# Does Rock Engineering Need to Quantify GSI?

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**Abstract.** Numbers form the basis of engineering; without them, we could not determine forces, stresses, and safety factors. In most engineering disciplines, the numbers used represent quantitative measurements; however, rock engineering is unique in that many of the numbers used are numerical descriptions of qualitative assessments rather than quantitative measurements. Examples include the numeric values from commonly used rock mass classification systems, such as the rock mass rating (RMR), Q-system, and geological strength index (GSI). This phenomenon of using numbers representing qualitative descriptions has been further exacerbated in recent years with the attempts to quantify GSI. The motivation behind these quantification attempts is to purportedly improve the accuracy and precision of GSI and provide experience for inexperienced engineers. In this paper, we critically review GSI quantification attempts throughout the years and argue against the paradigms of (1) determining an accurate numerical description of qualitative assessments and (2) the quantification process by adding the experience factor for inexperienced engineers. Using RS2 and RSData, we also demonstrate that determining a more precise GSI value does not result in significant changes to estimating rock mass strength.

**Keywords:** geological strength index (GSI) · quantified GSI · rock mass strength

## 1 Introduction

The introduction of the geological strength index (GSI) in 1994 by Hoek was unique in that it was the first classification system that emphasized the geology of the rock mass. Its original purpose was to replace the 1976 version of the Rock Mass Rating ($RMR_{76}$) and the Q-system for estimating the m and s parameters used in the Hoek-Brown failure criterion and "*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*" (Marinos et al. 2005). Marinos et al. (2005) described it as a "*careful engineering geology description of the rock mass which is essentially qualitative*". The first chart was published in 1997, with several updates made throughout the years. The 2000 GSI chart seems to be the most commonly used; however, there has not been a published formal consensus on which chart to use.


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Since its introduction, numerous attempts have been made to quantify GSI to make it more objective (thereby more precise and accurate) and less dependent on experience. The initial quantification attempts used correlations between GSI and other rock mass characterization parameters, but in recent years, they have included probabilistic and computing methods (Yang and Elmo 2022). Of note is that the quantification attempts have focused on the GSI charts for *jointed* rock masses; to the authors knowledge, there have yet to be any published attempts to quantify the GSI charts for other rock masses (e.g., heterogenous, veined rock masses).

Yang and Elmo (2022) have compiled a list of the 23 quantification attempts they found; however, this number is most likely underestimated as additional quantification attempts continue to be published. Several of these quantifications include correlations with RMR (Bieniawski 1973), Rock Quality Designation (RQD) (Deere et al. 1969), and the joint condition parameters found in $RMR_{89}$ (Bieniawski 1989), the Q-system (Barton et al. 1974), and RMi (Palmstrom 1995). As Yang and Elmo (2022) noted, the increasing number of published quantifications creates confusion for engineers, especially junior engineers, and raises the question, "does rock engineering need to quantify GSI?". The goal of this paper is to answer that question by (1) critically reviewing GSI quantification attempts, (2) arguing against the paradigms of (a) determining an accurate numerical description of qualitative assessments and (b) the quantification process adding the experience factor for inexperienced engineers, and (3) demonstrating that determining more precise GSI values does not produce significant changes when estimating rock mass strength.

## 2 Can We Quantify GSI?

An important but often ignored aspect surrounding the quantification of GSI is the terminology used. What does it mean when engineers refer to the practice of quantifying GSI? The correct definition of "*to quantify*" is to express or measure the quantity of. In turn, this raises the question of what we define as *quantity*. In the physical sciences, a quantity is generally a measurable property with both a numerical magnitude and a unit (Hölder 1901). A quantity, by definition, must support the notion of additivity. Regarding GSI, it does not make sense to add a GSI of 30 to a GSI of 50 to get a GSI of 80 (Yang and Elmo 2022). Despite the commonly used terminology in the literature, GSI remains a qualitative description of rock mass conditions and cannot be quantified. Therefore, in this paper, we use phrases such as *quantification of GSI* or *quantified GSI* solely based on referring to published work on the subject. However, we recommend discontinuing the terms *quantification* and *quantified* when referring to GSI.

Other misused terminology includes accuracy and precision; accuracy is the difference between a measurement and its true value, while precision is how close independent measures are to each other (Pérez-Díaz et al. 2020). An accurate GSI does not exist because GSI is not a quantity. Precise GSI estimates may be possible, but to describe a GSI estimate as precise requires multiple independent assessments of the same rock mass. It is important to note that these definitions can also be extended to different rock mass classification values.

