THE GEOLOGICAL STRENGTH INDEX (GSI): A CHARACTERIZATION TOOL FOR ASSESSING ENGINEERING PROPERTIES FOR ROCK MASSES

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ABSTRACT

The Geological Strength Index (GSI) is a system of rock mass characterization that has been developed in engineering rock mechanics to meet the need for reliable input data related to rock mass properties required as input for numerical analysis or closed-form solutions for designing tunnels, slopes, or foundations in rocks. The geological character of the rock material, together with the visual assessment of the mass it forms, is used as a direct input for the selection of parameters for predicting rock mass strength and deformability. This approach enables a rock mass to be considered as a mechanical continuum without losing the influence that geology has on its mechanical properties. It also provides a field method for characterizing difficult-to-describe rock masses. Recommendations on the use of GSI are given and, in addition, cases where the GSI is not applicable are discussed.

INTRODUCTION

A few decades ago, the tools for designing tunnels started to change. Numerical methods were being developed that offered the promise for much more detailed analysis of difficult underground excavation problems.

Numerical tools available today allow the tunnel designer to analyze progressive failure processes and the sequentially installed reinforcement and support necessary to maintain the stability of the advancing tunnel until the final reinforcing or supporting structure can be installed. However, these numerical tools require reliable input information on the strength and deformation characteristics of the rock mass surrounding the tunnel. As it is practically impossible to determine this information by direct in situ testing (except for back analysis of already constructed tunnels), there was an increased need for estimating the rock mass properties from the intact rock properties and the characteristics of the discontinuities in the rock mass. This resulted in the development of the rock mass failure criterion by Hoek and Brown [1980]. A brief history of the development of the Hoek-Brown criterion is to be published in the first issue of a new international journal entitled *Soils and Rocks* [Hoek and Marinos, in press].

The present paper is an update and extension of the paper by Marinos et al. [2005].

THE GEOLOGICAL STRENGTH INDEX (GSI)

Hoek and Brown recognized that a rock mass failure criterion would have no practical value unless it could be related to geological observations that could be made quickly and easily by an engineering geologist or geologist in the field. They considered developing a new classification system during the evolution of the criterion in the late 1970s, but they soon gave up the idea and settled for the already published RMR system. It was appreciated that the RMR system (and the Q-system) [Bieniawski 1973; Barton et al. 1974] were developed for the estimation of underground excavation and support and that they included parameters that are not required for estimating rock mass properties. The groundwater and structural orientation parameters in RMR and the groundwater and stress parameters in Q are dealt with explicitly in effective stress numerical analyses, and the incorporation of these parameters into the rock mass property estimate results is inappropriate. Thus, it was recommended that only the first four parameters of the RMR system (intact rock strength, RQD rating, joint spacing, and joint conditions) should be used for the estimation of rock mass properties if this system had to be used.

After several years of use, it became obvious that the RMR system was difficult to apply to rock masses that are of very poor quality. The relationship between RMR and the constants "m" and "s" of the Hoek-Brown failure criterion begins to break down for severely fractured and weak rock masses.

Additionally, since RQD in most of the weak rock masses is essentially zero, it became necessary to consider an alternative classification system. The required system would place greater emphasis on basic geological observations of rock mass characteristics; reflect the material, its structure, and its geological history; and would be developed specifically for the estimation of rock mass properties rather than for tunnel reinforcement and support. This new classification, now called GSI, started life in Toronto, Canada, with engineering geology input from David Wood [Hoek et al. 1992]. The index and its use for the Hoek-Brown failure criterion was further developed by Hoek

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[1994] and presented in Hoek et al. [1995] and Hoek and Brown [1997], but it was still a hard-rock system roughly equivalent to RMR. Since 1998, Evert Hoek and Paul Marinos, dealing with incredibly difficult materials encountered in tunneling in Greece, developed the GSI system to its present form to include poor-quality rock masses (Figure 1) [Hoek et al. 1998; Marinos and Hoek 2000, 2001]. Today, GSI continues to evolve as the principal vehicle for geological data input for the Hoek-Brown criterion.

