authors consider that such correlations may be inappropriate and misleading, not only for the reason that Deere addressed when creating RQD, namely that rock included in RQD must comprise only “sound” core, but also because of having to assess discontinuities as having zero tensile strength.

Field work by two of the authors in mid-2014 revealed the substantial problems associated with assessing RQD from exposures. The work involved mapping and rock-mass classification of seventeen structural regions in a wide variety of rocks in unlined spillways of major dams in South Africa (Pells and Pells, 2014). These same rock exposures had been previously subject to independent interpretation (van Schalkwyk *et al.* 1994). The RQD values from the two independent assessments are compared in Figure 2, and reveal large differences of interpretation.

Prompted by the large discrepancy in interpretation shown in Figure 2, a further study was instituted in which 13 practicing professionals were asked to independently classify three different exposures in the Sydney area (a diatreme; an exposure typical of Hawkesbury Sandstone, and Hawkesbury Sandstone altered to columnar jointing adjacent to a dolerite dyke – See Figure 3). The range of interpreted RQD values at these sites is shown in Figure 4.

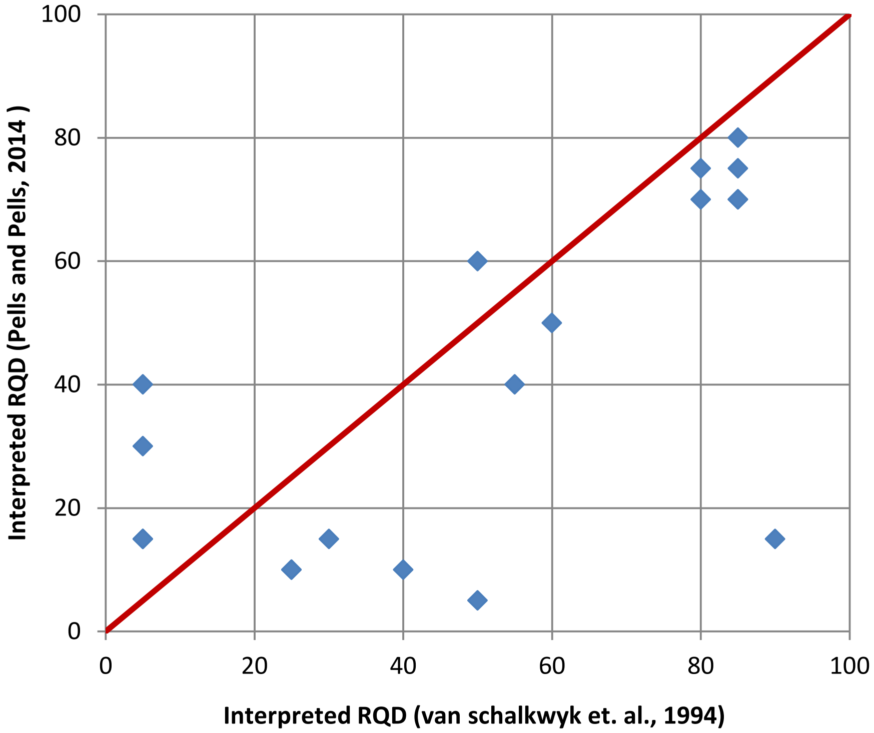

Figure 2 – Comparison between interpreted RQD values at various unlined spillway sites, Pells and Pells (2014) and van Schalkwyk *et al.* (1994).

Figure 3 –Hawkesbury Sandstone with atypical orthogonal joints influenced by adjacent dyke (West Pymble Quarry).

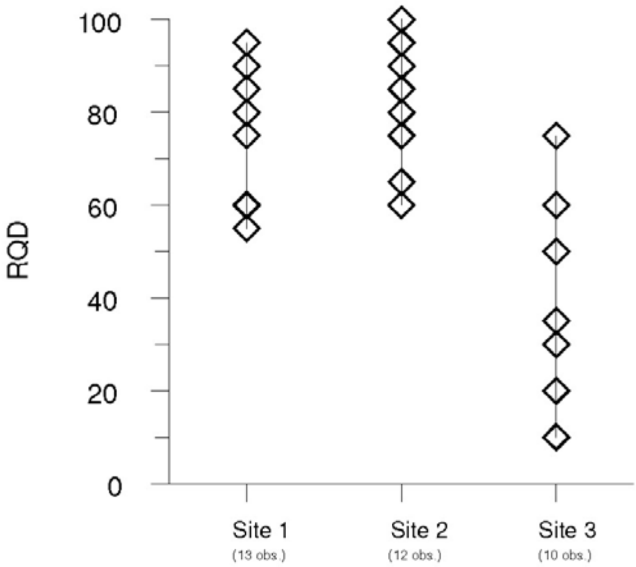

Figure 4 – The range of RQD values interpreted by independent professionals at three rock exposures in Sydney.

