Applicability of Classifications for Tunnelling – Valuable for Improving Insight, but Problematic for Contractual Support Definition or Final Design.

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Rock Mass Classifications have been applied worldwide since the 1940’s and nowadays form the backbone for empirical design approaches for rock tunnelling [1]. Singh and Goel [2] in the introduction to their book on classifications quote Lord Kelvin’s philosophy as almost a justification for why classifications developed and why they are still so necessary in rock engineering – viz. “When you can measure what you are speaking about, and express it in numbers, you know something about it, but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts, advanced to the stage of science.” This statement, however, lies at the heart of the continuing problem that has plagued applicability of rockmass classifications to tunnelling – that geological conditions vary and thus cannot be reliably and repeatably quantified in numeric terms. Hence, because of this imprecision there continues to be a disconnect between prediction and reality (Figure 1).

Figure 1: Characteristic mismatch between classification-based predictions and as-encountered conditions. Tunnel support class predicted and mapped data on the left, and design strength estimate predictions and field data on the right, (9 classifications, 11 observers – from Edelbro et al., 2007) [3].

This disconnect is not solely related to “uncertainty” and “inaccuracy” in the degree to which prescriptive characterization of natural variability in actual geology can be achieved. Some uncertainty arises because of ambiguous parameter definition. This to some degree is tractable by statistical evaluation [4]. Some though arises due to differences in observer perspective, and this is much more difficult to resolve (particularly when classification values have contractual significance). This “divergence of opinion” oftentimes is taken as true differences in fact, and frequently then forms the basis for claims. Partly as a result of this, tunnel contracting has moved progressively towards use of Geotechnical Baseline Reports (GBR’s) and risk sharing contract language [5]. GBR’s however have not proved to be a panacea to solving the fundamental disconnect. As a consequence there still remains a need to solve this problem – (i) ideally, by completely divorcing classifications from being tied directly to contract payments and (ii) by returning them to their original and most useful role – as aids to preliminary design – where they have real value – for improving insight and understanding of likely tunnelling rockmass conditions and variability.
1. Background
The progression from the first real tunnel design-related classifications of the 1940's and '50's [6], through introduction of RQD in the '60's and development in the mid-70's of Q and RMR [8][9] with links to the Hoek-Brown failure criterion [10] in the early '80's led to a maturity of rock mass characterization use by the 1990's [1][4]. This however, marked the emergence of an unfortunate trend away from real geological description to more a pursuit of numerical value data per se. As a consequence, through the 1980's and early '90's numerous adaptations and modifications to the original classifications appeared in the literature – some aimed at mining [11][12][13]. – some aimed at surface slopes [14][15], and – some aimed at application to TBM's [16][17][18]. In some cases these adaptations just added complexity which only served to widen credibility gaps.

2. Classifications for Design
GSI was introduced in the mid '90's complete with a series of charts for aiding its use. Although much more descriptive than the other classification systems, over the last decade it has nevertheless become the defacto standard for categorizing rockmass quality for input into most continuum numerical analysis codes [19]. An opposite trend, to a more quantitative approach, has continued in parallel though, mainly based on utilizing the sub-parameters from the Q system for defining input variables for application to individual fractures within discrete element models [20].

From the rockmass classification perspective though, industry has remained reluctant to completely abandon numerically-based classifications. In fact, over the last decade the numeric classifications have become even more entrenched, partly because of Palm and tablet style data entry and partly due to their increasing use in a contractual framework for compilations within Geotechnical Data and Baseline Reports, [5][21][22][23]. The RMI system, has tended this way, differing markedly from the GSI approach, by attempting to more prescriptively define key parameters numerically. However, practitioners have found this system very complex to use, thus it has not gained as widespread an acceptance as the other systems. Unfortunately, also in concert with its introduction it spawned a rather disputatious series of papers, workshops and articles discussing which classification and which input parameters were the most reliable [24][25][26][27][30]. This discussion, and the ongoing need for quantification of the divergence between classifications, in parallel, also fostered a plethora of correlation papers [28][29][31][32][33][34]. Most of these papers looked at the overall classifications, but some examined more specific parameter differences, viz RQD/Jn versus Block Size [35][36].