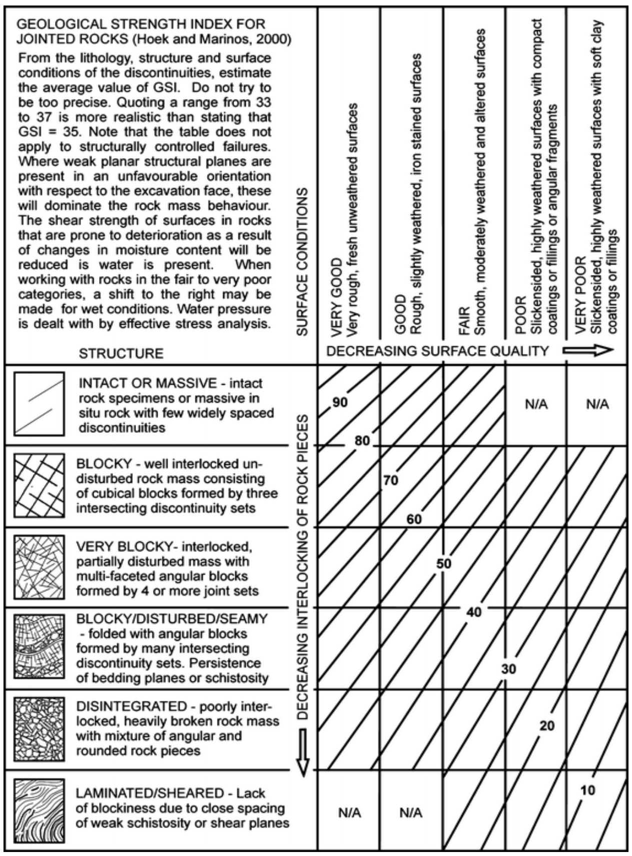

Figure 1.—General chart for GSI estimates from geological observations.

FUNCTIONS OF THE GEOLOGICAL STRENGTH INDEX

The heart of the GSI classification is a careful engineering geology description of the rock mass, which is essentially qualitative, because it was believed that numbers on joints were largely meaningless for weak and complex rock masses. Note that the GSI system was never intended as a replacement for RMR or Q, as it has no rock mass reinforcement or support design capability. GSI alone is not a tunnel design tool; its only function is the estimation of rock mass properties. It is intimately linked with the intact rock strength and should never be used independently of this parameter.

This index is based on an assessment of the lithology, structure, and condition of discontinuity surfaces in the rock mass, and it is estimated from visual examination of the rock mass exposed in outcrops, in surface excavations such as road cuts, and in tunnel faces and borehole cores. The GSI, by combining the two fundamental parameters of the geological process—the blockiness of the mass and the conditions of discontinuities—respects the main geological constraints that govern a formation. It is thus a geologically sound index that is simple to apply in the field.

Note that attempts to "quantify" the GSI classification to satisfy the perception that "engineers are happier with numbers" [Cai et al. 2004; Sonmez and Ulusay 1999] are interesting, but have to be applied with caution in order not to lose the geologic logic of the GSI system. The quantification processes used are related to the frequency and orientation of discontinuities and are limited to rock masses in which these numbers can easily be measured. These quantifications do not work well in tectonically disturbed rock masses in which the structural fabric has been destroyed. In such rock masses, the authors recommend the use of the original qualitative approach based on careful visual observations. Thus, the "quantification" system is only valid in the range of, say, 35 < GSI < 75, when the rock mass behavior depends on sliding and rotation of intact rock pieces, and where the spacing and condition of discontinuities that separate these pieces and not the intact rock strength control the behavior. When the intact rock pieces themselves can fail, then the quantification is no longer valid.

Once a GSI "number" has been decided upon, this number is entered into a set of empirically developed equations to estimate the rock mass properties that can then be used as input into some form of numerical analysis or closed-form solution. The index is used in conjunction with appropriate values for the unconfined compressive strength (UCS) of the intact rock, σ_{ci}, and the petrographic constant, m_i, to calculate the mechanical properties of a rock mass, in particular the compressive strength of the rock mass (σ_{cm}) and its deformation modulus (E). Updated values of m_i can be found in Marinos and Hoek [2000] or in the RocLab program [Rocscience, Inc. 2007]. Basic procedures are explained by Hoek and Brown [1997], but a refinement of the empirical equations and the relationship between the Hoek-Brown and Mohr-Coulomb criteria have been addressed by Hoek et al. [2002] for appropriate ranges of stress encountered in tunnels and slopes. Hoek and Diederichs [2006] recently presented new equations for estimating rock mass deformation modulus incorporating measured or estimated intact modulus.

