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Reliability Limits of Rock Mass Classifications and a Zonal Approach for Reducing Design Risk

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Abstract

Rock mass classification systems such as RMR, Q, and GSI have become indispensable tools in rock mechanics yet their empirical correlations are often applied with more confidence than warranted. These systems were developed for different purposes and rely on distinct input parameters, making value conversions between them frequently inadequate, as they fail to fully capture the complexity of actual geological conditions—especially in heterogeneous or tectonized rock masses.

This paper addresses the reliability limits of such approaches and introduces a practical method for reducing interpretative uncertainty through zoning of the rock mass based on the comparative application of multiple classification systems. The method compares classification results across intervals, identifies zones of agreement and divergence, and defines geotechnical domains through rule-based zoning.

This approach enables the identification and delineation of quasi-homogeneous geotechnical domains with similar engineering-geological and geotechnical characteristics, providing a more reliable basis for the assessment of deformability across different parts of a structure.

The method supports subsequent zoning tailored to excavation and support design and contributes to improved decision-making in complex geological environments such as deep mine shafts and dams.

Keywords

Rock mass classification, Rock Mass Zoning, Deformability Assessment, Risk Management.

1 Introduction

Rock mass zoning represents an important step in the site investigation phase for dams and underground structures. Through zoning, geotechnical domains are defined, for which deformability and strength parameters are assigned, forming the basis for the selection of support systems, numerical analyses, and stability assessment.

For this purpose, engineering practice relies on rock mass characterization, i.e., the assessment of rock mass quality, most commonly based on classification systems. Developed over different periods in accordance with the technological and scientific advancements of their time, numerous classification systems such as RMR, Q, and MRMR (Bieniawski 1989; Barton et al. 1974;Laubscher 1990)utilize partly similar and partly different input parameters. They evaluate rock mass properties, discontinuities, and the influence of groundwater in different ways, and they differ in scoring resolution and number of classes. Consequently, different systems applied to the same dataset may yield partially consistent or divergent results, reflecting their conceptual foundations and intended applications.

The authors of these classification systems aim to achieve a balance between simplicity for practical use and sufficient accuracy for reliable interpretation (Bieniawski 1992). The development of classification systems has primarily focused on improving evaluation criteria, adapting them to various geological and engineering conditions, and establishing empirical correlations for design purposes. However, in practice, empirical correlations between different classification systems are often applied based on individual engineering experience, and sometimes without full consideration of their limitations (Serafim and Pereira 1983; Hoek and Diederichs 2006).

Furthermore, reliance on a single classification system (often due to time constraints in data processing) may be insufficient. Likewise, converting results from one system to another may eliminate valuable information contained in their differences, thereby increasing interpretative uncertainty. The reliability of such approaches depends on the geological context, the degree of rock mass homogeneity, and the quality of input data. The use of conversions is particularly problematic in heterogeneous or tectonized rock masses, where differences between classification results tend to be more pronounced (Špago et al. 2015).Regional deviations between empirical correlations have also been reported by Jovanovski (2005).

2 Interpretative Uncertainty

The idea of using multiple classification systems is not new and has often been recommended. Each classification system aims to provide sufficiently reliable results for its intended application. By defining a structured approach for integrating the results of multiple classification systems, interpretative uncertainty can be reduced, thereby contributing to improved design quality and reduced engineering risk. Several factors influencing uncertainty should be distinguished: natural variability of geological and geotechnical characteristics of the rock mass, uncertainty related to the extent and quality of available data (data acquisition and processing), interpretative uncertainty arising from the manner in which classification results are interpreted (Baecher and Christian 2003).

Interpretative uncertainty represents the degree of indeterminacy in defining the boundaries and classes of geotechnical domains, resulting from methodological limitations, differences between applied classification systems, and the type, quality, and completeness of input data.

Differences in the results of individual classification systems may represent additional information about the structural and mechanical complexity of the rock mass. Different systems emphasize different controlling factors, such as discontinuity characteristics, intact rock strength, stress conditions, or groundwater influence (Marinos and Hoek 2000). Their parallel application to the same rock mass interval may therefore reveal changes that would remain unrecognized if only a single classification system were used. Comparative analysis of multiple classification results represents a form of internal cross-validation of classifications. Intervals of agreement increase confidence in the classification, while intervals of divergence indicate zones that require additional geological–geotechnical interpretation and may represent boundaries of geotechnical domains.

3 Methodological Framework

The application of the proposed framework requires adequately planned site investigations and the collection of data of sufficient diversity, detail, and reliability, as the outcome of zoning directly depends on the quality of the input dataset. Within such an approach, data acquisition and interpretation represent a key phase preceding analysis and design.

