

# Variability of the GSI Index Estimated From Different Quantitative Methods

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Received: 14 November 2014 / Accepted: 4 April 2015 / Published online: 11 April 2015  
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**Abstract** The main purpose of this paper is to present the results of a comparative analysis of the GSI values predicted by different empirical equations currently available in literature which apply the input parameters used in the best known rock mass classification systems, namely the  $RMR_{1989}$ , the  $Q$  and the  $RMi$ . For this aim, probabilistic analyses based on Monte Carlo simulations have been developed using, as inputs, the geomechanical field data collected for a real rock mass. Afterwards, the GSI outputs obtained from the different empirical approaches have been statistically analyzed and compared. The results of simulations indicate that the diverse relationships may predict dissimilar values of the GSI for the same rock mass. In general, the highest values have been obtained from the equations which apply the  $RMR_{1989}$  input ratings, while the methods based on  $RMi$  produced the lowest results. Sensitivity analyses performed on the simulation outputs show that, for the examined case study, the input parameters reflecting the degree of jointing of the rock mass, namely the  $RQD$  and the rock block volume, have the largest effects on the calculated GSI, while those describing the characteristics of discontinuities show lesser influence and may depend on the equation adopted. In particular, the GSI estimated from the methods

based on the  $Q$  and  $RMi$  inputs is especially sensitive to the infilling and roughness of discontinuities, while in the methods based on the  $RMR_{1989}$  ratings the discontinuity characteristics influencing the GSI value the most demonstrate to be the aperture, the roughness and the length. The analyses have mainly highlighted the possible uncertainties still related to the quantitative estimation of the GSI and allowed for the recognition of the input rock mass parameters that may have the highest impact on the GSI in the different estimation methods.

**Keywords** GSI · Quantitative methods · Monte Carlo simulations · Sensitivity analysis

## 1 Introduction

The Geological Strength Index (GSI) represents today the most worldwide used engineering index for categorizing the rock mass quality for input into continuum numerical analysis codes and closed form solutions based on the Hoek–Brown failure criterion (Marinos and Hoek 2000; Marinos et al. 2007; Carter 2010).

The index was introduced in the mid-nineties as a qualitative approach to relate the Hoek–Brown criterion to geological field observations in hard rocks (Marinos et al. 2007; Day et al. 2012) and has been successively extended to accommodate also the most

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variable of rock masses, including extremely poor quality sheared rock masses of weak schistose materials and the typical heterogeneous lithological formations such as flysch and molasses (Hoek et al. 1998; Marinis and Hoek 2000, 2001; Hoek et al. 2005; Marinis et al. 2006).

The GSI system was specifically formulated to attempt to characterize rock masses from a more geological perspective, so as to better meet the need for delivering reliable input data related to those properties considered to govern the mechanical behaviour of a rock mass (Carter and Marinis 2014).

According to Marinis and Hoek (2000) and Marinis et al. (2007), the heart of the GSI system is a careful engineering geology description of the rock mass which is currently based first upon the lithology and secondary on structure (or blockiness) and condition of the discontinuity surfaces assessed from visual examination of rock exposures.

As such, the estimation of the GSI number, which theoretically varies in the nominal range 0–100, is essentially a qualitative procedure whose accuracy may, therefore, depend on the level of experience and judgment of the observer directly involved in field mapping.

Carter (2010) also pointed out as a main problem with rock mass classification misuse in civil contract works may arise from classification mismatch due to subjective observational differences which, in some cases, can result from the manipulation of classification parameter selection made in order to maintain consistency of perceived geological description suitable for the observer's contractual perspective.

For such reasons, the issue of quantifying the GSI has become, over the years, more and more a priority and several attempts to reduce subjectivity in GSI estimation and to benchmark its range started to emerge in literature. In particular, quantitative methods for quantify GSI based on a numerical quantification of the parameters defining the rock mass structure in terms of blockiness and interlocking degree and of the condition of discontinuities, have been fine-tuned and presented by some Authors (see e.g. Hoek et al. 1995; Sonmez and Ulusay 1999; Cai et al. 2004; Cai and Kaiser 2006; Russo 2007, 2009; Day et al. 2012; Hoek et al. 2013).

All these methods are generally based on empirical equations which apply input parameters and ratings borrowed from the best known rock mass classification index systems, principally the RMR (Bieniawski

1989), the Q (Barton et al. 1974) and the RMi (Palmström 1995).

Quantitative methods can be used successfully for estimating GSI in rock masses that can be thought of as blocky, which behaviour mainly depends on sliding and rotation of intact rock pieces and is controlled by the condition of discontinuities that separate individual blocks. On the other hand, such methods become inappropriate for rocks lying at both ends of the rock competence scale and for tectonically disturbed rock masses in which the structural fabric has been destroyed, for which the original descriptive techniques are recognized to work best (see Marinis et al. 2007; Carter et al. 2008; Hoek et al. 2013; Carter and Marinis 2014).