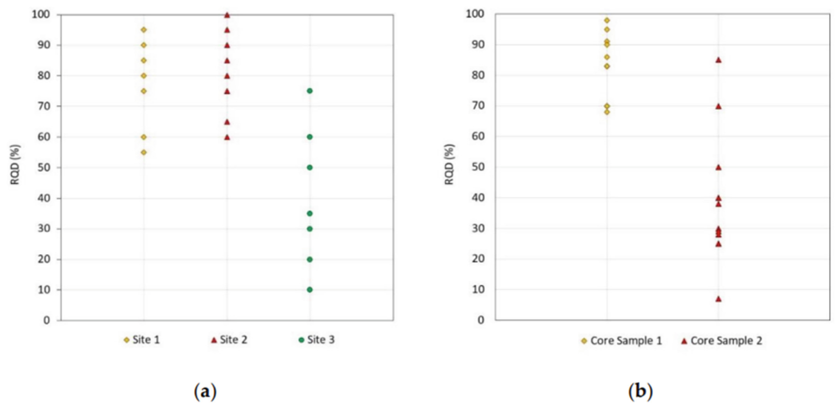



**Fig. 1.** RQD values calculated by different rock engineering professionals for (a) three separate outcrops (Pells et al. 2017) and (b) pictures of two core samples (Yang and Elmo 2022)

## 3 Limitations of GSI Quantification Attempts

Despite the popularity of quantified GSI charts, there needs to be more discussion on their limitations. To date, Yang and Elmo (2022) have provided the only review of the limitations of these GSI quantification attempts and their key points are summarized in this section.

### 3.1 Limitation 1: The Parameters Used in the Quantifications

The limitations of the parameters used to quantify GSI charts are often not discussed but are an important aspect of the quantifications. One parameter that is commonly used to quantify the rock mass structure in the GSI chart is RQD; its limitations have been thoroughly discussed by Pells et al. (2017) and Yang et al. (2020) and include subjectivity (when distinguishing between natural and mechanical fractures and choosing to adhere to the hard and soundness criteria), directional dependency, scale dependency (RQD values change as the core run length increases), and its reliance on an arbitrary and non-scientifically validated 10 cm threshold, among others. Figure 1 demonstrates the subjectivity and lack of precision of RQD.

Common parameters used to quantify the joint surface condition in the GSI chart include the joint condition factors from RMR ($JCond_{89}$ and its associated parameters), RMi, and the Q-system. These joint condition factors are not quantitative measurements but represent a numeric value assigned to a qualitative assessment. As a result, they remain subjective and have the added disadvantage of removing the geology from the problem. The subjectivity of $JCond_{89}$ is demonstrated in Fig. 2.

### 3.2 Limitation 2: The Missing Experience Factor

One of the main reasons behind rock engineering's push to quantify GSI is to reduce its dependency on experience. The subjective nature of the original qualitative GSI chart

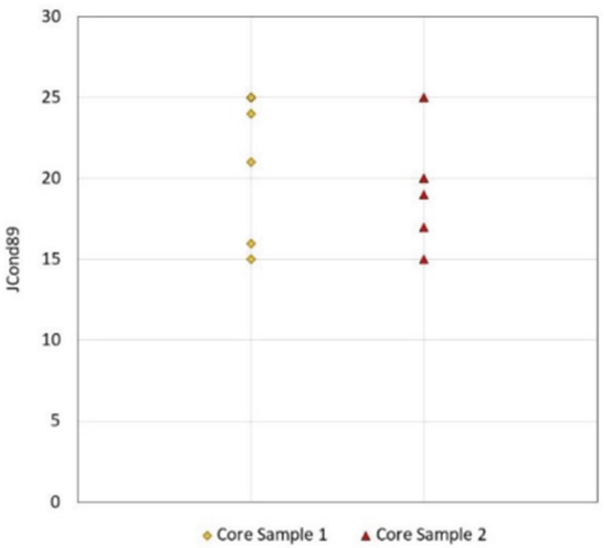



**Fig. 2.** $JCond_{89}$ values determined by different rock engineering professionals for pictures of two core samples (Yang and Elmo 2022)

results in engineers relying on their experience when estimating GSI. However, as shown in Sect. 3.1, many parameters used in quantifying the GSI chart (e.g., RQD, $JCond_{89}$, etc.) are also subjective, and their estimation relies on the engineer's experience collecting the data. These quantification attempts to increase the number of subjective parameters an engineer will estimate in the field, thus expanding the subjectivity and potentially increasing the reliance on engineering experience rather than providing the experience factor for inexperienced engineers.