The methodological framework proposed in this study is based on the following steps:

1. *Collection and compilation* of a dataset that enables the application of multiple classification systems.
2. *Independent application of two or more classification systems* to the same intervals within the dataset.
3. *Verification of the correct application of each classification system (QA/QC)* – first control.
4. *Comparative interpretation of results* obtained from different classification systems.
5. *Identification of intervals of agreement and intervals of divergence*.
6. *Analysis of the causes of divergence* – second control and interpretation of differences.
7. *Definition and application of logical zoning criteria*.
8. *Definition of geotechnical domains* through the fulfilment of all established logical criteria.

Within the parallel application, classifications related to the hydrogeological behaviour of the rock mass may also be incorporated, particularly in dam projects, where permeability represents a dominant zoning criterion.

3.1 Intervals of Agreement and Divergence

Intervals of agreement represent sections of the profile in which different classification systems indicate the same or similar rock mass class. Intervals of divergence represent sections of the profile in which classification systems yield different class ratings (e.g., good rock versus poor rock). Divergence may result from differences in how individual classification systems account for the influence of groundwater, discontinuities, stress conditions, or scoring resolution.

3.2 Zoning Logic

Zoning is performed following the interpretative synthesis of results obtained from multiple classification systems.

In this process, predefined rules are applied, such as:

- minimum domain length in relation to the project scale,
- prioritization of fault and fractured zones, depending on the type and function of the designed structure,
- constraints imposed by lithology,
- selection of a representative class in cases of differing classifications across systems.

The definition of a minimum domain length is necessary to avoid excessive zoning detail that lacks practical significance. Faulted and highly fractured zones, as well as intervals with pronounced rock mass jointing, must be prioritized, as they represent zones of weakness and may significantly influence excavation stability. Zoning should be carried out within the framework of the corresponding lithological type of rock mass.

In cases where different classification systems assign different categories to the same interval, the selection of a representative class is based on predefined decision principles. Depending on the project, the following approaches may be adopted:

- *conservative principle* (adoption of the less favourable category – on the side of safety),
- *hierarchical principle* (e.g., priority given to a system that incorporates stress conditions),
- *project-dependent principle* (e.g., for dams, priority is given to a classification that better reflects permeability).

When three or more classification systems are applied, a “rule of the apparently more favourable category” may be defined. In such cases, if two or more classifications indicate a less favourable category, the less favourable value is adopted as representative. Clearly defined decision-making principles enable, where necessary, formalization of the procedure and its application to large datasets, thereby improving the efficiency of the analysis.

A geological–geotechnical domain defined in this manner represents a quasi-homogeneous zone within which the variability of classification results remains within defined ranges that generally correspond to the same rock mass category. Such defined geotechnical domains form the basis for further, more detailed zoning in relation to excavation and support design, enabling more rational dimensioning and reduction of design-related risk. Following the completion of the zoning process, representative rock mass parameters (e.g., deformability, strength parameters, or GSI) can be assigned to each geotechnical zone, derived from the statistical range of classification results within that zone using commonly applied engineering procedures. Proposed methodological framework is presented in Fig. 1.

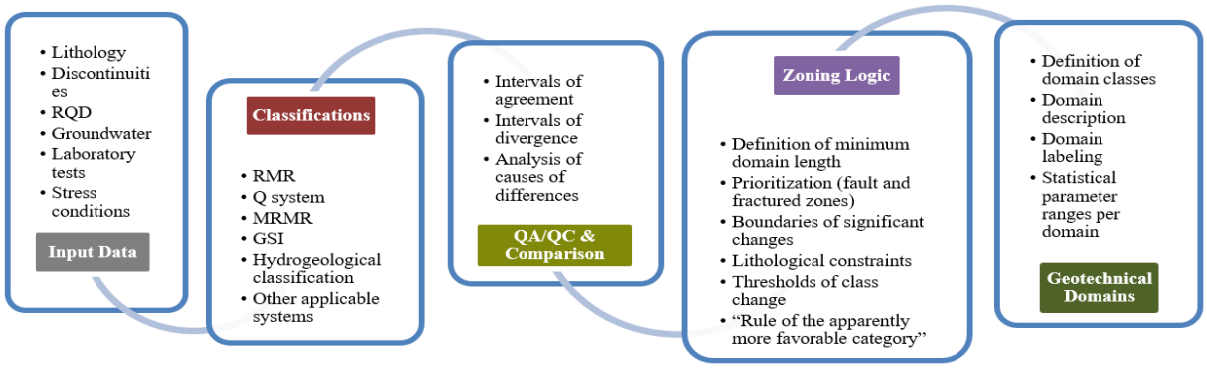


Fig. 1 Proposed methodological framework for rock mass zoning based on the comparative application of classification systems.