Independently from the estimation method adopted, the GSI may show high spatial variability in a rock mass mainly in response to the inherent variability of the degree of jointing and of the discontinuities characteristics and, thus, it can be regarded as a random variable following a particular probability distribution (e.g. Cai 2011).

Conceptually, one of the best ways to investigate the possible variation of a random variable is to utilize probabilistic simulations, by which the variability of the input parameters used to calculate the output parameter can be consistently modelled and quantified.

In rock engineering, examples in which strength and deformability of rock masses have been evaluated through a probabilistic approach have become, year on year, more and more numerous (e.g. Kim and Gao 1995; Hoek 1998, 1999; Russo et al. 2001; Pötsch et al. 2004; Sari 2009; Sari et al. 2010; Cai 2011; Idris et al. 2013). However, none of these works specifically focused on the comparison between the GSI values theoretically obtainable from different quantitative methods. Actually, a first attempt has recently been made by Sari (2014), although limited to the comparison between few of the available equations.

Taking inspiration from this issue, the main purpose of this paper is to provide a more comprehensive investigation of the possible variability of the GSI index calculated using the empirical relationships most commonly applied in the current rock engineering practice.

For this goal, probabilistic analyses based on the Monte Carlo simulation methodology have been performed using, as inputs, consistent geomechanical field data collected for a real rock mass and the GSI

output datasets obtained by applying the different equations statistically analyzed and compared.

## 2 Empirical Relationships in Use for Estimating the GSI

A number of empirical relationships to quantitatively estimate the GSI have been progressively proposed in literature since the appearance of the GSI index in the middle of the nineties.

Those well-known and more commonly applied today have been considered in the present work and are summarized in Table 1.

As can be discerned, the methods at hand can be divided in three main groups: one including the relationships based on the rock mass input parameters used in the RMR<sub>1989</sub> classification system (Bieniawski 1989), another encompassing those using the parameters applied in the Q-system (Barton et al. 1974), and the last including the expressions employing the input parameters of the R<sub>Mi</sub> index system (Palmström 1995).

As well known, the RMR and Q systems originated, and have been specifically updated mainly for estimating tunnel support in civil engineering applications and only later they were extended for assessing rock mass

properties (Barton et al. 1974; Bieniawski 1989; Grimstad and Barton 1993; Barton 2002, 2006; Galera et al. 2007; Barton and Bieniawski 2008). Further adaptations and modifications to the original classifications also occurred over the years, mainly aimed at mining, surface slopes, dam design and TBM applications (see e.g. Laubscher 1977; Romana 1985; Sapigni et al. 2002; Romana 2003; Ozdemir and Nilsen 1993; Barton 1999; Bieniawski et al. 2007, 2008).

The R<sub>Mi</sub> index was principally developed to characterize the strength of a rock mass for use in rock engineering and design. Its value is also applied as input for estimating stability and rock support in underground openings and for determining the constants of the Hoek–Brown failure criterion for rock masses (see Palmström 1995, 1996a, b, 2000; Palmström and Singh 2001).

All classification systems are essentially based on ratings for the parameters reflecting rock mass jointing and discontinuity conditions.

Although there are similarities between these systems, actually they present differences in the way the input parameters are combined to calculate the reference index (i.e. the RMR index derives from an addition of ratings while Q and R<sub>Mi</sub> indexes use a combination of multiplication, division and exponential calculation)

**Table 1** Empirical relationships commonly used to estimate the GSI

Equation ID	Author(s) reference	Relationship proposed	Rock mass classification system
1	Hoek et al. (1995)	$GSI = R_1 + R_2 + R_3 + R_4 + R_5 (= 15) - 5$	RMR <sub>1989</sub> (Bieniawski 1989)
2	Hoek et al. (2013)	$GSI = 1.5 R_4 + 0.5 RQD$	
3	Hoek et al. (1995)	$GSI = 9 \ln \left( \frac{RQD}{J_n} \times \frac{J_r}{J_a} \right) + 44$	Q (Barton et al. 1974)
4	Barton (1995)	$GSI = 15 \log \left( \frac{RQD}{J_n} \times \frac{J_r}{J_a} \right) + 50$	
5	Hoek et al. (2013)	$GSI = \frac{52J_r/J_a}{(1 + J_r/J_a)} + 0.5RQD$	
6	Cai and Kaiser (2006)	$GSI = \frac{26.5 + 8.79 \ln J_c + 0.9 \ln V_b}{1 + 0.0151 \ln J_c - 0.0253 \ln V_b}$	R <sub>Mi</sub> (Palmström 1995)
7	Russo (2009)	$GSI = 153 - \frac{165}{\left[ 1 + \left( \frac{JP}{0.19} \right)^{0.44} \right]}$	

R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub>, R<sub>4</sub>, R<sub>5</sub> = ratings of the RMR<sub>1989</sub> classification system referred, respectively to UCS, RQD, spacing of discontinuities, condition of discontinuities and groundwater (see § 2.1)

J<sub>n</sub>, J<sub>r</sub>, J<sub>a</sub> = ratings of the Q system referred, respectively to the number of the joint sets and to the roughness/waviness and alteration/infilling of joints (see § 2.2)

J<sub>c</sub>, J<sub>P</sub>, V<sub>b</sub> = Numbers for Joint Condition factor, Jointing Parameter and unitary Volume of Rock Blocks used in the R<sub>Mi</sub> system (see § 2.3)

RQD = value for the Rock Quality Designation

and in the input parameters included, in addition to their scores and weights in calculation.