The work on the South African spillways was part of a major study financed by various Australian authorities responsible for dam construction and maintenance, so the discovery of substantial differences in quantitative classification of the same rock masses by different operators had important consequences. Later in this paper we return to this matter, but first we must deal with the use of RQD in widely used quantitative rock mass classification systems.

RQD in Rock Mass Classification Systems

Rock Mass Rating (RMR) and Q systems

In the early 1970s, Bieniawski (1973) and Barton *et al.* (1974) published their Rock Mass Rating (**RMR**) and **Q** classification systems. Both are now widely adopted in practice for design of mines, tunnels, rock slopes, and foundations, and for assessment of rock excavation and erosion (US Corps of Engineers 1997).

As originally defined, both systems were fundamentally dependent on RQD; essentially modifying RQD by incorporating other factors deemed to impact on rock mass strength and stiffness.

Barton *et al.* (1974) followed Cecil (1975) in modifying RQD by reducing it for the number of joint sets (RQD/J_n); and then incorporated joint roughness, joint alteration (J_r/J_a) and rock load and water pressures (J_w/SRF), in defining the **Q**-value.

For the RMR system, Bieniawski (1973) modified RQD by assigning a rating to this index, and then combined this with ratings for strength, defect orientations and conditions, and groundwater pressures.

After 40 years of application, Lowson and Bieniawski (2013) recommended against further use of RQD in the RMR system. Their explanation was:

> *"This parameter was included originally among the six RMR parameters because the case histories collected in 1972 all involved RQD. Over the years it became apparent that RQD was difficult to determine at tunnel face, being directed to borehole characterization.*
> *For the best practical use, this led to the preferred use of "fracture frequency" as an inverse of "fracture density", as depicted in Chart D* (see Figure 5 herein). *Neither of these approaches changed the basic allocation of rating values to these parameters."*

In a similar vein, Jakubec and Esterhuizen (2007) formalised a modification of Laubscher's Mining Rock Mass Rating (**MRMR**) wherein RQD is replaced by fracture frequency, a change first flagged by Laubscher (1993).

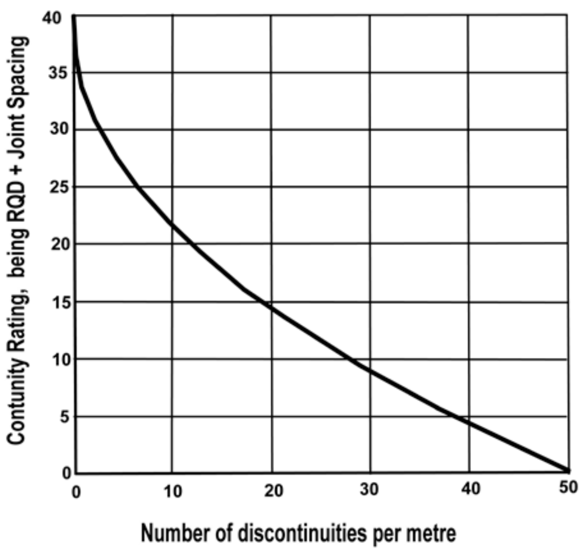

Figure 5 - Chart D for combined rating of the discontinuity density parameters RQD, plus discontinuity spacing (from Lowson and Bieniawski 2013).

Geological Strength Index (GSI)

A development in rock mass classification was the adoption by Hoek of some of Bieniawski's RMR components to create the Geological Strength Index (**GSI**) (Hoek 1994 and Hoek, Kaiser and Bawden 1995). The specific intent of GSI was to allow estimation of rock mass shear strength through to the Hoek-Brown failure criterion (Hoek and Brown 1988). GSI was also based on RQD because it required to be computed from the numerical values in the 1976 version of Bieniawski's RMR, but always with a value of 10 for Groundwater.

