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Original Paper

# The geological strength index: applications and limitations

**V. Marinos (✉) · P. Marinos (✉) · E. Hoek (✉)**

V. Marinos · P. Marinos
School of Civil Engineering, Geotechnical Department, National Technical University of Athens,
9 Iroon Polytechniou str., 157 80 Athens, Greece

E. Hoek
Consulting Engineer, Vancouver, Canada

✉ V. Marinos
E-mail: vmarinos@central.ntua.gr

✉ P. Marinos
E-mail: marinos@central.ntua.gr

✉ E. Hoek
E-mail: ehoek@attglobal.net

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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, particularly those related to rock-mass properties required as inputs into numerical analysis or closed form solutions for designing tunnels, slopes or foundations in rocks. The geological character of rock material, together with the visual assessment of the mass it forms, is used as a direct input to the selection of parameters relevant for the prediction of rock-mass strength and deformability. This approach enables a rock mass to be considered as a mechanical continuum without losing the influence that its geology has on its mechanical properties. It also provides a field method for characterizing difficult-to-describe rock masses. After a decade of application of the GSI and its variations in quantitative characterization of rock mass, this paper attempts to answer questions that have been raised by the users about the appropriate selection of the index for a range of rock masses under various conditions. Recommendations on the use of GSI are given and, in addition, cases where the GSI is not applicable are discussed. More particularly, a discussion and suggestions are presented on issues such as the size of the rock mass to be considered, its anisotropy, the influence of great depth, the presence of ground water, the aperture and the infilling of discontinuities and the properties of weathered rock masses and soft rocks.

**Keywords** Geological strength index · Rock mass · Geological structure · Mechanical properties · Selection of the GSI

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**Résumé** Le Geological Strength Index (GSI) est un système de classification des massifs rocheux développé en mécanique des roches. Il permet d"obtenir les données relatives aux propriétés de masses rocheuses, données nécessaires pour des simulations numériques ou permettant le dimensionnement d"ouvrages:tunnels, pentes ou fondations rocheuses. Les caractéristiques géologiques de la matrice rocheuse ainsi que celles relatives à la structure du massif correspondant sont directement utilisées pour obtenir les paramètres appropriés relatifs à la déformabilité et la résistance de la masse rocheuse. Cette approche permet de considérer une masse rocheuse comme un milieu continu, le rôle des caractéristiques géologiques sur les propriétés mécaniques n"étant pas oblitèré. Elle apporte aussi une méthode de terrain pour caractériser des masses rocheuses difficiles à décrire. Après une décennie d"application du Geological Strength Index et de ses variantes pour caractériser des masses rocheuses, cet article tente de répondre aux questions formulées par les utilisateurs concernant le choix le plus approprié de cet index pour une large gamme de massifs rocheux. Des recommandations quant à l"usage du GSI sont données et, de plus, des cas où le GSI n"est pas applicable sont discutés. Plus particulièrement, des suggestions sont apportées sur des questions relatives à la taille de masse rocheuse à considérer, son anisotropie, l"influence des grandes profondeurs, la présence d"eau, l"ouverture et le remplissage des discontinuités ainsi que les propriétés des masses rocheuses altérées et des roches tendres.

**Motsclés** Geological Strength Index · Massif rocheux · Structure géologique · Propriétés mécaniques · Conditions d"utilisation du GSI

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# Introduction

## Design in rock masses

A few decades ago, the tools for designing tunnels started to change. Although still crude, numerical methods were being developed that offered the promise for much more detailed analysis of difficult underground excavation problems which, in a number of cases, fall outside the ideal range of application of the tunnel reinforcement classifications such as the RMR system introduced by Bieniawski (1973) and the Q system published by Barton et al. (1974) both furthermore expanded in the following years. There is absolutely no problem with the concept of these classifications and there are hundreds of kilometres of tunnels that have been successfully constructed on the basis of their application. However, this approach is ideally suited to situations in which the rock mass behaviour is relatively simple, for example for RMR values between about 30–70 and moderate stress levels. In other words, sliding and rotation of intact rock pieces essentially control the failure process. These approaches are less reliable for squeezing, swelling, clearly defined structural failures or spalling, slabbing and rock-bursting under very high stress conditions. More importantly, these classification systems are of little help in providing information for the design of sequentially installed temporary reinforcement and the support required to control progressive failure in difficult tunnelling conditions.