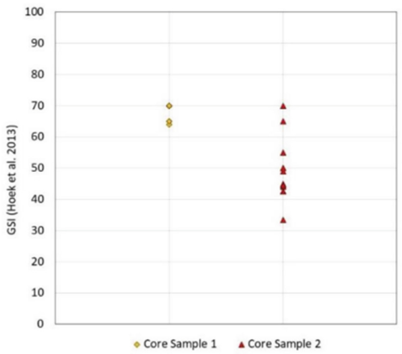
### 3.3 Limitation 3: The Missing Precision

Figures 1 and 2 in Sect. 3.1 demonstrate a significant scatter in the RQD and JCond89 measurements. This scatter indicates a lack of precision when assessing those parameters and, subsequently, imprecise quantified GSI values. This is further demonstrated in Fig. 3, which shows a significant scatter of GSI values (and later a lack of precision) calculated using the RQD and $JCond_{89}$ values from Figs. 1 and 2 above and the Hoek et al. (2013) quantification (Eq. 1).

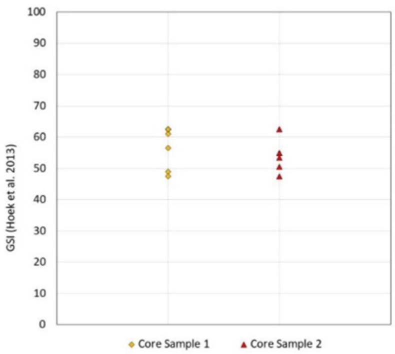
$$GSI = 1.5JCond_{89} + RQD/2\, for\, RQD \leq 80 \tag{1}$$

### 3.4 Limitation 4: The Missing the Geology

As previously mentioned, assigning numbers to qualitative descriptions of geology removes the geology from the problem. The quantitative versions of GSI exacerbate the irreversibility problem associated with the qualitative GSI charts, where we can end




(a)




(b)

**Fig. 3.** GSI values estimated using Eq. (1) (Hoek et al. 2013). (a) GSI values estimated assuming a $JCond_{89}$ rating of 20 and using RQD values from Fig. 1. (b) GSI values estimated assuming an RQD of 50% and using $JCond_{89}$ values from Fig. 2 (Yang and Elmo 2022)

up with the same Hoek-Brown failure envelopes for completely different rock masses. For example, using the Hoek and Marinos (2000) qualitative GSI chart, a blocky rock mass with very good joint surface conditions and a massive rock mass with fair joint surface conditions both have the same GSI value of 60, meaning that they would have the same Hoek-Brown failure envelope. To ensure that we keep the actual rock mass conditions in mind, engineers must include a description of the blockiness of the rock mass and the joint surface conditions with their GSI value; however, this practice is almost impossible to do when we use the equations found in the quantified versions.

### 3.5 Limitation 5: The Impracticality of Data Collection

Marinos et al. (2005) stated that one of the primary purposes of developing GSI was to create something practical to use in the field. The quantified GSI charts remove this practicality; many of the parameters used in the quantifications are often not collected (such as the parameters in RMi and data for $RMR_{89}$, as many companies only collect data for $RMR_{76}$) or collected differently than what is outlined in the associated quantification paper. This can make it confusing for the (often junior) engineers to use in the field.

## 4 Design Implications

While reviewing quantified GSI charts, the authors noted that only a few, if any, of the papers demonstrated the benefit of having a more precise GSI. Using the rock mass properties from the Nathpa Jhaki Hydroelectric Project in India (Hoek 2007), we demonstrated that determining a more precise GSI has minimal design implications regarding rock mass strength. We also examined the impact of $m_i$ and UCS on rock mass strength. The rock mass at the site consists of a jointed quartz mica schist with a GSI = 65, UCS = 30 MPa, and $m_i$ = 15 (Hoek 2007). The tunnel is at a depth of approximately

**Table 1.** Different GSI and $m_i$ scenarios with a UCS of 30 MPa

| Scenario | UCS (MPa) | GSI | $m_i$ |
|---|---|---|---|
| 1a | 30 | 60 | 9 |
| 2a | 30 | 65 | 9 |
| 3a | 30 | 70 | 9 |
| 4a | 30 | 60 | 12 |
| 5a | 30 | 65 | 12 |
| 6a | 30 | 70 | 12 |
| 7a | 30 | 60 | 15 |
| 8a | 30 | 65 | 15 |
| 9a | 30 | 70 | 15 |