Correlations

Several correlations between the above classification indices have been published. They are raised here as being germane to later discussion.

Bieniawski (1993) gives a correlation, derived from case study data, as:

$$Q = e^{\frac{RMR-44}{9}} \qquad (3)$$

Hoek, Kaiser and Bawden (1995) published the same equation but as relating Q' to GSI, where Q' comprises the first two parts of Barton's Q index, namely $Q' = \frac{RQD}{J_n} \times \frac{J_r}{J_a}$. Thus:

$$Q' = e^{\frac{GSI-44}{9}} \qquad (4)$$

It seems illogical that the same equation relates Q' to GSI, and Q to RMR. The writers accept equation 3 as being based on source data.

Influence of RQD variability on Rock Mass Index interpretation

From the form of Barton's equation for Q, it follows that any % error in RQD causes an equal % error in the Q-value.

RQD is not used directly in RMR, but rather as a rating. Therefore it is not obvious what error will result from a certain % error in RQD. By running several hundred practical scenarios, it is found that +/-30% error in RQD results typically in < 6% error in RMR. Only in extreme cases with high water pressures, unfavourable joint orientations, and a 30% underestimate of an already low RQD does the error reach about 25%.

As originally published (Hoek, Kaiser and Bawden 1995) GSI was RMR without the groundwater and joint orientation factors. This means that within a GSI range of 10 to 100, a 30% error in RQD causes <5% error in GSI.

The significance of mathematical sensitivity to errors in RQD depends on the practical reality in respect to accuracy of RQD assessment. And here is where the data collected in the field studies in South Africa and Australia are disturbing. They showed that the variation in assessed RQD between multiple professionals (which can be taken as errors) was so great that the resulting quantitative rock mass classifications were inconsistent to the point of destroying confidence in their application.

However, a revelation arising from the full field project covering unlined rock spillways at 10 major dams in South Africa (mentioned above), and a further 20 dams in Australia (Pells 2015) was to discover remarkably good, operator-independent, agreement between GSI values computed from the RMR components as per Hoek, Kaiser and Bawden (1995), a process that required careful work in the field and time in the office, and GSI values assessed very quickly in the field using the look-up chart of Figure 6, discussed below. Like many fellow practitioners, the authors had assumed that use of the look-up chart was second-best to proper calculation of GSI using the RMR parameters.

The details and consequences of this finding are discussed in the remaining part of this paper.

Hoek's Look-up Chart

It appears that the first version of the chart shown in Figure 6 was published by Hoek, Kaiser and Bawden (1995). It appeared in a simplified version in the software *Roclab* (2002). Modified, material-specific charts were published by Hoek and Marinos (2000).

The purpose of the original chart was to allow short-hand estimation of GSI for assessing the parameters of the Hoek-Brown failure criterion.