Numerical tools available today allow the tunnel designer to analyse these 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 a need for some method 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).

## The geological strength index (GSI): development history

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) were developed for the estimation of underground excavation and support, and that they included parameters that are not required for the estimation of 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. Hence, 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.

In the early days the use of the RMR classification (modified as described above) worked well because most of the problems were in reasonable quality rock masses ($30<RMR<70$) under moderate stress conditions. However, it soon 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.

Both the RMR and the Q classifications include and are heavily dependent upon the RQD classification introduced by Deere (1964). Since RQD in most of the weak rock masses is essentially zero or meaningless, it became necessary to consider an alternative classification system. The required system would not include RQD, 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 with engineering geology input from David Wood (Hoek et al. 1992). The index and its use for the Hoek and Brown failure criterion was further developed by Hoek (1994), 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 tunnelling in Greece, developed the GSI system to the present form to include poor quality rock masses (Fig. 1) (Hoek et al. 1998; Marinos and Hoek 2000, 2001). They also extended its application for heterogeneous rock masses as shown in Fig. 2 (Marinos and Hoek 2001)

## 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 felt that the numbers associated with RMR and Q-systems were largely meaningless for the weak and heterogeneous 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—its only function is the estimation of rock-mass properties.

This index is based upon 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 and is thus a geologically sound index that is simple to apply in the field.

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 which 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 of the intact rock $\sigma_{ci}$ and the petrographic constant $m_i$, to calculate the mechanical properties of a rock mass, in particular the compressive strength of the rock mass and its deformation modulus ($E$). Updated values of $m_i$, can be found in Marinos and Hoek (2000) or in the RocLab program. Basic procedures are explained in Hoek and Brown (1997) but a more recent refinement of the empirical equations and the relation between the Hoek–Brown and the Mohr–Coulomb criteria have been addressed by Hoek et al. (2002) for appropriate ranges of stress encountered in tunnels and slopes. This paper and the associated program RocLab can be downloaded from http://www.rocscience.com.