As a consequence, correlations between classification indexes have been proved to present large inaccuracies (Palmström 2009) and the necessity of comparing different independent systems for characterizing a rock mass has been recurrently recommended by many Authors as the most suitable approach during the design process (see e.g. Carter 1992; Palmström and Broch 2006; Barton and Bieniawski 2008; Palmström 2009; Carter 2010; Carter and Marinos 2014).

A short compendium of the principal characteristics of the three classification systems is reported in the following.

### 2.1 RMR System

The Rock Mass Rating system (1989 version) (Bieniawski 1989) provides a classification of the rock mass in five classes of geomechanical quality on the base of the  $RMR_{1989}$  index. This index is calculated as the sum of six basic input ratings ( $R_1$ – $R_6$ ) related to selected rock mass parameters: the UCS of intact rock material ( $R_1$ ), the RQD ( $R_2$ ), the spacing ( $R_3$ ) and condition ( $R_4$ ) of the most relevant discontinuities, the ground water conditions ( $R_5$ ) and the orientation of the main discontinuity set with respect to the engineering work under design ( $R_6$ ).

The classification index is obtained as

$$RMR_{1989} = R_1 + R_2 + R_3 + R_4 + R_5 + R_6 \quad (1)$$

The basic ratings for calculating the  $RMR_{1989}$  are schematized in Table 2.

The rating  $R_4$  specifically reflects the condition of the rock mass discontinuities and is calculated as the sum of five sub-ratings ( $R_{4a}$ – $e$ ) each related to a property of

discontinuities, specifically the length, the aperture, the roughness, the infilling and the weathering.

The  $RMR_{1989}$  index theoretically range from a minimum of 0 to a maximum of 100 and is, then, consistent with the GSI scale.

### 2.2 Q-System

The Q-system (Barton et al. 1974) was originally developed as an empirical design method for estimating the rock supports in tunnels and caverns using many underground excavation case histories. The value of the Q index used to classify the rock mass is defined by six parameters combined in the following equation

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \quad (2)$$

where RQD = given as the value for the parameter;  $J_n$  = rating for the number of joint sets;  $J_r$  = rating for the joint roughness and waviness;  $J_a$  = rating for the joint alteration and infilling;  $J_w$  = rating for ground water; SRF = rating for the rock mass stress situation. The Q index theoretically spans in a very wide range, indicatively from 0.001 to 1000 or more.

### 2.3 RMi System

The RMi index (Palmström 1995) expresses an approximate measure of the uniaxial compressive strength of a rock mass, given as

$$RMi = \sigma_c \times JP \quad (3)$$

where  $\sigma_c$  is the uniaxial compressive strength of the intact rock material (in MPa) measured on samples with diameter 50 mm and JP is the “Jointing

**Table 2** Basic ratings scheme for calculating the  $RMR_{1989}$  index

Rating	Parameter (rating range)
R1	Uniaxial compressive strength of intact rock (0–15)
R2	Rock quality designation (3–20)
R3	Spacing of discontinuities (5–20)
R4	Condition of discontinuities (0–30)
	R4a—length (0–6)    R4b—aperture (0–6)    R4c roughness (0–6)    R4d infilling (0–6)    R4e Weathering (0–6)
R5	Groundwater condition (0–15)
R6	Orientation of discontinuities (–50 to 0)

Parameter”, expressing the reduction in strength of the intact rock caused by joints. The JP scores the main joint features of a rock mass and is calculated as

$$JP = 0.2 \times jC^{0.5} \times Vb^D \quad (4)$$

with the coefficient D equal to

$$D = 0.37 \times jC^{-0.2} \quad (5)$$

where jC is the “joint condition” factor, which incorporate the characteristics of roughness/undulation, alteration/infilling and length of joints

$$jC = \frac{jR \times jL}{jA} \quad (6)$$

with jR = jS × jW = joint smoothness factor (small scale roughness) × joint waviness factor (large scale roughness). The factor jR is similar to the Jr of the Q system; jL = joint length factor; jA = joint alteration factor (similar to the Ja number in the Q system). Vb is the elementary rock block volume given in m<sup>3</sup>. Being an expression of the rock mass compressive strength the Rmi index hasn't range limitation.

### 3 Probabilistic Assessment of the GSI

#### 3.1 Monte Carlo Simulations

The Excel add-in program Crystal Ball (Oracle Corp.) has been employed in the present study to perform probabilistic analyses using Monte Carlo (M-C) simulations applied to all empirical equations for calculating the GSI.

In the M-C method a large number of values of each input parameter is generated randomly by sampling from their previously defined probability distributions and/or frequency histograms and then combined in a mathematical relationship to calculate an equivalent number of values of the output parameter.