SUGGESTIONS FOR USING GSI

After more than a dozen of years of application of the GSI and its variations for the characterization of the rock mass, this paper attempts to answer questions that have been raised by users about the appropriate selection of the index for various rock masses under various conditions.

When Not to Use GSI

The GSI classification system is based on the assumption that the rock mass contains a sufficient number of "randomly" oriented discontinuities such that it behaves as a homogeneous isotropic mass. In other words, the behavior of the rock mass is independent of the direction of the applied loads. Therefore, it is clear that the GSI system should not be applied to those rock masses in which there is a clearly defined dominant structural orientation or structurally dependent gravitational instability. However, the Hoek-Brown criterion and the GSI chart can be applied with caution if the failure of such rock masses is not controlled by such anisotropy (e.g., in the case of a slope when the dominant structural discontinuity set dips into the slope and failure occurs through the rock mass). For rock masses with a structure such as that shown in the bottom row of the GSI chart (Figure 1), anisotropy is not a major issue, as the difference in the strength of the rock and that of the discontinuities within it is often small. Anisotropy in cases of stress-dependent instability is discussed later in this paper.

It is also inappropriate to assign GSI values to excavated faces in strong hard rock with a few discontinuities spaced at distances of similar magnitude to the dimensions of the tunnel or slope under consideration. In such cases, the stability of the tunnel or slope will be controlled by the three-dimensional geometry of the intersecting discontinuities and the free faces created by the excavation. Obviously, the GSI classification does not apply to such cases.

Geological Description in the GSI Chart

In dealing with specific rock masses, it is suggested that the selection of the appropriate case in the GSI chart should not be limited to the visual similarity with the sketches of the structure of the rock mass as they appear in the charts. The associated descriptions must also be read carefully, so that the most suitable structure is chosen. The most appropriate case may well lie at some intermediate point between the limited number of sketches or descriptions included in the charts.

Projection of GSI Values Into the Ground

Outcrops, excavated slopes, tunnel faces, and borehole cores are the most common sources of information for estimating the GSI value of a rock mass. How should the numbers estimated from these sources be projected or extrapolated into the rock mass behind a slope or ahead of a tunnel?

Outcrops are an extremely valuable source of data in the initial stages of a project, but they suffer from the disadvantage that surface relaxation, weathering, and/or alteration may have significantly influenced the appearance of the rock mass components. This disadvantage can be overcome by trial trenches but, unless these are machine-excavated to considerable depth, there is no guarantee that the effects of deep weathering will have been eliminated. Judgment is therefore required in order to allow for these weathering and alteration effects in assessing the most probable GSI value at the depth of the proposed excavation.

Excavated slope and tunnel faces are probably the most reliable source of information for GSI estimates, provided that these faces are reasonably close to and in the same rock mass as the excavation under investigation.

Borehole cores are the best source of data at depth, but it must be recognized that it is necessary to extrapolate the one-dimensional information provided by the core to the three-dimensional in situ rock mass. However, this is a problem common to all borehole investigations, and most experienced engineering geologists are comfortable with this extrapolation process.

For stability analysis of a slope, the evaluation is based on the rock mass through which it is anticipated that a potential failure plane could pass. The estimation of GSI values in these cases requires considerable judgment, particularly when the failure plane can pass through several zones of different quality. Mean values may not be appropriate in this case.

For tunnels, the index should be assessed for the volume of rock involved in carrying loads, e.g., for about one diameter around the tunnel in the case of tunnel behavior or more locally in the case of a structure such as the elephant foot of a steel arch. In more general terms, the numerical models may include the variability of GSI values over the tunnel in "layers." Drs. Edmund Medley and Dimitrios Zekkos are currently considering developing a function defining the variation of GSI with depth for a specific case.