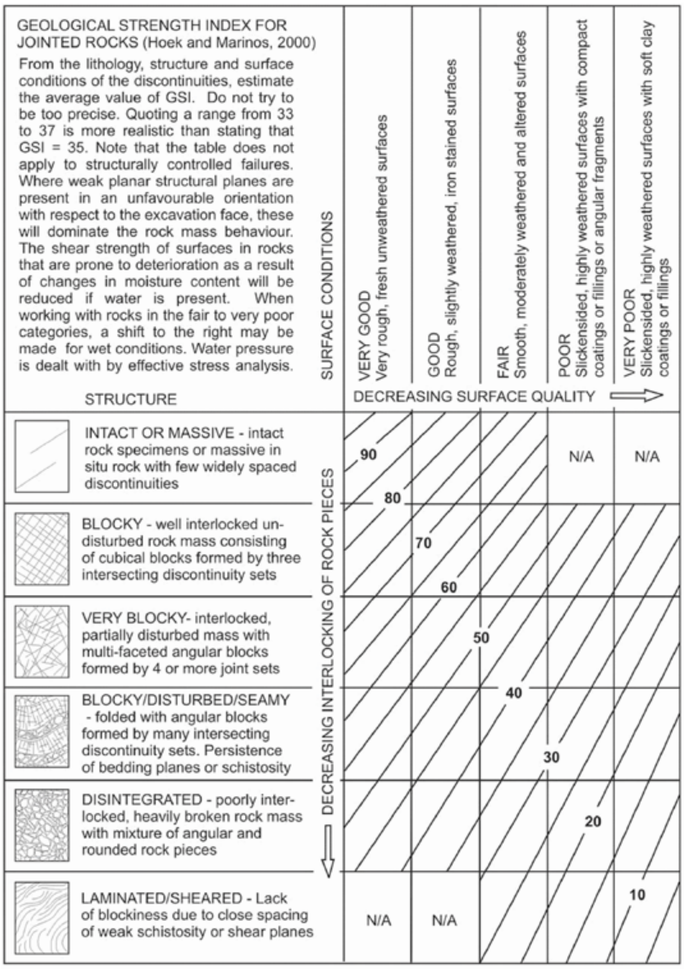

Figure 6 - GSI look-up chart from Hoek (2007) – published with permission of E Hoek.

Figure 6 makes no reference to RQD. Also there are no requirements to determine numerical ratings covering substance strength, joint shear strength, alteration, continuity and spacing.

Figure 7 shows the comparisons, for the 30 rock spillways, between GSI values computed from RMR components determined from field mapping and GSI values assessed quickly by use of the look-up chart. Figure 8 shows the same kind of data from the 13 professionals mapping the three quarry exposures in Sydney.

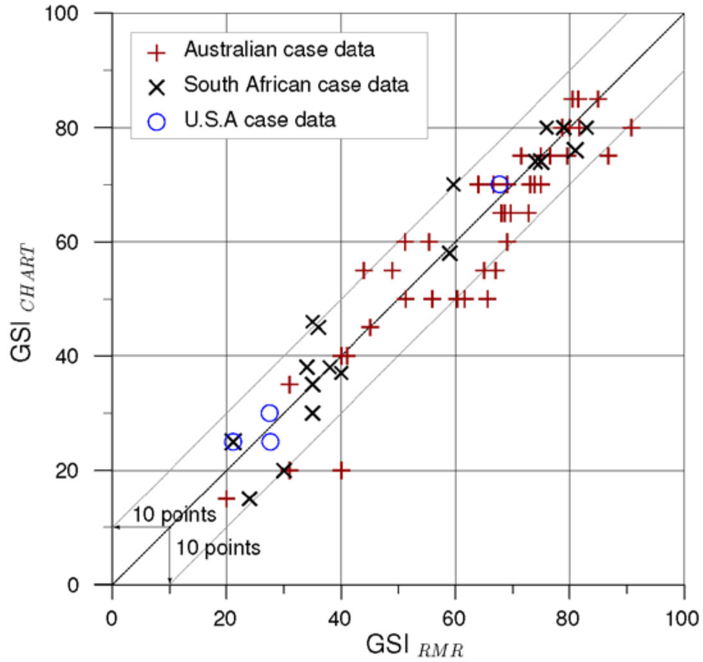

Figure 7 - Comparison of GSI_{RMR} vs GSI_{CHART}, from spillway investigations (Pells 2015).

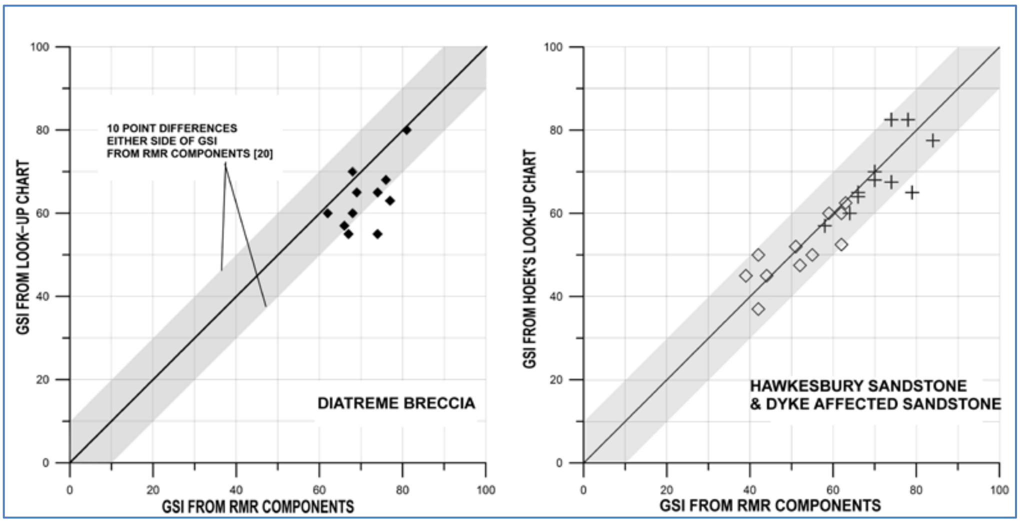

Figure 8 - Comparison between two methods of assessing GSI – rock exposures in Sydney.