In this work, the Monte Carlo method has been applied by performing 5000 iterations by means of the Latin Hypercube sampling technique and using the probability distributions, continuous or discrete, previously established, on the base of field survey data, for each input parameter used in the GSI equations.

For the sake of simplicity, all parameters have been considered to be independent in simulations, although, in fact, interdependence may exist. Though the

covariance between variables is recognized to play an important role in probabilistic analyses, the issue seems still not extensively dealt with in rock engineering literature and many authors assumed independence of parameters due to lack of specific research results (e.g. Hoek 1998; Russo 2009; Cai 2011; Idris et al. 2013; Sari 2009, 2014).

An attempt to investigate the effect of incorporating relationships between rock mass parameters in Monte Carlo simulations and to check their influence on the estimation of RMR index and Hoek–Brown parameters has recently been undertaken by Sari (2012). In his work, a correlation matrix defining the relationships between inputs was constructed basing on opinions and judgment of some distinguished experts in rock engineering and engineering geology. The main conclusion was that the consideration of parameter correlations would not significantly affect the results generated by Monte Carlo simulations, and only a slight decrease of the standard deviations of the output rock mass parameters was observed.

#### 3.2 Derivation of Rock Mass Input Parameters

The considered case study includes the data from 99 geostructural surveys carried out for the engineering classification of a rock mass based on the RMR<sub>1989</sub> system. The surveys were performed during the drill-and-blast excavation of a 6 m span tunnel realized for a hydroelectric power plant in the Italian Alps, which involved pre-Mesozoic metamorphic hard rock formations.

The rock mainly consists of unweathered quartz-mica schist containing quartz, albite, biotite, white mica, glaucophane and garnet, having an average value of the uniaxial compressive strength of intact rock of about 100 MPa.

The rock mass is generally crossed by four principal discontinuity sets mainly striking NE–SW and E–W, plus some random joints. Relevant discontinuities are, for most part, unfilled, with slightly rough and moderately weathered surfaces and with feeble apertures at the excavation surfaces.

In general, all mapped discontinuities are classified as slightly-moderately undulating at the metric scale (large scale roughness or waviness).

The RQD was assessed from the Volumetric Joint Count J<sub>v</sub> using the equation proposed by Palmström (2005)

$$RQD = 110 - 2.5J_v \tag{7}$$

with  $RQD = 0$  for  $J_v > 44$  and  $RQD = 100$  for  $J_v < 4$ .

To translate the original  $RMR_{1989}$  ratings for the discontinuity characteristics, directly assessed during field surveys, to the corresponding ratings of the Q and RMi classification systems, the reference tables purposely presented by Palmström (2009) and reproduced in Appendix, have been adopted.

The values for the unitary rock block volume ( $V_b$ ) of the rock mass have been estimated using the simplified relation of Palmström (1995)

$$V_b(m^3) = \beta \times J_v^{-3} \tag{8}$$

where  $\beta$  is a “block shape factor” (Palmström 1995). Basing on field observations and measurements, a

representative value of 60, typical for moderately long and flat prismatic blocks (Palmström 2005) has been assumed for  $\beta$ .

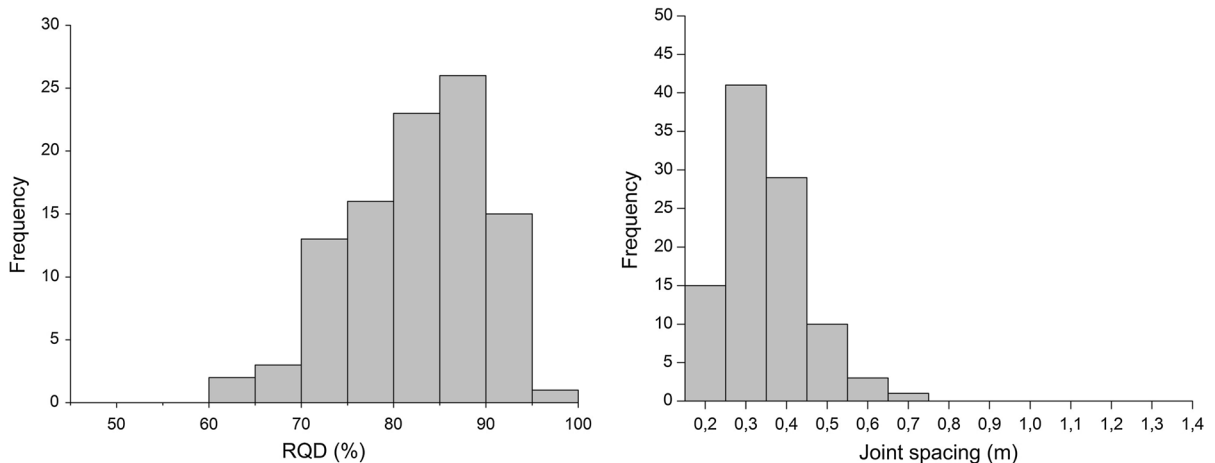
The frequency histograms and probability density functions that best describe the distributions and variability of field mapping data are summarized in Table 3 for each input parameter used to calculate the GSI.