Anisotropy

As discussed above, the Hoek-Brown criterion (and other similar criteria) assumes that the rock mass behaves isotropically and that failure does not follow a preferential direction imposed by the orientation of a specific discontinuity or a combination of two or three discontinuities. In these cases, the use of GSI to represent the whole rock mass is meaningless, as the failure is governed by the shear strength of these discontinuities and not of the rock mass.

However, cases where the criterion and the GSI chart can reasonably be used have been discussed above.

However, in a numerical analysis involving a single well-defined discontinuity such as a shear zone or fault, it is sometimes appropriate to apply the Hoek-Brown criterion to the overall rock mass and to superimpose the discontinuity as a significantly weaker element. In this case, the GSI value assigned to the rock mass should ignore the single major discontinuity. The properties of this discontinuity may fit the lower portion of the GSI chart or they may require a different approach, such as laboratory shear testing of soft clay fillings.

In general terms, when confinement is present, the stress-dependent regime is controlled by the anisotropy of the rock masses (e.g., slates, phyllites, etc.). A discussion of anisotropy rock mass behavior in tunneling beyond the commonly used classification systems is presented by Button et al. [2004]. In these cases, it would be necessary to develop an orientation-dependent GSI. This is a recent idea to try to simplify the treatment of anisotropic problems. However, in view of the potential for complicating the understanding of GSI, an alternative approach may be to use an orientation-dependent UCS. This is more logical from a physical point of view and, being almost completely interchangeable with GSI from a mathematical point of view, should work just as well. The GSI value in this case would be high, and the rock mass strength would be determined by the orientation-dependent σ_{ci} value.

With the capacity of present-day microcomputers, it is also possible to model anisotropy by superimposing a large number of discontinuities on an isotropic rock mass which is assigned a higher GSI value. These discontinuities can be assigned shear strength and stiffness characteristics that simulate the properties of the schistosity, bedding planes, and joints in the rock mass. Such models have been found to work well and give results that compare well with more traditional anisotropic solutions.

Aperture of Discontinuities

The strength and deformation characteristics of a rock mass are dependent on the interlocking of the individual pieces of intact rock that make up the mass. Obviously, the aperture of the discontinuities that separate these individual pieces has an important influence on the rock mass properties.

There is no specific reference to the aperture of the discontinuities in the GSI chart, but a "disturbance factor" D has been provided in the most recent version of the Hoek-Brown failure criterion [Hoek et al. 2002] and is also used in the Hoek and Diederichs [2006] approach for estimating deformation modulus. This factor ranges from D=0 for undisturbed rock masses, such as those excavated by a tunnel boring machine, to D=1 for extremely disturbed rock masses, such as open-pit mine slopes that have been subjected to very heavy production blasting. The factor allows for the disruption of the interlocking of the individual rock pieces as a result of opening of the discontinuities. The influence of this factor is of great significance to the calculated factors of safety.

At this stage, there is relatively little experience in the use of this factor, and it may be necessary to adjust its participation in the equations as more field evidence is accumulated. However, the experience so far suggests that this factor does provide a reasonable estimate of the influence of damage due to stress relaxation or blasting of excavated rock faces. Note that this damage decreases with depth into the rock mass and, in numerical modeling, it is generally appropriate to simulate this decrease by dividing the rock mass into a number of zones with decreasing values of D being applied to successive zones as the distance from the face increases. On the other hand, in very large open-pit mine slopes in which blasts can involve many tons of explosives, blast damage has been observed up to 100 m or more behind the excavated slope face. This would be a case for D=1 and there is a very large reduction in shear strength associated with damage. Hoek and Karzulovic [2000] have given some guidance on the extent of this damage and its impact on rock mass properties. For civil engineering slopes or foundation excavation, the blast damage is much more limited in both severity and extent, and the value of D is generally low.

This problem becomes less significant in weak and tectonically disturbed rock masses, as excavation is generally carried out by "gentle" mechanical means and the amount of surface damage is negligible compared to that which already exists in the rock mass.

Geological Strength Index at Great Depth

In hard rock at great depth (e.g., 1,000 m or more) the rock mass structure is so tight that the mass behavior approaches that of the intact rock. In this case, the GSI value approaches 100 and the application of the GSI system is no longer meaningful.