A test of consistency between operators using only the look-up charts was conducted by another five senior professionals, assessing exposures of ignimbrite north of Newcastle, New South Wales. One exposure was jointed, fresh rock, and the second was disturbed and faulted; near the contact with underlying Carboniferous shales. The look-up chart GSI values for the exposure of fresh ignimbrite ranged from 65 to 70. For the complex faulted rock, the values were between 35 and 45.

The field data from all the multi-operator experiments therefore confirmed that GSI could be estimated with reasonable accuracy by experienced professionals using only Hoek's look-up chart, with no recourse to RQD. This finding has been partly supported by Hoek (2007 on-line *Course Notes and Book*), who recommended that "*that GSI should be estimated directly by means of the chart ... and not from the RMR classification".* However, this is tempered by Hoek, Carter and

Diedrichs (2013) to the effect that GSI be computed by yet another method, namely a combination of RQD and the Joint Condition Rating, the latter derived from RMR as per Bieniawski (1989). The equation is:

$$GSI = 1.5*JCond_{89} + RQD/2 \quad (5)$$

Equation 5 has been tested using the data from the South African and Australian sites, as shown in Figure 9. This shows that computing GSI from Equation 5 (labelled "GSI_{2013}") gives poorer agreement with the original GSI definition than achieved simply from the look-up chart (compare with Figure 7).

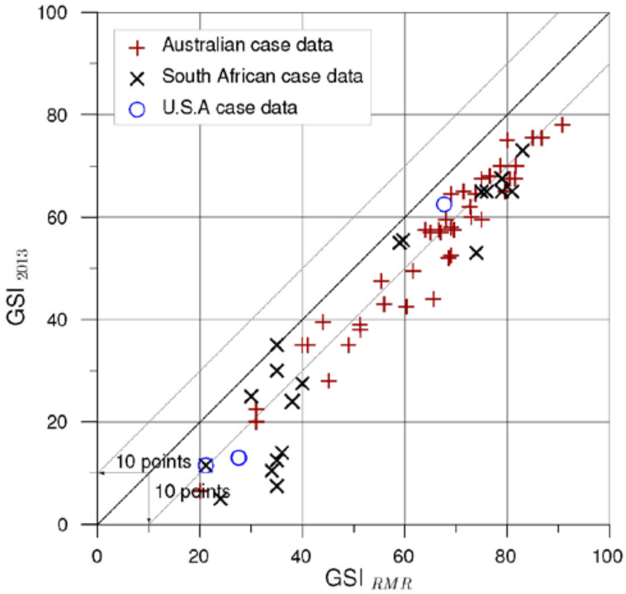

Figure 9 - Comparison of GSI_{RMR} versus GSI_{2013} (Equation 5); from Pells (2015).

Estimation of RMR and Q' from GSI

GSI is not a synonym for RMR, and it is incorrect to transpose correlations made using RMR to being correlations with GSI. Thus the correlation of rock mass modulus with RMR (Bieniawski 1989) should not be taken as the correlation between mass modulus and GSI.

Significant errors can result in determining RMR values from estimated GSI values, via correlation equations such as Equations 3 and 4, above. Directly computed RMR values should be used when invoking the empirical correlations relating to rock mass modulus or tunnel support categories. In so doing, RQD should not be used, but rather fracture frequency as per Lowson and Bieniawski (2013).

Applications of GSI

Rock-mass erodibility

As already noted, GSI was introduced as a means of estimating rock mass parameters in the Hoek-Brown failure criterion. However, it is Geological Strength Index and there are situations where it can be used directly as such an index. The following is one such application.

Unlined dam spillways can be subject to significant erosion, incurring unacceptable safety and economic risks. Examples of such erosion are shown in Figure 10 in high strength quartzite at the

Mokolo Dam, South Africa, and in Figure 11 in high strength granite at Copeton Dam, Australia. The prediction and analysis of such erosion is complex, and no satisfactory, generalised analytical solutions exist (Pells 2015).