In the table, the parameters reflecting the discontinuity characteristics specifically refer to the descriptive terms adopted in the  $RMR_{1989}$  classification system (Bieniawski 1989).

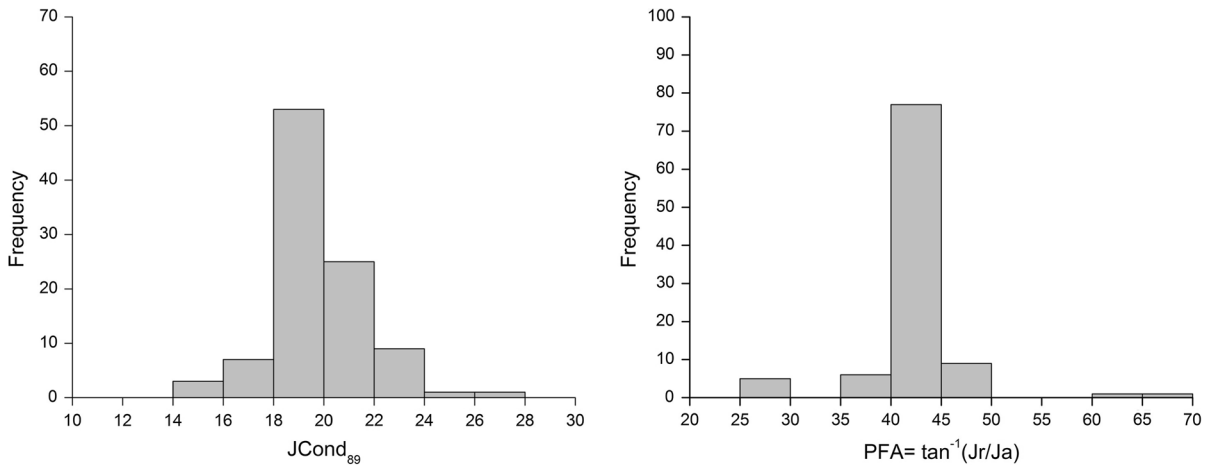
To synthesize the main characteristics of the rock mass, the histograms in Fig. 1 display the distributions for RQD and discontinuity spacing obtained from the statistical elaboration of the survey data.

**Table 3** Rock mass parameters used as inputs in Monte Carlo simulations for estimating the GSI

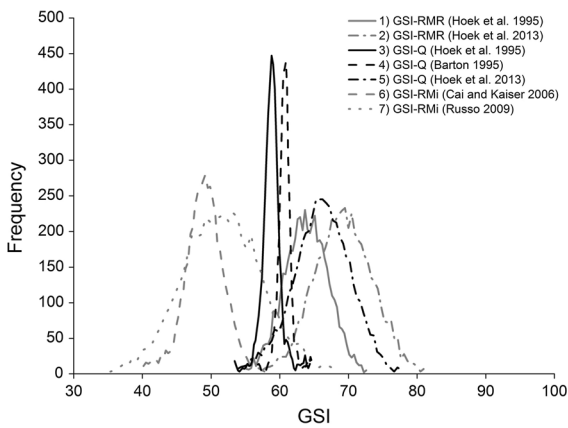
Parameter	Distribution type (Mean ± SD) or frequency
UCS (MPa)	Normal ( $100 \pm 35$ ; truncated at min = 35 MPa and max = 200 MPa)
Number of joint sets	3 % three sets; 97 % four or more sets
RQD (%)	Normal ( $82.22 \pm 7.41$ ; truncated at max = 100 %)
Block volume $V_b$ ( $cm^3$ )	Lognormal ( $65,928.12 \pm 61,632.02$ )
Joint spacing (m)	Normal ( $0.34 \pm 0.10$ ; truncated at min = 0.2)
Discontinuity length	20 % 1–3 m; 80 % 3–10 m
Discontinuity aperture	18 % none; 5 % < 0.1 mm; 74 % 0.1–1 mm; 3 % 1–5 mm
Discontinuity roughness	11 % rough; 83 % slightly rough; 6 % smooth
Discontinuity infilling	95 % none; 5 % hard friction materials
Discontinuity weathering	2 % unweathered; 98 % moderately weathered



**Fig. 1** Statistical distributions of field mapping data for RQD (left) and joint spacing (right)



**Fig. 2** Statistical distributions of data for  $JCond_{89}$  (left) and Peak Friction Angle (right) of discontinuities