The failure process that controls the stability of underground excavations under these conditions is dominated by brittle fracture initiation and propagation, which leads to spalling, slabbing, and, in extreme cases, rock bursts. Considerable research effort has been devoted to the study of these brittle fracture processes, and Diederichs et al. [2004] provide a useful summary of this work.

When tectonic disturbance is important and persists with depth, these comments do not apply and the GSI charts may be applicable, but should be used with caution.

Discontinuities With Filling Materials

The GSI charts can be used to estimate the characteristics of rock masses with discontinuities with filling materials using the descriptions in the columns for "poor" or "very poor" condition of discontinuities. If the filling material is systematic and thick (e.g., more than a few centimeters) or shear zones are present with clayey material, then the use of the GSI chart for heterogeneous rock masses (discussed below) is recommended.

Influence of Water

The shear strength of the rock mass is reduced by the presence of water in the discontinuities or filling materials when these are prone to deterioration as a result of changes in moisture content. This is particularly valid in the "fair" to "very poor" categories of discontinuities, where a shift to the right may be made for wet conditions. The shift to the right is more substantial in the low-quality range of rock mass (last rows and columns of the chart).

Water pressure is dealt with by effective stress analysis in design, and it is independent of the GSI characterization of the rock mass.

Weathered Rock Masses

The GSI values for weathered rock masses are shifted to the right of those of the same rock masses when these are unweathered. If the weathering has penetrated into the intact rock pieces that make up the mass (e.g., in weathered granites), then the constant m_i and the unconfined strength of the σ_{ci} of the Hoek-Brown criterion must also be reduced. If the weathering has penetrated the rock to the extent that the discontinuities and the structure have been lost, then the rock mass must be assessed as a soil and the GSI system no longer applies.

Heterogeneous and Lithologically Varied or Complex Rock Masses

GSI has been extended to accommodate the most variable of rock masses, including extremely poor quality sheared rock masses of weak schistose materials (such as siltstones, clay shales, or phyllites) often interbedded with strong rock (such as sandstones, limestones, or quartzites). A GSI chart for flysch, a typical heterogeneous lithological