Correlations with GSI, because of its more qualitative input have been more difficult. Nevertheless, several attempts have been made to develop a “quantitative” GSI chart, (ref. Figure 2 right side lower diagrams). This is an ironic twist – as this was exactly what GSI was originally set up to avoid – prescriptive codings. Nevertheless, there does appear to be some merit in this approach, as these nomogram charts still allow a graphical “smudge” to be drawn defining actual, field-observed rockmass quality variability. Their introduction is important also because it marks an industry recognition that rockmass classification for design should not end up with a “single value number” but rather should be defined as a spread or range [4]. This speaks also to an ongoing problem of support definition using classifications in practice and to the significant difference between applicability in blocky ground (Classes I to III typically) and ground with low stability (Classes IV to VI). For the latter, it is often difficult at the tunnel face (or even worse through a TBM port) to get much understanding of the structure and composition of the rockmass. Arguably, the more numeric classification systems may in fact be inappropriate for these conditions, particularly if practitioners adopt only a single value number estimate for such complicated rock masses [30][36].

The left side chart on Figure 2, provides a probabilistically contoured combined GSI and Q nomogram in the same style as the nomograms included in the right side lower diagrams, but structured to provide a more practical basis for improving observer repeatability, in much the same way as has been done for decades by statistically contouring stereonets to better define joint sets. Because observer repeatability can be improved by use of such contoured plots, the chart in Figure 2 has the potential also for helping resolve some of these definition difficulties, while also at the same time, addressing many of the contractual problems of using “single value” classification numbers in GBR’s.
The curves across the chart in Figure 2 relate block volume, – characterizing rockmass brokenness, plotted using the RMi parameter $V_b$, correlated with the Q-system quotient $RQD/J_n$ based on regression of Palmström’s 1995 plot (viz. $RQD/J_n = ((5 + \log(V_b))^1.75),[36]$ – to $Jr/J_a$ from the Q system, (a crude measure of shear strength) and the RMR 76 Joint Condition parameter; $C_j$, related one to the other through $Jr/J_a = e^{((C_j -17.186)/4.5458)}$. In the plot, the RMR Joint Condition parameter has been chosen for the x-axis as it incorporates descriptors that (a) provide a well defined scale that reflects shear strength and (b) includes terms that define joint continuity, and hence address rock bridge conditions in a way that no other classification descriptor currently captures well. The main $Q'$ and GSI curves were then plotted across the chart on Figure 2 on the basis of correlations between the two principal Q-system quotients $RQD/J_n$ and $Jr/J_a$, respectively reflecting block volume and shear strength [9][37][44]. These were then linked to GSI (RMR 76) by the well known correlation $RMR=9\ln(Q) + 44$, as this relationship, despite numerous others having been published, appears to have stood the test of time,[31][45]

In keeping with the original formulation of the GSI chart, Q and GSI (=RMR 76) within the relationships used to develop the chart assume no water pressure influence or stress reduction effects, ie., $J_w=1$, dry and $SRF=1$, normal conditions. With the RMR water parameter term set to dry (=10) and no orientation derating adjustment used, there is equivalence also between the RMR 76 values and the original data entry scales for GSI [43]. While these refinements are helpful for clarification of rock quality for improving insight regarding rockmass variability, it must be borne in mind that such charts should be considered merely the starting point for undertaking more rigorous design using derived Hoek-Brown parameters suitable for the rock conditions of concern [42].

3. Classifications for Payment

The divergence of classifications each from each other, and the whole issue of quantifying classification differences becomes even more thorny when they are to be used as part of contractual bid documents. Classifications, since their inception, have been heavily utilized in both civil and mining construction, but with one profound difference, certainly in North America – the legalistic framework in which they have been applied. In the mining industry they are routinely utilized to describe rockmass conditions for optimizing implementation of a mining methodology, [12][13] and rarely are they used in any context where the parameter values have legal payment overtones. In civil practise, by contrast, the main use of classifications, other than for generating understanding for design is for support or excavation class
definition,[29] which inevitably ties them to payment aspects of the civil contract. In fact, this has long been recognized as one of the major benefits of classifications – that they could be used for assessing geology and rockmass quality along a planned tunnel route. Their use in this role [40] and as a basis, also in general terms, for zoning a tunnel for assessment of project costs is appropriate, but not without pitfalls. The advent of Geotechnical Baseline Reports and Geotechnical Data Reports, [5][21][22] is at last seen as a serious attempt by the construction industry to orchestrate a way of using classifications to advantage whilst minimizing potential contractual claim situations by various risk-sharing measures [23]. This however has not removed the observational problems inherent in their application.