**Fig. 3** Frequency distributions of the GSI values obtained from Monte Carlo simulations

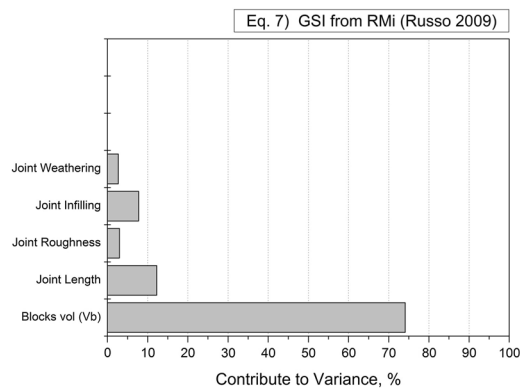
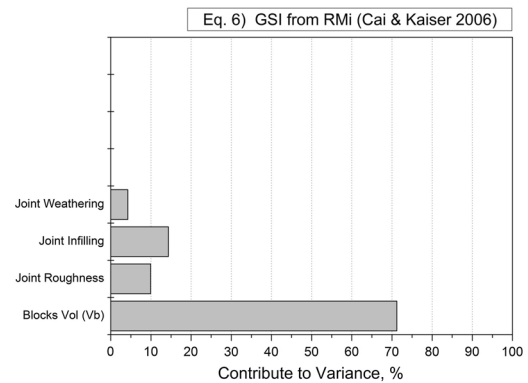
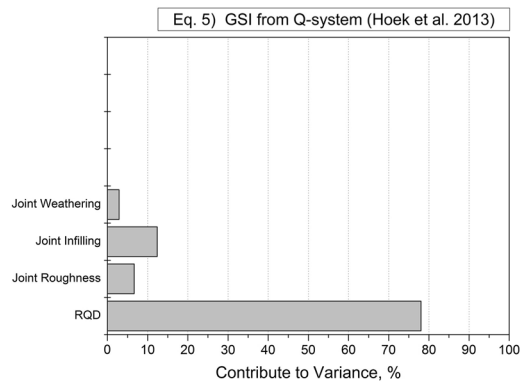
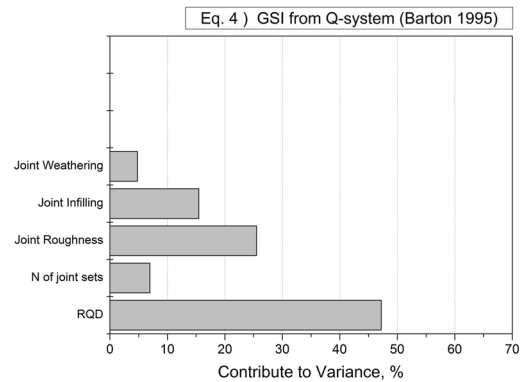
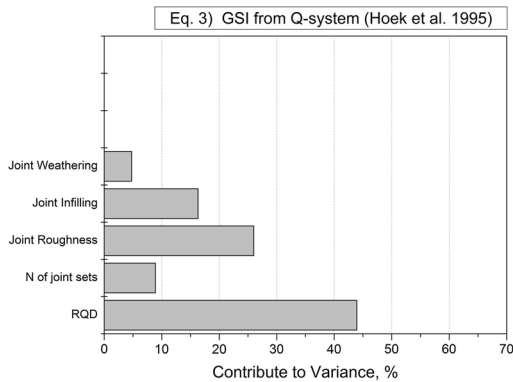
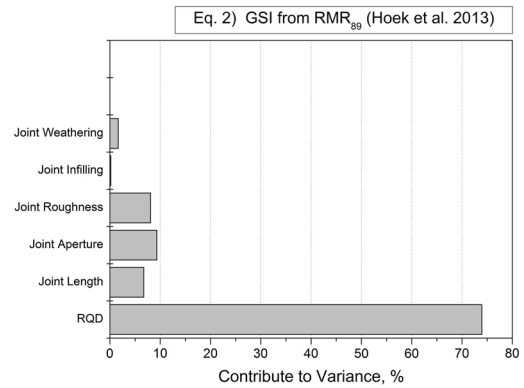
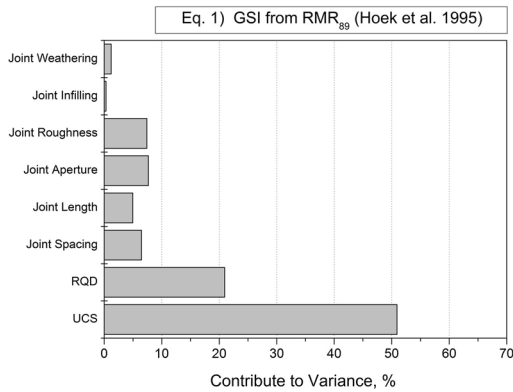
Moreover, Fig. 2 shows the histograms for indicators describing the condition of discontinuities, namely the joint condition rating ( $JCond_{89}$ ) defined by Bieniawski (1989) and the peak friction angle (PFA) estimated by the quotient  $[\tan^{-1}(Jr/Ja)]$  (Barton et al. 1974).

### 4 Simulation Results

The frequency distributions of the GSI values calculated using the different empirical relationships are displayed in Fig. 3 and the summary statistics computed for the GSI outputs presented in Table 4.