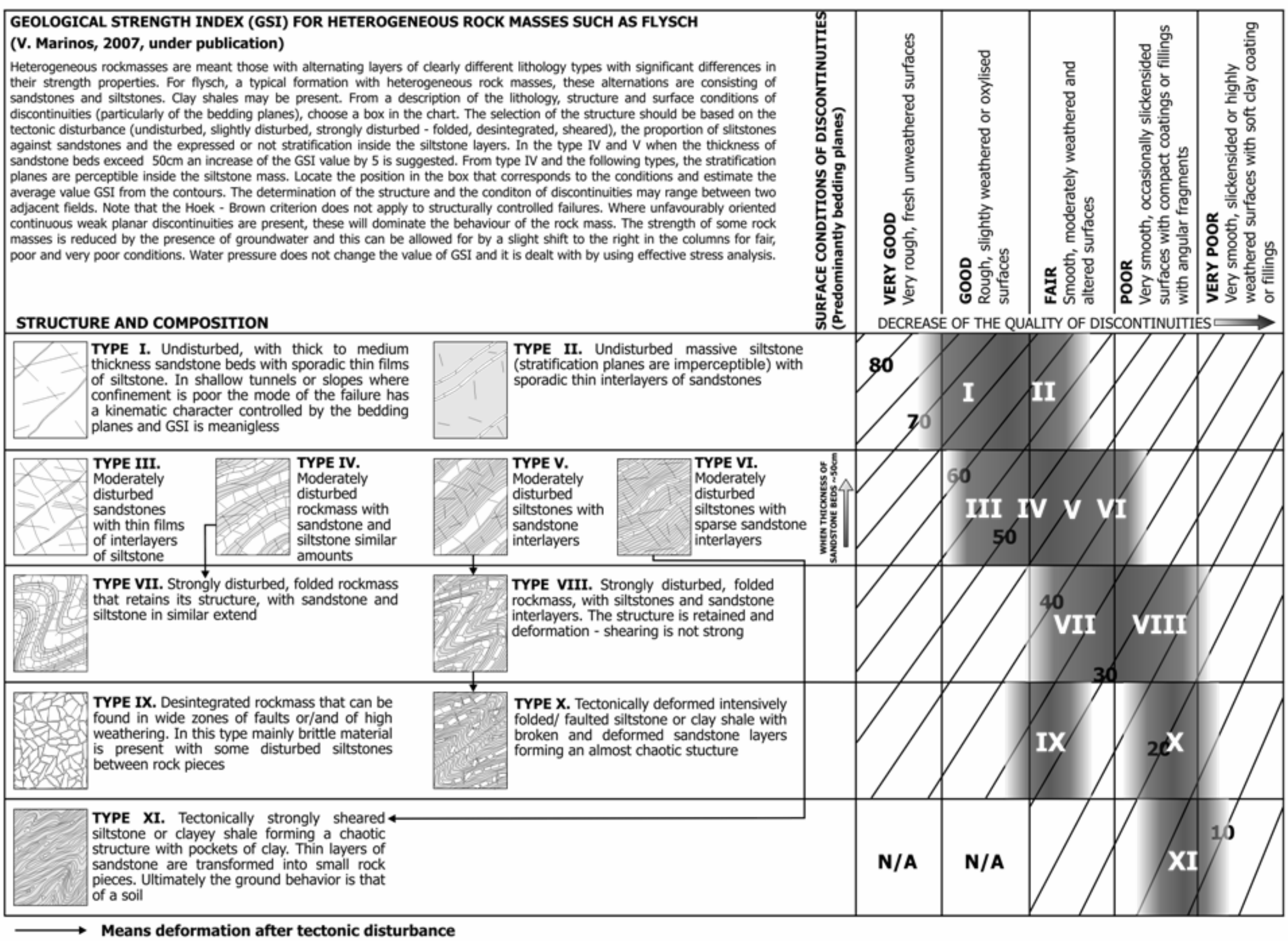

Figure 2.—Geological Strength Index for heterogeneous rocks such as flysch.

formation with tectonic disturbance, was published by Marinos and Hoek [2001]. This chart has recently been revised and is reproduced in Figure 2. This revision is based on recent experience from a number of tunnels constructed in Greece. It includes cases of siltstones with little disturbance and a variety of cases of siltstones alternating with good rock (e.g., sandstone).

For lithologically varied but tectonically undisturbed rock masses, such as the molasses, a new GSI chart was presented by Hoek et al. [2005] (Figure 3). For example, molasse consists of a series of tectonically undisturbed sediments of sandstones, conglomerates, siltstones, and marls produced by the erosion of mountain ranges after the final phase of an orogeny. The molasses behave quite differently from flysch, which has the same composition but was tectonically disturbed during the orogeny. They behave as continuous rock masses when they are confined at depth, and the bedding planes do not appear as clearly defined discontinuity surfaces. Close to the surface the layering of the formations is discernible, and only then similarities may exist with the structure of some types of flysch.