**Table 2.** Different GSI and $m_i$ scenarios with a UCS of 35 MPa

| Scenario | UCS (MPa) | GSI | $m_i$ |
|---|---|---|---|
| 1b | 35 | 60 | 9 |
| 2b | 35 | 65 | 9 |
| 3b | 35 | 70 | 9 |
| 4b | 35 | 60 | 12 |
| 5b | 35 | 65 | 12 |
| 6b | 35 | 70 | 12 |
| 7b | 35 | 60 | 15 |
| 8b | 35 | 65 | 15 |
| 9b | 35 | 70 | 15 |

300 m, and to simplify the modelling, it was assumed to have a diameter of 12 m. Kaiser (2019) noted that the coefficient of variation of UCS tests could be greater than 25% for homogeneous rocks and greater than 35% for heterogeneous rocks; accordingly, the UCS values in this scenario were varied by ±5 MPa. The GSI was also varied by ±5, and the $m_i$ values followed the range provided in Hoek (2007) (Tables 1, 2, 3). Additional rock mass properties that were assumed for the modelling are found in Table 4.

## 4.1 Precise GSI Values and Rock Mass Strength

Hoek-Brown curves were generated in RSData (Rocscience 2022) and plotted in Excel for each scenario in Tables 1 – 3 (Figs. 4, 5, 6, 7).

The following observations can be made from Figs. 4, 5, 6, 7, 8:

**Table 3.** Different GSI and $m_i$ scenarios with a UCS of 25 MPa

| Scenario | UCS (MPa) | GSI | $m_i$ |
|---|---|---|---|
| 1c | 25 | 60 | 9 |
| 2c | 25 | 65 | 9 |
| 3c | 25 | 70 | 9 |
| 4c | 25 | 60 | 12 |
| 5c | 25 | 65 | 12 |
| 6c | 25 | 70 | 12 |
| 7c | 25 | 60 | 15 |
| 8c | 25 | 65 | 15 |
| 9c | 25 | 70 | 15 |

**Table 4.** Additional rock mass properties used in modelling

| Rock mass property | Value |
|---|---|
| Poisson's ratio | 0.33 |
| Unit weight | 27 $kN/m^3$ |
| Young's modulus | Determined using the simplified Hoek Diederichs approach (Hoek and Diederichs 2005) |

- The Hoek-Brown curves show slight variation when GSI is varied by ± 5 while $m_i$ is held constant, especially at lower $\sigma_3$ values.
- Both the UCS and $m_i$ parameters affect the Hoek-Brown curves similarly to GSI, but their precisions are often overlooked when estimating rock mass strength. As previously noted, the UCS test values can have a significant coefficient of variation (>25% for homogeneous rocks and >35% for heterogeneous rocks) (Kaiser 2019), making it difficult to determine a true "representative" value. Various UCS values could be used when determining the Hoek-Brown curves, resulting in different curves similar to when varying GSI. Furthermore, while determining the mi parameter from lab testing is recommended, the mi ranges provided by Hoek (2007) are often used instead. Varying the $m_i$ parameter within the specified $m_i$ range provided in Hoek (2007) results in a similar variation between the curves as varying GSI. Attempts to determine a more precise GSI (such as through its quantification) to estimate more precise rock mass strength are essentially meaningless when both the UCS and $m_i$ parameters are as, if not more, imprecise and have a similar impact on the Hoek-Brown curves.
- Hoek-Brown curves are not unique; different combinations of UCS, GSI, and $m_i$ can result in very similar if not the same, curves. Examples include the curves for:

- Scenarios 5a (UCS = 30 MPa, GSI = 60, $m_i$ = 12), 7a (UCS = 30 MPa, GSI = 60, $m_i$ = 15), 4b (UCS = 30 MPa, GSI = 60, $m_i$ = 12), 8c (UCS = 25 MPa, GSI = 65, $m_i$ = 15), and 6c (UCS = 25 MPa, GSI = 70, $m_i$ = 12).
- Scenarios 6a (UCS = 30 MPa, GSI = 70, $m_i$ = 12), 8a (UCS = 30 MPa, GSI = 65, $m_i$ = 15), 5b (UCS = 35 MPa, GSI = 65, $m_i$ = 12), and 7b (UCS = 35 MPa, GSI = 60, $m_i$ = 15) (Fig. 8).