**Table 4** Summary statistics of the GSI values resulting from Monte Carlo simulations

	Equation (1) GSI-RMR <sub>1989</sub> (Hoek et al. 1995)	Equation (2) GSI-RMR <sub>1989</sub> (Hoek et al. 2013)	Equation (3) GSI-Q (Hoek et al. 1995)	Equation (4) GSI-Q (Barton 1995)	Equation (5) GSI-Q (Hoek et al. 2013)	Equation (6) GSI-RMi (Cai-Kaiser 2006)	Equation (7) GSI-RMi (Russo 2009)
Mean	63.86	69.27	58.68	60.63	66.02	48.97	51.54
Median	63.84	69.23	58.77	60.68	66.17	49.04	51.51
SD	3.2	4.26	2.1	1.52	4.42	3.21	5.91
Coeff. of variation (%)	5.0	6.1	3.5	2.5	6.6	6.5	11.5
Min	52.73	53.65	49.09	53.62	47.27	34.66	26.92
Max	75.55	85.61	66.45	68.81	83.56	58.68	71.96
Range width (max–min)	22.82	31.96	17.36	15.19	36.29	24.02	45.04





◀ **Fig. 4** Sensitivity charts for the input parameters used to calculate the GSI in the different quantitative methods

As can be observed, the results of analysis indicate that the different empirical relationships may predict dissimilar values for the same rock mass.

In general, the relationships that use the RMR<sub>1989</sub> input ratings (Eqs. 1 and 2) show the highest values for the GSI, while those based on RMI parameters (Eqs. 6 and 7) produce the lowest results.

In particular, the RMI-based equation of Cai and Kaiser (2006) (Eq. 6) provides the minimum mean value of 48.9, which is about 29 % lower than the maximum of 69.2 obtained from the RMR<sub>1989</sub> expression of Hoek et al. (2013) (Eq. 2).

The equations based on the Q-System mostly predict intermediate mean values, with the exception of the one proposed by Hoek et al. (2013) (Eq. 5) which demonstrate to fit better with the results of the RMR<sub>1989</sub> correlations.

It is worth noting that the GSI calculated using the relationship of Russo (2009) (Eq. 7) shows the highest Coefficient of Variation, thus indicating a tendency for such a method to provide more scattered results. On the other hand, the traditional Q-based expressions (Eqs. 3 and 4) demonstrate the lowest CVs.

All GSI datasets generated by the probabilistic simulations seem to follow normal or lognormal distributions.

## 5 Sensitivity Analysis

Sensitivity analyses have been performed to find out, for the examined case study, the input parameters influencing the GSI value the most.

For this purpose, the “contribution to variance” method, which allows the sensitivity information to be calculated and displayed as the percent of the output variance contributed by each input parameter, has been used on simulations results.

The findings of analysis are presented in the sensitivity charts of Fig. 4.

It is apparent from the graphs that, irrespective of the equation used, the parameters reflecting the degree of jointing of the rock mass, namely the RQD and the unitary block volume (Vb), are invariably the most influential parameters in defining the GSI, rather in accordance with some previous statements (see e.g.

Carter 1992; Palmström 1995, 1996; Carter and Marinos 2014).

Also the rating for the uniaxial compressive strength (UCS) of intact rock, when contemplated, shows a prominent influence on the GSI.

Among the parameters expressing the characteristics of discontinuities, which show rather limited ranges in the examined dataset, the most relevant in calculations seem to vary from one method to another likely as a result of the different suite of parameters considered in the diverse classifications and of the weight each parameter assumes in the relationships.

In particular, for the rock mass examined it is observed that when the equations based on the RMR<sub>1989</sub> system are used, the aperture, the roughness and the length demonstrate the greatest impact on the GSI, while the joint infilling and weathering show lesser influence.

On the other hand, the infilling and the roughness parameters, in addition to the length of discontinuities when considered, exhibit the highest influence in the methods based on the Q and RMI systems.

In general, in all applied methods the weathering parameter demonstrates a low impact.

## 6 Conclusions

The results of performed simulations have indicated that the different empirical relationships currently in use for calculating the GSI may predict dissimilar values for the same rock mass.

In general, the highest values were derived from the expressions which apply the RMR<sub>1989</sub> input ratings, while the methods based on the RMI parameters invariably predicted the lowest results. The equations based on the Q-system mostly produced intermediate mean values, with the exception of the one proposed by Hoek et al. (2013) which demonstrated to fit better with the results of the RMR<sub>1989</sub> correlations.

Divergences are principally linked to the inherent differences existing between the different classification systems upon which the equations for calculating the GSI are based; these differences mainly relate to the diverse origin and structure of the classification schemes and to the type of input parameters considered, in addition to their weights in calculations (see Carter 1992; Tzamos and Sofianos 2007; Palmström 2009).

Divergences also arise from the known inaccuracies in correlating parameters used to quantify the same rock mass property in the different classification systems, in particular those describing the degree of jointing of the rock mass (i.e. RQD/Jn, RQD, joint spacing and block volume) and the roughness, weathering and infilling of discontinuities, which are differently expressed and quoted in the diverse classification schemes (see e.g. Barton 1987; Carter 1992; Milne et al. 2002; Palmström 2005; Palmström and Broch 2006; Palmström 2009).