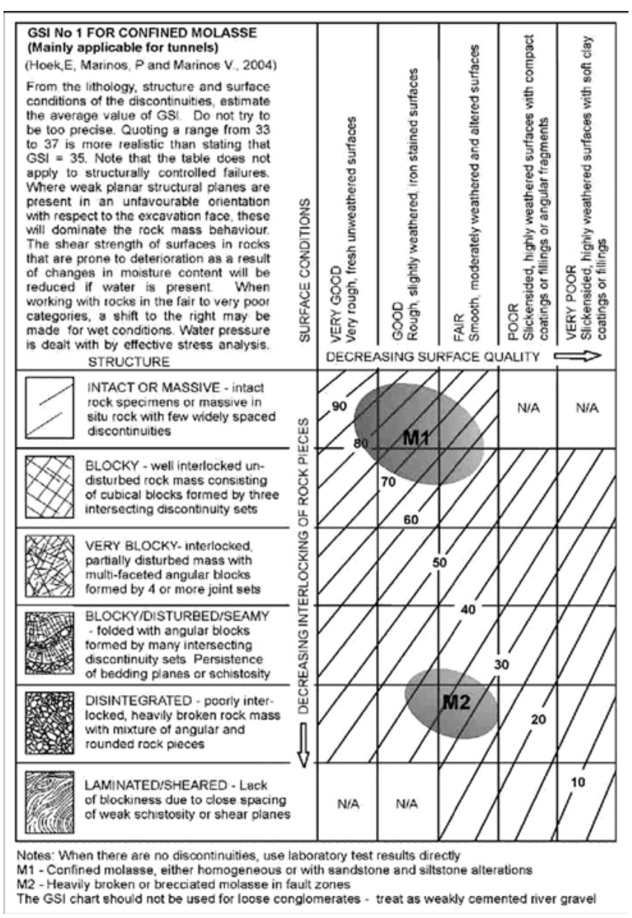

Figure 3.—Chart for confined molasse (mainly applicable for tunnels).

In design, the intact rock properties σ_{ci} and the m_i must also be considered. A "weighted average" of the properties of the strong and weak layers should be used.

Marinos et al. [2006] recently presented a quantitative description, using GSI, for rock masses within an ophiolitic complex. Included are types with large variability due to their range of petrographic types, their tectonic deformation, and their alternation (Figure 4). The structure of the various masses include types from massive strong to sheared weak, while the conditions of discontinuities are, in most cases, fair to very poor due to the fact that they are affected by serpentinization and shearing. This description allows the estimation of the range of properties and the understanding of the dramatic change in tunneling, from stable conditions to severe squeezing within the same formation at the same depth.

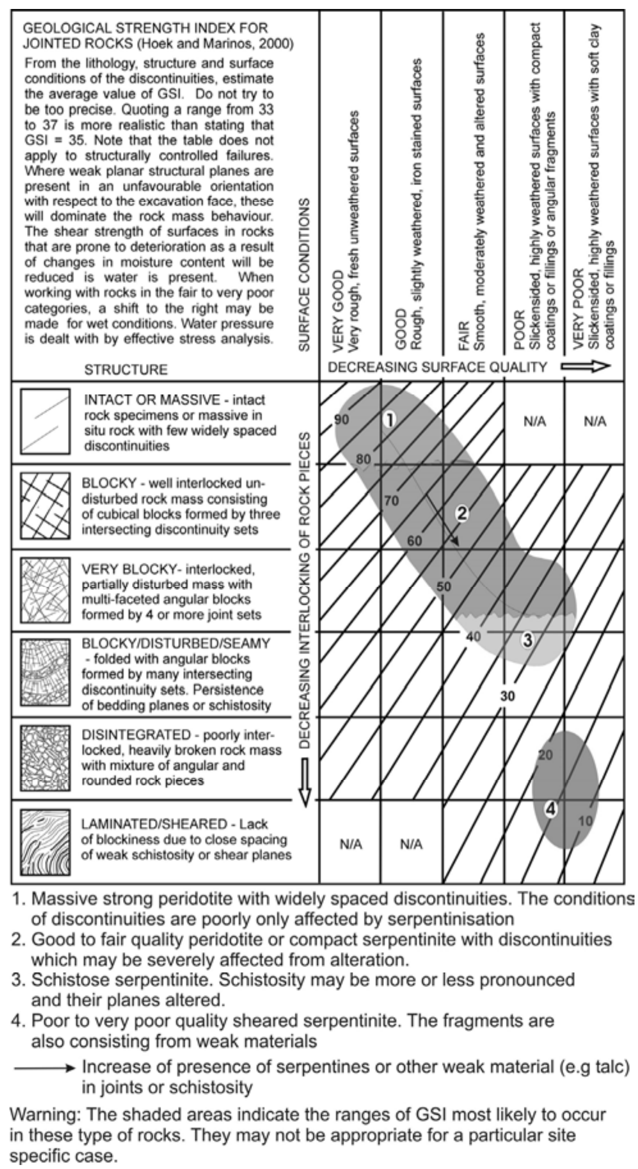

Figure 4.—Ranges of GSI for various qualities of peridotite-serpentinite rock masses in ophiolites.

Rocks of Low Strength of Recent Age

When rocks such as marls, claystones, siltstones, and weak sandstones are developed in geologically stable conditions in a posttectonic environment, they usually present a simple structure with no or few discontinuities. When these rocks form continuous masses with no discontinuities, the rock mass can be treated as intact with engineering parameters given directly by laboratory testing. In such cases, the GSI classification is not applicable.