Use of multiple classifications and hand sketched histogram plotting of key parameters, although advocated for years [4][37] – still seems a rarity. Graphic plotting of a “smudge” on a GSI chart, such as Figure 2, can however help address some of the major contractual problems with classifications, by forcing improvements in consistency. This has the potential to resolve one of the main dispute problems in a contractual framework, namely the inability of two observers to precisely define the same specific numerical values for a given classification parameter when there are contractual overtones. The move to more and more EPC styles of contracting has exacerbated this problem in that there are often now three parties involved in defining a rock class for payment purposes – the Owner’s geologist, the Contractor’s geologist and the Contractor’s Design Engineer’s geologist. This means that three interpretations could result – as each might have some degree of bias in what he or she wishes to describe with respect to the observed face condition. As an example of the possibilities for classification differences having direct contractual payment significance, explore the data in Table 1, below:

<table>
<thead>
<tr>
<th>Classification Parameters</th>
<th>RQD, GSI &amp; RMR,76</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQD</td>
<td>20</td>
</tr>
<tr>
<td>RQD - RMR</td>
<td>17</td>
</tr>
<tr>
<td>Joint sets</td>
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<tr>
<td>Major</td>
<td>9</td>
</tr>
<tr>
<td>Spacing</td>
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<tr>
<td>Narrow</td>
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<tr>
<td>Joint Condition</td>
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<td>Moderate</td>
<td>20</td>
</tr>
<tr>
<td>Strength</td>
<td>20</td>
</tr>
<tr>
<td>RQD, RMR</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 1 – Classification mismatch problems resulting from subjective observational differences

In this table it can be seen that there are only minor differences in individual parameter definitions – viz all three observers are assessing that the RQD likely is from 70-80%, with the bottom of the range picked by one observer and the top picked by another – in this case observing that face conditions were degraded due to blasting damage. Similarly, the number of “controlling” joint sets defined by each observer also differs only by one class division – but again depends on a subjective assessment of the face and appreciation of possible excavation damage enhancement to rockmass fracturing. In the adjustments segment of the table, again only one division difference in stress and orientation factors is evident in the definitions – arguably also in this case all within the range that could be considered appropriate. Nevertheless all these small subjective differences mount up and the end result is that the same tunnel face in this situation is classified with three different support categories.
4. Back-Analysis for Benchmarking Classifications

While classifications can be helpful for gaining insight [4][40], they should not be applied with their attendant support charts as the sole method for defining what support should be utilized. The final decision about what support is needed depends on actual tunnel conditions [28][29][33][26] and as such should be decided based on careful evaluation of any local stability problems, which demands implementing appropriate support. Blindly following rockmass classification predictions is not sensible, neither is blindly spraying shotcrete – as this often merely hides kinematic problems – not solves them.

Some estimates and checks of actual rock mass quality can however be made by back-analyzing convergence data, using numerical modelling approaches or more simply based on comparison of behaviour back to Lauffer’s or Bieniawksi’s stand time graphs, [8][7][45] or to the more recently published Franklin and Palassi [47] stand-time chart as shown on the right of Figure 3. In fact, such charts provide a powerful and effective means for calibrating and back-analyzing field rockmass classification accuracy.

Figure 3; Bieniawski [45] and Franklin & Palassi [47] stand-time charts showing back-analysis for 6m span heading for 24hr and 1 month unsupported span times. (NOTE: Inset diagram from Lauffer, 1958 defines unsupported span to face for use of curves to be assumed as tunnel span at maximum value).

Figure 4: Tunnelling Case Record Stand-time Data compared with Mining Crown Pillar Data (from Carter & Miller, 1996 [48]). Note: Two clear data trends, the crowns reflecting longevity from ravelling, and the tunnelling cases showing immediate roof fall behaviour – with the vertical spread between the tunnelling and mining data likely reflecting differences in underground span dimensions.
Application of these simple checks might help restrain wide divergence from reality in different observer’s field determinations of rockmass quality, and help diminish the problems illustrated earlier in Table 1. Figure 4 in fact illustrates how easily “time to spalling” and a crude assessment of rockmass behaviour can be established, thus allowing such charts to be used as a diagnostic indicator of classification reliability. Two zones are highlighted in the chart on the left of Figure 4 – a zone with RMR’s > 80, Q’s >100 (coloured blue) where the two data trends coalesce, to the right of which very long term stability seems assured. Open excavations of considerable span can be made in these types of rock without need for support (ref. upper right photo), although, these days, for health and safety protocol reasons, a minimum nominal support would often be stipulated. The second rock quality, (shown in orange) – for an RMR of about 20, Q=0.1 exhibits instant spalling, and if unsupported will freely cave – ultimately reaching surface if left unrestrained (ie., sufficient void space exists for the rubble to fall into). This is the design basis for a classic caving mine [11]. It is also the design basis for crown pillar dimensioning [49].