These observations demonstrate that attempts to determine a precise GSI – whether through quantification or other methods – are meaningless given the minor variations in the Hoek-Brown curves and the effects of UCS and $m_i$. Providing an envelope of curves (i.e., a range of GSI, UCS, and $m_i$ values) rather than one single curve would better account for the variability of a rock mass and, subsequently, the inherent variability of rock mass parameters.

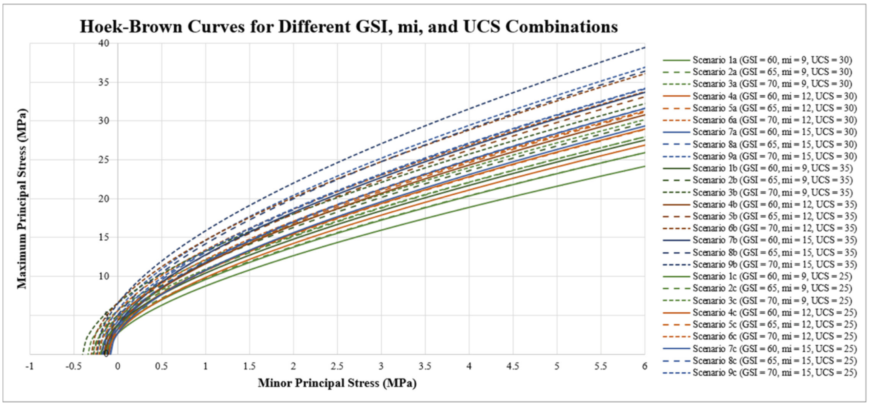



**Fig. 4.** Hoek-Brown curves for the scenarios in Tables 1 – 3

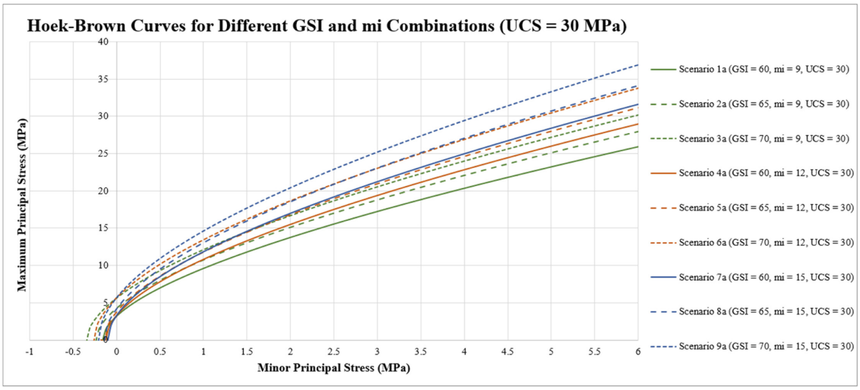



**Fig. 5.** Hoek-Brown curves for the scenarios in Table 1

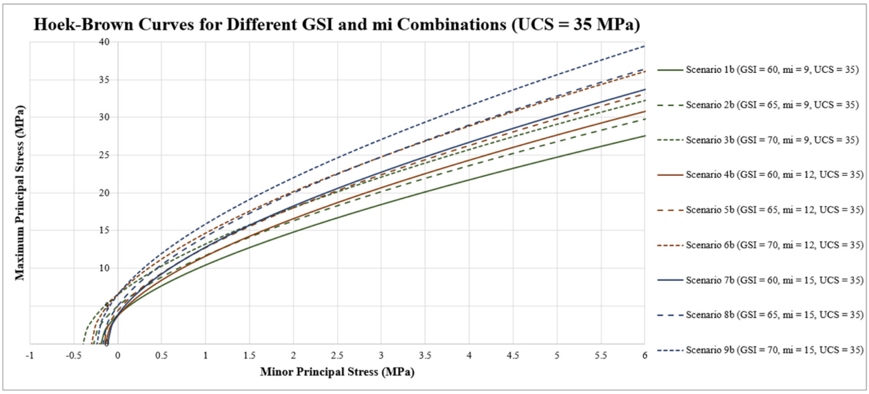



**Fig. 6.** Hoek-Brown curves for the scenarios in Table 2

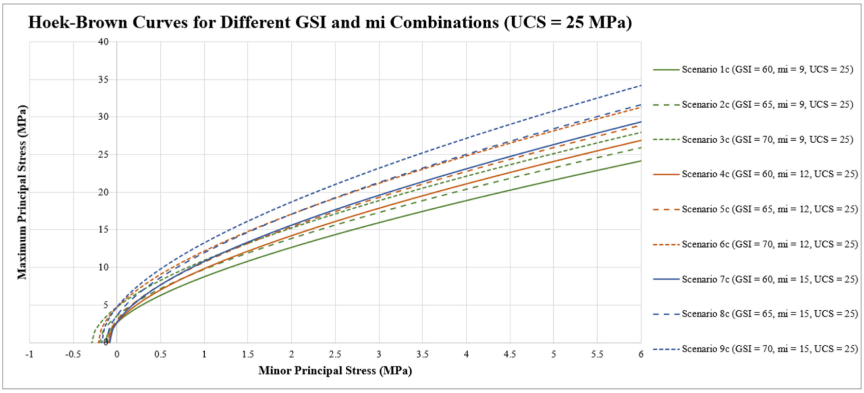



**Fig. 7.** Hoek-Brown curves for the scenarios in Table 3

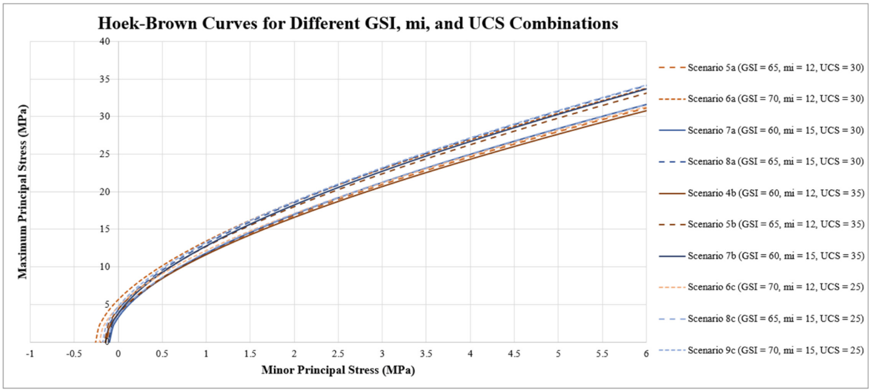



**Fig. 8.** Hoek-Brown curves for specific scenarios to demonstrate the lack of uniqueness

**Table 5.** Scenarios modelled in RS2 and their associated depth of failure

| Scenario | UCS (MPa) | GSI | mi | Depth of failure (m) |
|---|---|---|---|---|
| 1a | 30 | 60 | 9 | 7.990 |
| 4a | 30 | 60 | 12 | 7.824 |
| 5a | 30 | 65 | 12 | 7.288 |
| 6a | 30 | 70 | 12 | 7.230 |
| 7a | 30 | 60 | 15 | 7.532 |
| 4c | 25 | 60 | 12 | 8.006 |
| 4b | 35 | 60 | 12 | 7.56 |