4 Case studies

The applied classifications and their comparison are adapted to the specific engineering context of the analysed structure. For the mining shaft, three classification systems were applied to assess ground conditions and support requirements, while for the dam cross-section case, two classification systems were used. In both cases, geometry and the zone of influence play an important role. For the dam, the interpretation covers the entire dam profile, whereas for the shaft excavation, the zone of influence is more limited. The same interval-based evaluation methodology was applied in both cases, in accordance with borehole intervals and laboratory testing results of core samples, followed by rock mass zoning along the borehole profile.

4.1 Example 1 – Mining Shaft

An interval-based zoning approach is demonstrated using data for a mining shaft exceeding 1500 m in depth (Fig. 2), provided by Hidroenergo MVB, Belgrade. The investigation borehole was drilled continuously along the axis of the planned shaft, and the results were extrapolated to the surrounding rock mass within the shaft influence zone. The following classification systems were applied: Rock Mass Rating (RMR), Mining Rock Mass Rating (MRMR), and Q-system (Bieniawski 1989; Laubscher 1990; Barton et al. 1974). The classification was first performed for individual drilling intervals and subsequently aggregated by grouping intervals of the same class, resulting in the left part of the table shown in Fig. 2.

Geotechnical units were then defined in accordance with the described methodology, and corresponding GSI value ranges were assigned as reference values for subsequent parameter assignment to geotechnical domains. Geotechnical domains were then delineated, representing the zoned shaft alignment in accordance with indicative excavation and support conditions.

Figure 2 clearly demonstrates that divergences between classification systems do not represent random variation, but rather form spatially organized intervals corresponding to changes in engineering geological conditions. These intervals represent natural boundaries of geotechnical domains and enable more reliable rock mass zoning compared to the use of individual classification systems alone. Subsequently, by assigning appropriate parameters to the geotechnical domains based on investigation results, more detailed geotechnical modelling can be performed. This directly supports support design selection and risk control in deep excavations.

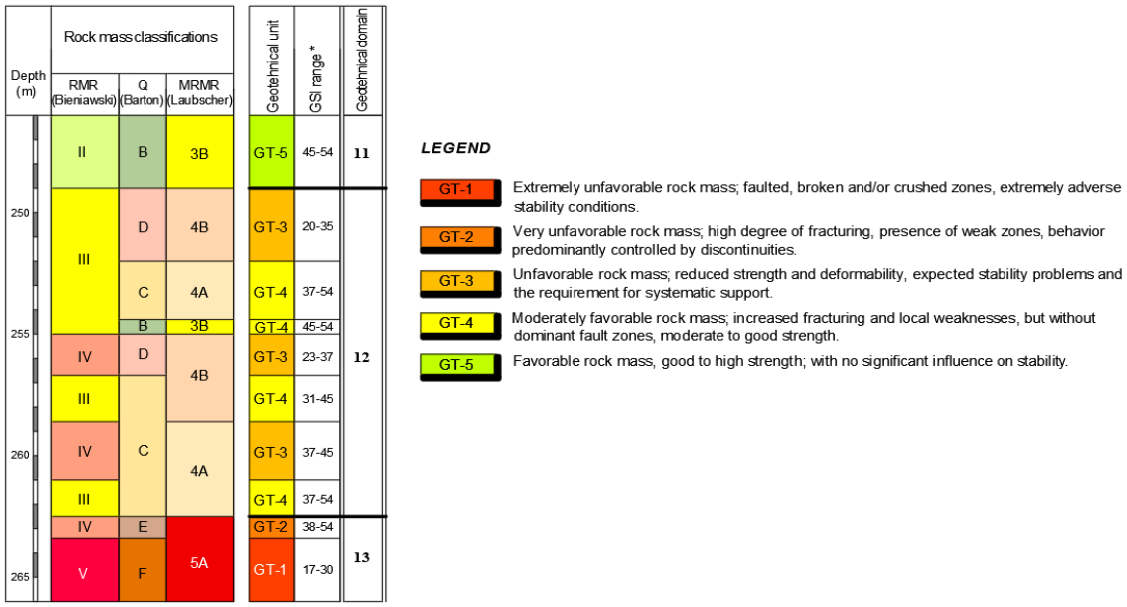


Fig. 2 Comparative rock mass classification results (RMR, Q and MRMR) and derived geotechnical domains (11–13) along the shaft profile (depth 246–266 m), with indicative GSI ranges associated with geotechnical units and corresponding engineering behaviour.