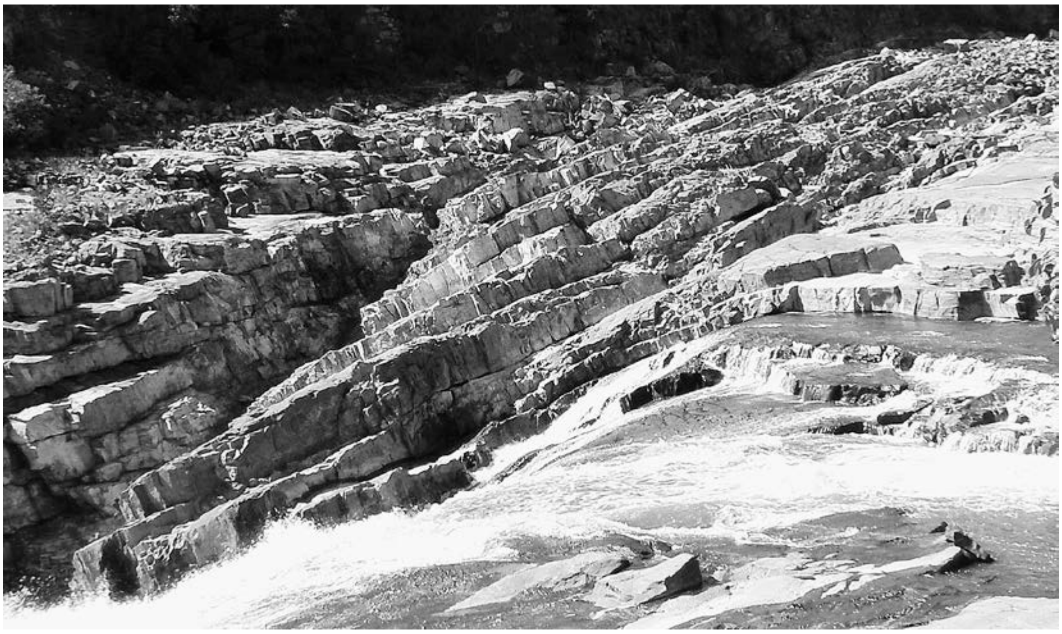

Figure 10 – Erosion at Mokolo Dam spillway, Waterberg Mountains, South Africa.

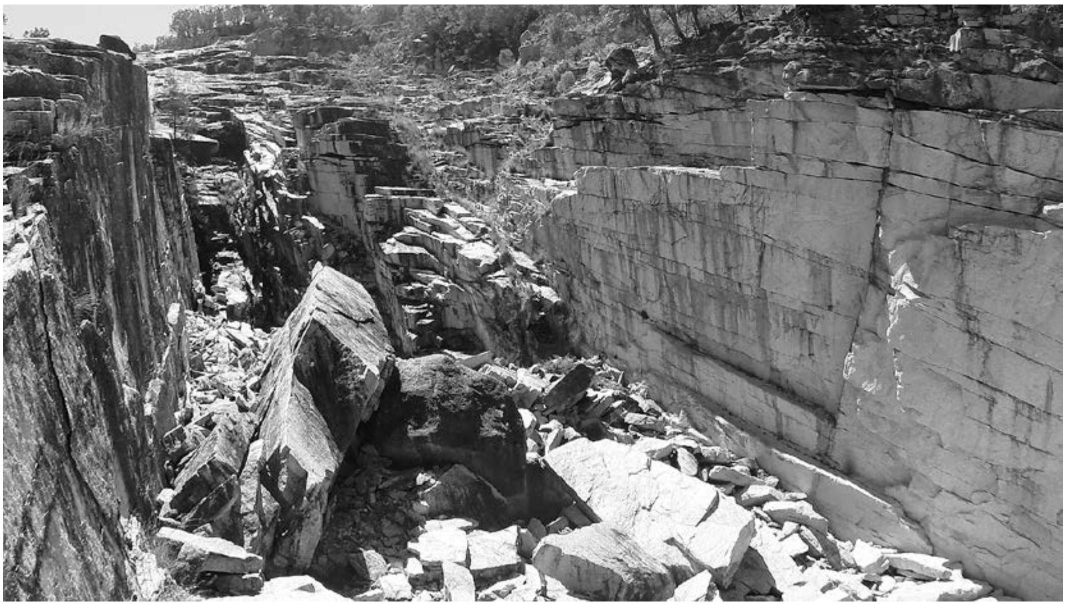

Figure 11 - Slot erosion in very high strength granite, Copeton Dam spillway, NSW, Australia.