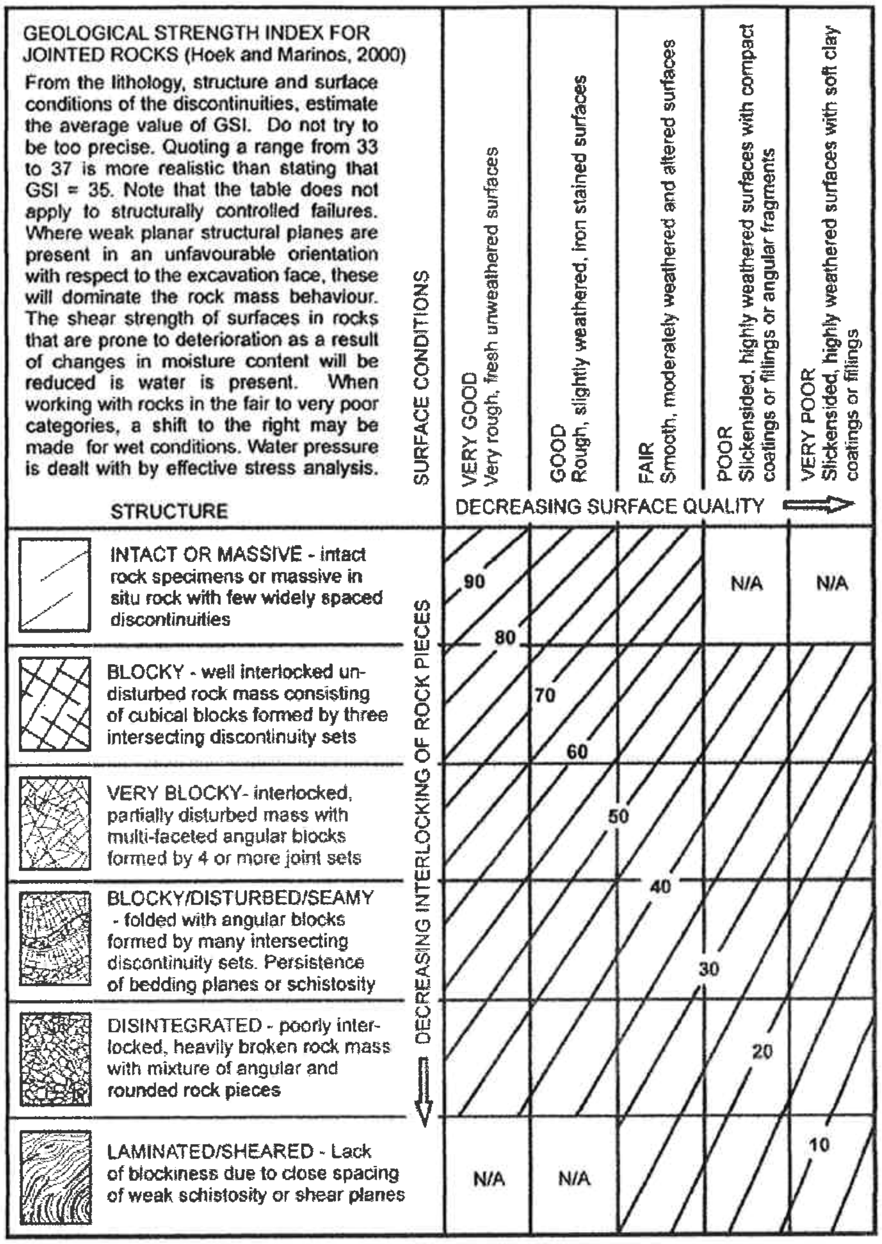
Note that attempts to "quantify" the GSI classification to satisfy the perception that "engineers are happier with numbers" (Cai et al. 2004; Sonmez and Ulusay 1999) are interesting but have to be applied with caution. The quantification processes used are related to the frequency and orientation of discontinuities and are limited to rock masses in which these numbers can easily be measured. The 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.

# Suggestions for using GSI

After a decade 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 upon the assumption that the rock mass contains a sufficient number of "randomly" oriented discontinuities such that it behaves as an isotropic mass. In other words, the behaviour 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. Undisturbed slate is an example of a rock mass in which the mechanical behaviour is highly anisotropic and which should not be assigned a GSI value based upon the charts presented in Figs. 1, 2. 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 their anisotropy (e.g. in the case of a slope when the dominant structural discontinuity set dips into the slope and failure may occur through the rock mass). For rock masses with a structure such as that shown in the sixth (last) row of the GSI chart (Fig. 1), anisotropy is not a major issue as the difference in the strength of the rock and that of the discontinuities within it is small.



GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS (Hoek and Marinos, 2000)

From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced is water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.