### 4.2 Precise GSI Values and Depth of Failure

The tunnel scenario specified in Sect. 4 was modelled in RS2 (Rocscience 2022) to determine the depth of failure (i.e., the depth of the plastic zone/yielded elements) measured from the centre of the tunnel. Scenarios 1a, 4a, 5a, 6a, 7a, 4c, and 4b were modelled to demonstrate the effects of varying GSI, UCS, and mi on the depth of the failure. The results are summarized in Table 5 and show that varying GSI, UCS, and $m_i$ have minimal impact on the depth of failure. Quantifying GSI to obtain a more precise value has little effect on the depth of failure, especially given how other factors (UCS and $m_i$) impact the results.

## 5 Conclusion

Given the arguments presented in this paper, the authors think that GSI does not need to be quantified (and that, by definition, GSI cannot be quantified) and that, instead, we should accept the variability of rock masses and rock mass parameters by reporting a range of values. When determining a GSI value is necessary, the qualitative GSI chart should be used, and the blockiness, joint conditions, and chart version should all be reported alongside the GSI range.

However, the answer to the question in the title ("Does rock engineering need to quantify GSI?") also lies with the reader after reading this paper. Given the arguments presented, some may answer by saying, "no, rock engineering no longer needs to quantify GSI," while others may support these quantification attempts. Whatever your answer, we urge you to think critically about any proposed GSI quantification attempts and keep the limitations outlined in this paper in mind.

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