The "Kirsten Index" (K) which was based on the Q-system and developed for rippability assessments (Kirsten 1982), has been used as an index for rock mass erodibility (Moore and Kirsten 1988). Based on field investigations of unlined dam spillways in South Africa, van Schalkwyk *et al.* (1994) presented a correlation between magnitude of erosion, the Kirsten Index and; hydraulic loading as represented by the unit stream power dissipation incurred during peak historical spillway discharge (Π_{UD}). Different correlations based on essentially the same field data for fractured rock and the same indices (K and Π_{UD}) were subsequently presented by Annandale (1995) and Kirsten *et al.* (2000).

The fact, discovered as part of this study, that different operators mapping the same areas in the same spillways obtained significantly different Kirsten Index values, and the fact that determining K, RMR and Q, takes extensive work, suggested consideration be given to using GSI from the look-up chart as the measure of rock mass strength. Pells (2015) showed that a reasonable correlation existed between erosion magnitude, unit stream power (Π_{UD}) and rock mass strength as represented by GSI. However, joint orientation is a significant factor in vulnerability to erosion. Therefore a better evaluation of the spillway erosion data was obtained by modifying GSI with an appropriate orientation adjustment factor, of the kind used in the RMR system (Bieniawski 1973)

The resulting index, labelled Erosion GSI (**eGSI**) was found to provide an improved representation of erosion vulnerability in five classes (see Figure 12).