4.2 Example 2 – Dam Cross-Section "Pambukovica"

The cross-section of the planned Pambukovica dam for flood protection is located upstream of Ub in Serbia (investigation and design carried out by Energoprojekt-Hidroinženjering, Belgrade). The assessment of rock mass quality directly influences the selection of dam type, as well as the technical design of the dam and associated structures.A total of seven investigation boreholes were drilled along the axis of the planned dam. Data interpolation was performed between the boreholes, with extrapolation applied at the ends of the dam profile. Two classification systems were applied: RMR and Q.

In the presented example (Fig. 3), spatial differences between interpretative boundaries defined based on the RMR and Q classifications indicate zones of increased interpretative uncertainty. Given that only two classification systems were applied and that the structure represents a high-risk hydraulic facility, a conservative boundary may be adopted for the purpose of rock mass zoning.

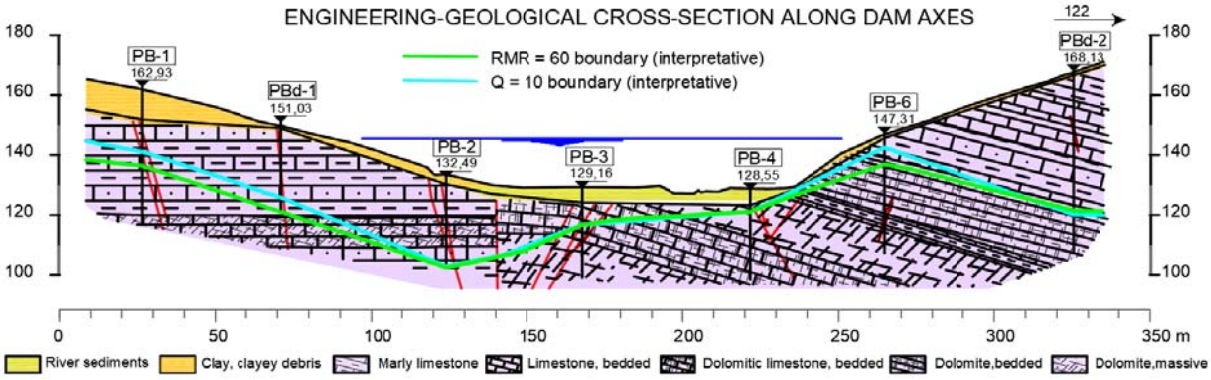


Fig. 3 Engineering-geological crossection along Dam axes with interpretative boundaries of RMR=60 and Q=10.

In cases of more pronounced differences, the application of a third classification system may be considered. In such cases, domains would first be defined at each borehole using the same methodology as for the shaft example, followed by interpretation along the engineering-geological cross-section. In all cases, these boundaries should, as far as possible, be evaluated in relation to other relevant data, such as seismic refraction surveys and similar investigations, in order to achieve a final interpretation. This is particularly important for permeability control and dam safety assessment.

5 Discussion

In complex geological conditions, individual classification systems often do not provide a sufficient interpretative model for design purposes. Their isolated application may lead to an oversimplified representation of the rock mass and the neglect of important aspects of its behaviour. As demonstrated in the examples shown in Fig. 2 and Fig. 3, intervals of divergence between classification systems are clearly delineated along the borehole profile and the dam site, representing zones of increased interpretative uncertainty. Divergences in the results of different classification systems, when properly applied, do not represent errors, but rather reflect the differing sensitivity of individual systems to structural characteristics, groundwater conditions, and stress state. In this sense, differences between classification results can be regarded as an additional source of information on the complexity of the rock mass. The comparative analysis of multiple classification systems enables the identification of intervals of agreement and divergence, providing a basis for more reliable rock mass zoning. This approach is consistent with the concept of defining geotechnical domains based on classification results (Savić et al. 2021). The application of clearly defined logical and engineering rules in this process reduces interpretative risk and improves the reliability of input parameters for geotechnical modelling. However, the method remains dependent on the quality and representativeness of input data.

6 Conclusion

Empirical rock mass classification systems are of great importance and represent a fundamental tool for assessing rock mass quality and engineering behaviour. If, after verification of correct application and elimination of potential procedural errors, differences between classification results still persist, these should not be regarded as shortcomings, but rather as an additional source of information which, when properly interpreted, enables more reliable definition of geotechnical domains. Divergences between classification results often indicate zones of increased structural complexity and potentially unfavorable rock mass behaviour. The proposed zoning framework, based on the comparative analysis of classification systems and the application of logical decision rules, represents a practical approach for reducing interpretative uncertainty and improving the reliability of geotechnical ground models. Conceptually, the method is universal and can be applied under various engineering conditions, using different classification systems, including future developments. This approach reduces interpretative uncertainty, improves input reliability, and directly contributes to safer and more robust engineering design.

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