5. Conclusions
Two main observations arise from the foregoing discussions:
(1) Mining industry experience suggests that conceptually nothing is fundamentally wrong with the four principal classifications, (Q, GSI, RMR, or RMi), for design application, especially if multiple classification use is adopted around a probabilistic graphical chart, such as shown in Figure 2.
(2) Rather, the problem with classification misuse seems to be mostly confined to civil contract works, mainly as a consequence of their being tied to contract payment terms.

Invariably, given the nuances of payment arrangements in many contracts, experience shows that, almost irrespective of which classification is used, individual parameter selection can be curiously manipulated to maintain consistency of perceived geological description suitable for the observer’s contractual perspective. When checked against more quantifiable rockmass performance behaviour – by extensometers, by convergence arrays and/or by back-analysis modelling, these cases can show a clear disconnect. As illustrated by the graphic photos of 100 year old stopes in Figure 4, real openings behave in a way that can be checked by a variety of means. In the mining industry, classifications are used extensively and frequently form the sole basis for opening design. For example, using the Mathew's method [12][13] for stope design the first thing that is calculated is N’, defined as the first two quotients of Q = RQD/Jn x Jr/Ja. Here, because the mining engineer is interested in actually developing stopes which are just on the margin of stability – in order to maximise ore recovery while at the same time controlling dilution (sloughing from sidewalls and crown), rockmass quality definition must be very precise and very close to reality or designs are not economic. Back-analysis checking even using sophisticated modelling of stope geometry combined with mine site observation of rockmass behaviour and instrumented data, (with inclusion of cable bolting and other support) suggests good conformance of observed rockmass quality with classification data. This again reinforces the argument that classifications per se are not the problem, it is their application and misuse in a contractual context that is the real issue.

It is patently obvious, therefore, that some resolution of this problem is needed, mainly on the application side. In addition, contract arrangements and practitioner mapping reliability both need to be enhanced if classifications are to continue to be used within GBR’s and GDR’s for defining base case rock conditions and deviations therefrom. To resolve the contractual problem it seems that more reliance on third party evaluation is needed right from project initiation. In at least two recent cases – one in S.America and one in N.America, the concept of an independent adjudicator role has been introduced. Here, instead of the Owner's engineer or the Contractor's engineer defining the classification at the face, a fully independent geological engineering organization or individual, funded 50% by the Contractor and 50% by the Owner, defines the classifications in the tunnel on a daily round-by-round basis, where these are to be used as payment terms; and both parties must accept the defined classification. In one of these cases, for administrative purposes, the independent geological engineering group is under contract to the main Contractor, in the other case the group has been contracted through the Owner. In both cases strict rules have been agreed by all parties regarding mapping procedures as the tunnel is advanced. In addition, specific mapping sheets have been developed with a format that has also been agreed by all parties. These mapping sheets typically include a comprehensive face and crown map sketch and have been developed to attempt to also address the second issue – namely that of the significant divergences in classification of a given rock mass by different individual observers. In the mapping sheets multiple
classification parameter entry data has been incorporated (predominantly RMR and Q listings, and in the one case also including a GSI chart). Sufficient detail is then plotted on these sheets that anyone can go back and check the details. The procedure in both cases is that the mapping at the face is carried out independently and neither the Contractor nor the Owner are permitted to interfere. The resulting maps are then issued simultaneously to both participants and form the basis for discussions on any disagreements or claims. Such an approach, if executed consistently in connection with a reasonably accurate Geotechnical Baseline Report, appears to have the make-up to allow daily agreements to be reached, thereby saving any arguments from ending up in front of a Dispute Review Board or in legal proceedings.

This contorted extra level of contractual effort, while apparently workable, might not be necessary in all cases if probabilistic approaches using contoured data sets plotted in a “bulls-eye” chart such as in the left diagram on Figure 2 were more routinely adopted by the tunnelling industry. These, it is thought, would better constrain observations to reality, thereby better controlling mismatching differences between observers. In much the same way as stereonet definition of joint sets, agreement between observers of contoured “bulls-eyes” might well be much more easily achieved than might be the case for individual Q or RMR parameter values. Clarification of rockmass quality in terms of means and ranges would then become much more prescriptive and repeatable than at present, and just like the benefits of contoured stereonets for defining jointing trends, if applied constructively such charts could bring clarity to the use of classifications both for input to design and also for definition of “classes” for payment purposes.

6. Acknowledgements
While the views expressed in this paper are solely the author’s, many of the observation have arisen from participation in review board meetings in projects where others have noticed similar trends. Thanks in particular are due to Dr’s Hoek, Barton and Palmström for critical review and comments and also to many owner’s and contractor’s organisations for providing the insight on which this paper is based.

7. References