**Fig. 1** General chart for GSI estimates from the geological observations

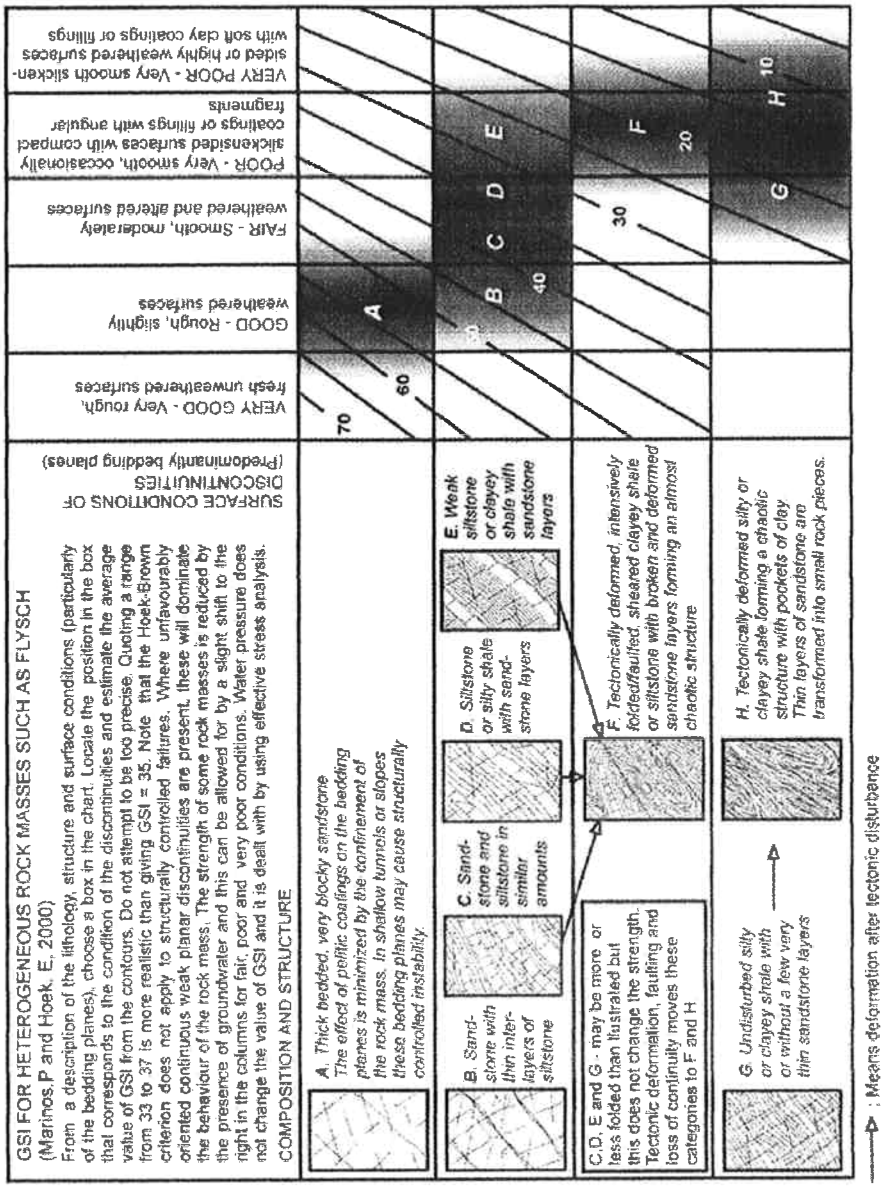


**Fig. 2** Geological strength index estimates for heterogeneous rock masses such as Flysch

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 included in the charts.

## Projection of GSI values into the rock

Outcrops, excavated slope and tunnel faces and borehole cores are the most common sources of information for the estimation of 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 (where permissible) 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. Judgement 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 structure under investigation. In hard strong rock masses it is important that an appropriate allowance be made for damage due to mechanical excavation or blasting. As the purpose of estimating GSI is to assign properties to the undisturbed rock mass in which a tunnel or slope is to be excavated, failure to allow for the effects of blast damage when assessing GSI will result in the assignment of values that are too conservative. Therefore, if borehole data are absent, it is important that the engineering geologist or geologist attempts to "look behind" the surface damage and try to assign the GSI value on the basis of the inherent structures in the rock mass. 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.

Borehole cores are the best source of data at depth, but it has to 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. Multiple boreholes and inclined boreholes can be of great help in the interpretation of rock-mass characteristics at depth.

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 behaviour or more locally in the case of a structure such as an elephant foot.

For particularly sensitive or critical structures, such as underground powerhouse caverns, the information obtained from the sources discussed above may not be considered adequate, particularly as the design advances beyond the preliminary stages. In these cases, the use of small exploration tunnels can be considered and this method of data gathering will often be found to be highly cost effective.

Figure 3 provides a visual summary of some of the adjustments discussed in the previous paragraphs. When direct assessment of depth conditions is not available, upward adjustment of the GSI value to allow for the effects of surface disturbance, weathering and alteration are indicated in the upper (white) part of the GSI chart. Obviously, the magnitude of the shift will vary from case to case and will depend upon the judgement and experience of the observer. In the lower (shaded) part of the chart, adjustments are not normally required as the rock mass is already disintegrated or sheared and this damage persists with depth.