In cases where discontinuities are present, the use of the GSI chart for "blocky" or "massive" rock masses (Figure 1) may be applicable. The discontinuities in such weak rocks, although they are limited in number, cannot be better than "fair" (usually "fair" or "poor"); thus, the GSI values tend to be in the range of 45–65. In these cases, the low strength of the rock mass results from low intact strength σ_{ci}.

PRECISION OF THE GSI CLASSIFICATION SYSTEM

The "qualitative" GSI system works well for engineering geologists since it is consistent with their experience in describing rocks and rock masses during logging and mapping. In some cases, engineers tend to be uncomfortable with the system because it does not contain parameters that can be measured in order to improve the precision of the estimated GSI value.

The authors do not share this concern, as they believe that it is not meaningful to attempt to assign a precise number to the GSI value for a typical rock mass. In all but the very simplest of cases, GSI is best described by assigning it a range of values. For analytical purposes, this range may be defined by a normal distribution with mean and standard deviation values assigned on the basis of common sense. GSI, with its qualitative principles of geological descriptions, is not restrained by the absence of good exposures or the limitations of quantitative core descriptions.

Although GSI is a totally independent system, in the earlier period of its application it was proposed that correlation of "adjusted" RMR and Q values with GSI be used for providing the necessary input for the Hoek-Brown criterion. Although this procedure may work with the better-quality rock masses, it is unreliable in the range of weak (e.g., GSI<35), very weak, and heterogeneous rock masses, where these correlations are not recommended.

Whenever GSI is used, a direct assessment, based on the principles and charts presented above, is recommended. Fortunately, most GSI users have no difficulty in thinking of it as a totally independent system. However, in cases of comparisons or back analysis where other classification systems have been used, some kind of correlation with these other systems is needed. In such cases, it may be useful to consult the paper by Tzamos and Sofianos [in press]. The four classification-characterization systems (RMR, Q, RMi [Palmström 1996], and GSI) were investigated, and all systems ratings are grouped in a common fabric index chart. The reader is reminded not to lose sight of the real geological world in considering such correlations.

GSI AND CONTRACT DOCUMENTS

One of the most important contractual problems in rock construction and particularly in tunneling is the issue of "changed ground conditions." There are invariably arguments between the owner and the contractor on the nature of the ground specified in the contract and that actually encountered during construction. In order to overcome this problem, there has been a tendency to specify the anticipated conditions in terms of tunneling classifications. More recently, some contracts have used the GSI classification for this purpose, and the authors are strongly opposed to this trend.

As discussed earlier in this paper, GSI was developed solely for the purpose of estimating rock mass properties. Therefore, GSI is only one element in a tunnel design process and cannot be used, on its own, to specify tunneling conditions. It must be associated with the intact rock strength, the petrographic constant m_i, and all of the characteristics (such as anisotropy) of the rock mass that may impose a different mode of failure than that of a stressed homogeneous isotropic rock mass.

The use of any classification system to specify anticipated tunneling conditions is always a problem as these systems are open to a variety of interpretations, depending on the experience and level of conservatism of the observer. This can result in significant "changes" in excavation or support type and can have important financial consequences.

The geotechnical baseline report [Essex 1997] was introduced in an attempt to overcome some of the difficulties and has attracted an increasing amount of international attention in tunneling.

CONCLUSIONS

Rock mass characterization has an important role, not only to define a conceptual model of the site geology, but also for the quantification needed for analyses "to ensure that the idealization (for modeling) does not misinterpret actuality" [Knill 2003]. If it is carried out in conjunction with numerical modeling, rock mass characterization presents the prospect of a far better understanding of the mechanics of rock mass behavior [Chandler et al. 2004]. The GSI system has considerable potential for use in rock engineering because it permits many characteristics of a rock mass to be quantified, thereby enhancing geological logic and reducing engineering uncertainty. Its use allows the influence of variables, which make up a rock mass, to be assessed and thus the behavior of rock masses to be explained more clearly. One of the advantages of the GSI is that the geological reasoning it embodies allows adjustments of its ratings to cover a wide range of rock masses and conditions, but it also allows us to understand the limits of its application.

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