For the examined case study, sensitivity analyses showed that, irrespective of the equation adopted, the GSI is most sensitive to the input parameters which reflect the rock mass jointing, namely the RQD and the elementary block volume ( $V_b$ ), therefore highlighting the need for a careful and reliable quantification of these parameters during field characterization.

As far as the joint characteristics are concerned, the GSI estimated from the methods based on the Q and RMI inputs is sensitive to the ratings assigned to the infilling and roughness of discontinuities, while in the methods based on the RMR<sub>1989</sub> the discontinuity parameters influencing the GSI value the most are the aperture, the roughness and the length.

In this regard it has to be outlined that the parameter “infilling” of discontinuities, which plays a primary role also in the quantification of the “joint alteration” factors ( $J_a$ ,  $j_A$ ) used in Q and RMI systems, conversely to other measurable discontinuity parameters like e.g. length, aperture and roughness (e.g. Priest 2004; Palmström 2001; Morelli 2014), is essentially assessed through qualitative observations

and descriptions. Hence, the accuracy of its evaluation in the field may be influenced by the sound experience and judgment of the observer. In this light, particular care must be taken to ensure that adequate attention is given to defining this parameter during field mapping, for which the execution of specific tests to characterize the physical and mineralogical properties of the infilling material is highly recommended.

The findings of the presented study highlight the possible uncertainties still related to the quantitative estimation of the GSI and suggest that the application of more than one independent approach would be advisable to provide a more accurate estimation of this index and a better definition of its possible variability.

However, in doing this it is essential to be well-conscious of the inaccuracies possibly connected to the use of the different quantitative estimation methods and to be clearly aware of the single input rock mass parameters which may have, for each method, the highest impact on the calculated GSI.

Moreover, as the reliability of these quantitative methods mostly dependent on the correct evaluation of the input parameters, a careful engineering geological description of the rock mass carried out by experienced and well-trained observers, who should also have a sound geological background, still remains an indispensable prerequisite to reducing subjectivity variation in GSI quantification.

## Appendix

See Table 5.

**Table 5** Combined ratings for discontinuity characteristics used in the RMR, Q and RMI systems (from Palmström 2009)

Discontinuity characteristics		RMR <sub>1989</sub>	Q	RMI
Joint Length		R4a	–	jL
Parting	<1 m	6	Not included	3
Very short joint	0.3–1 m	6		2
Short joint	1–3 m	4		1.5
Medium joint	3–10 m	2		1
Long joint	10–30 m	1		0.75
Filled joint	>10 m	0		0.5

**Table 5** continued

Discontinuity characteristics		RMR <sub>1989</sub>		Q		RMi	
Joint separation or aperture		R4b		–		–	
Very tight	None	6		Not included		Not included	
	<0.1 mm	5					
Tight	0.1–0.5 mm	4					
Moderately open	0.5–1 mm						
	1–2.5 mm	1					
Open	2.5–5 mm						
	5–10 mm	0					
Very open	10–25 mm						
Joint Smoothness		R4c		Js <sup>a</sup>		jS <sup>a</sup>	
Very rough		6		2		2	
Rough or irregular		5		1.5		1.5	
Slightly rough		3		1.25		1.25	
Smooth		1		1		1	
Polished		0		0.75		0.75	
Slickensided		0		0.5		0.5	
Joint undulation or waviness		–		Jw <sup>a</sup>		jW <sup>a</sup>	
Discontinuous joint		Not included		4		4	
Strongly undulating				2.5		2.5	
Moderately undulating				2		2	
Slightly undulating				1.4		1.4	
Planar				1		1	
Joint infilling		R4d		Ja <sup>b</sup>		jA <sup>b</sup>	
		th < 5 mm	th > 5 mm	th < 5 mm	th > 5 mm	th < 5 mm	th > 5 mm
No filling		6	–	–	–	–	–
Friction materials (silts, sand, etc.)		5	2	4	8	4	8
Hard, cohesive materials (clay, talc, chlorite, etc.)		4	2	6	8	6	8
Soft, cohesive materials (soft clay)		2	0	8	12	8	12
Swelling clay materials		0	0	10	18	10	18
Joint alteration or weathering		R4e		Ja <sup>b</sup>		jA <sup>b</sup>	
Healed or welded joint		6		0.75		0.75	
Unweathered, fresh joint walls		6		1		1	
Slightly weathered joint walls (coloured, stained)		3		2		2	
Altered joint walls (no loose materials)		0		4		4	
Coating of friction materials (silt, sand, calcite, etc.)		1		3		3	
Coating of cohesive materials (clay, chlorite, etc.)		0		4		4	

<sup>a</sup> Joint roughness factor Jr(jR) = Js(jS) × Jw(jW)

<sup>b</sup> Q and RMi apply a combination of joint weathering and infilling ratings to define the factors Ja-jA, while RMR has input of both weathering and infilling

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