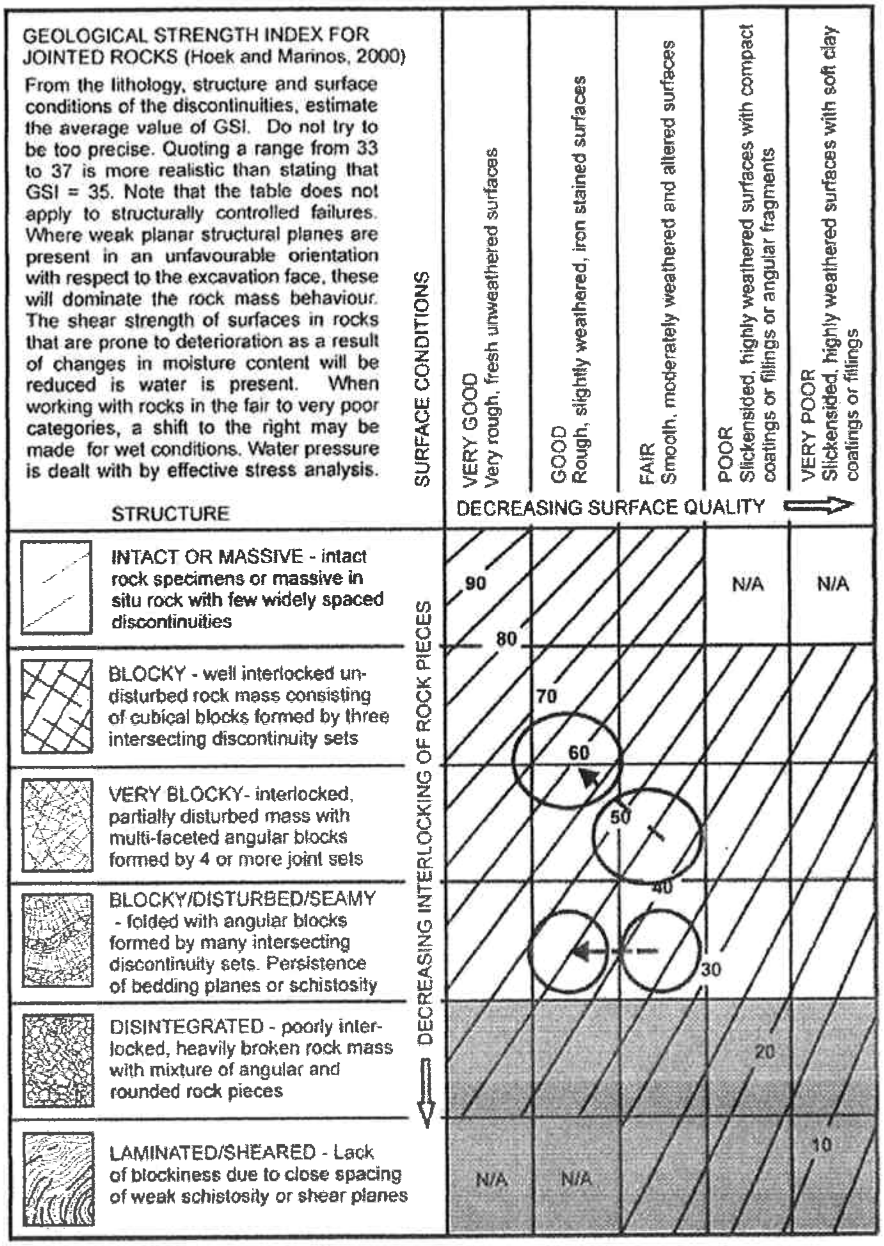


**Fig. 3** Suggested projection of information from observations in outcrops to depth. *White area* a shifting to the left or to the left and upwards is recommended; the extent of the shift shown in the chart is indicative and should be based on geological judgement. *Shadowed area* shifting is less or not applicable as poor quality is retained in depth in brecciated mylonitized or shear zones

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## Anisotropy

As discussed above, the Hoek–Brown criterion (and other similar criteria) requires that the rock mass behave 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 is meaningless as the failure is governed by the shear strength of these