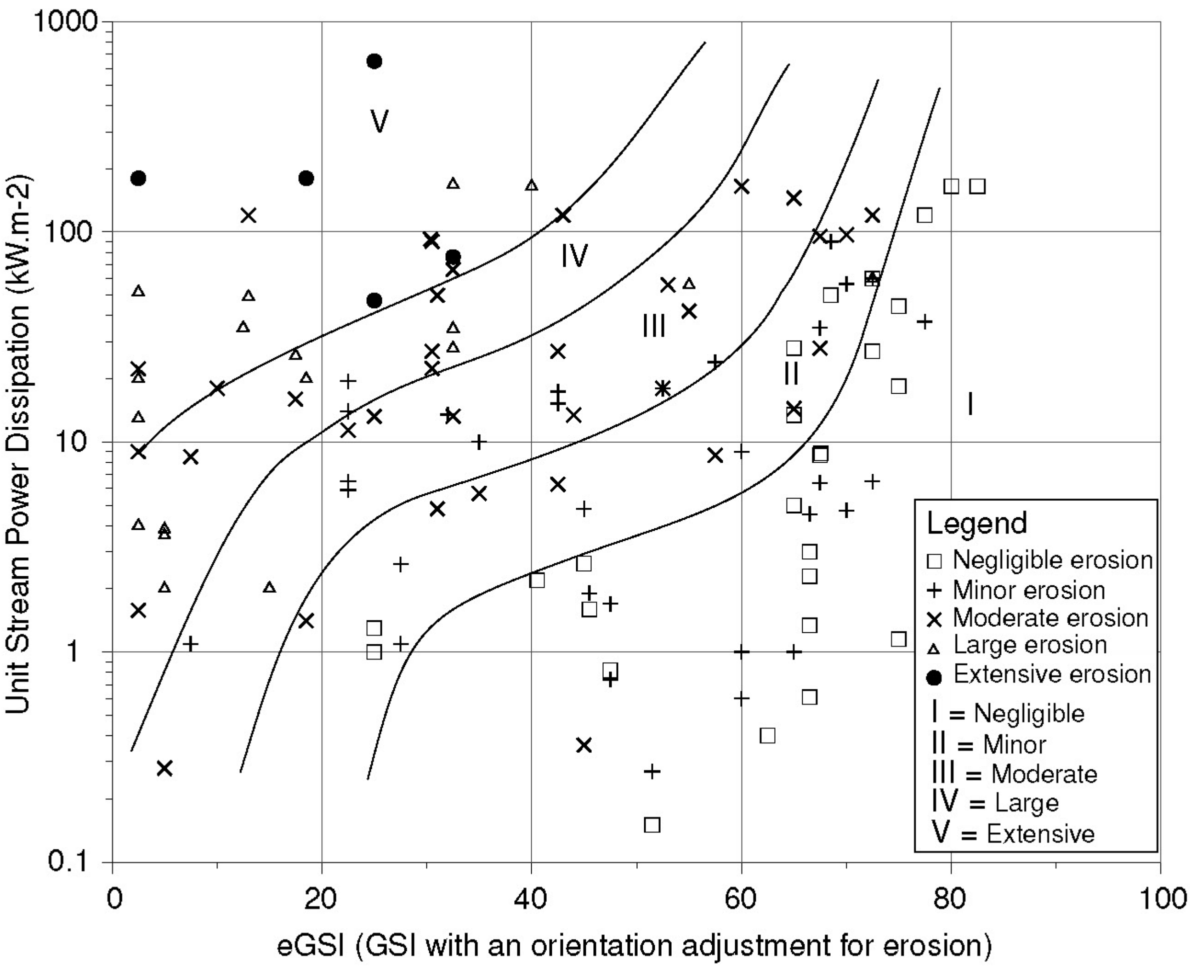

Figure 12 – Erosion categories from field data.

Calculating rock mass shear strength

It is not within the framework of this paper to comment on the validity of Hoek-Brown mass shear strength parameters derived from GSI. However, based on the field data documented herein, and on the authors' individual experiences, it is concluded that GSI is usually not known to better than about 10 points for a single exposure, and ±15 points for a Structural Region. Of importance is the fact that GSI occurs as an exponential in the Hoek-Brown equation for rock mass shear strength parameters (where σ_{ci}= material UCS), viz:

$$(\sigma_1-\sigma_3)/\sigma_{ci} = [m_b(\sigma_3/\sigma_{ci}) + s]^a \quad (6)$$

$$a=0.5 +1/6[e^{-GSI/15} - e^{-20/3}] \quad (7)$$

$$m_b = m_i\, e^{(GSI-100)/28} \quad (8)$$

$$s= e^{(GSI-100)/9} \quad (9)$$

For zero confining stress (σ_3=0) errors in shear strength arising from errors in GSI are independent of rock type (m_i) and substance UCS, and from the derivative of Equation 6 it is shown that for a 10 point uncertainty in GSI, the uncertainty in the computed rock mass unconfined strength, ranges from 100% at true GSI of 15, to 75% at true GSI of 25, and ~56% for true GSI greater than 70.

For confined conditions the uncertainty in shear strength arising from uncertainty in GSI is complex. A parametric study has shown that for confining stress >1MPa a 10 point uncertainty in GSI causes a 20% to 40% uncertainty in computed shear strength.

The significant sensitivity of the Hoek-Brown failure criterion to GSI is a matter that practitioners must consider when using rock mass shear strengths derived using Equations 6 for design purposes.

Conclusions

Based on a review of inherent limitations of RQD, the inconsistent changes in definition, the maturing understanding of RMR and GSI, and extensive multi-operator field experimentation, it is concluded that RQD should be phased out in rock mass classification.

In particular:

1. The definitions of RQD have become different in different parts of the world, and in many countries the definition is no longer consistent with the original methodology and logic of its creator, Don Deere.
2. Most applications of the dominant classification systems, RMR, Q, GSI and MRMR, require RQD to be estimated from exposures. This is a process fraught with error and personal bias, as demonstrated by the factual data presented in this paper.
3. The inherent limitations of RQD have already been recognised by the original creators of the RMR and MRMR systems, who have recommended it be replaced by fracture frequency.
4. It has been demonstrated that GSI can be estimated from Hoek's look-up chart as accurately as calculated from its components which include RQD.

Use of GSI for calculating rock mass strength via the Hoek-Brown failure criterion must be done with prudence because the computed strength parameters are sensitive to uncertainty in GSI determinations.

Where RMR values are required for use in the empirical correlations for rock mass modulus or tunnel support categories, and where rock strength and groundwater are key issues, calculations of RMR should be made using the fundamental components as per Lowson and Bieniawski (2013).

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