Characterization of Hoek–Brown constant $m_i$ of quasi-isotropic intact rock using rigidity index approach

Seyed Morteza Davarpanah$^1$ · Mohammad Sharghi$^2$ · Balázs Vásárhelyi$^1$ · Ákos Török$^1$

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Abstract
An accurate determination of Hoek–Brown constant $m_i$ is of great significance in the estimation of the failure criteria of brittle rock materials. So far, different approaches such as rigidity index method (R-index), uniaxial compressive strength-based method, and tensile strength-based method, and the combination of these two methods (combination based method) have been proposed to calculate the value of $m_i$. This paper aims to thoroughly review the previously existing methods to calculate the value of $m_i$ and make comparison between the obtain results to propose the new material constants that provide the best fit with the experimental data. In order to fulfill this goal, a large number of data for different quasi-isotropic intact rock types from the literature were collected and statistically analyzed. Additionally, based on rock types, new material constants are introduced for igneous, sedimentary, and metamorphic rocks. The obtained results proves that for different rock groups (igneous, sedimentary, and metamorphic rocks), R-index method provides the best fit with the experimental data among the others, and it is also independent of rock type. Interestingly enough, there is significant differences in the predicted $m_i$ values using different methods, which is more probably due to the quantity and quality of data used in the statistical analysis.

Keywords Combination method · Hoek–Brown material constant ($m_i$) · R-index method · Rock types$^1$ · TS-based method · UCS-based method

Abbreviations

\begin{align*}
m_i & \quad \text{Hoek–Brown material constant} \\
m_b & \quad \text{Hoek material constant for rock mass} \\
\text{GSI} & \quad \text{Geological Strength Index} \\
\text{TS} & \quad \text{Tensile strength} \\
\text{UCS} & \quad \text{Uniaxial compressive strength} \\
R & \quad \text{Rigidity index} \\
\beta & \quad \text{Intermediate fracture mechanics parameter} \\
\mu & \quad \text{The coefficient of friction for pre-existing sliding crack surfaces} \\
\sigma_1, \sigma_3 & \quad \text{Major and minor principal stress} \\
\sigma_c & \quad \text{Uniaxial compressive strength (UCS)} \\
\sigma_{ci} & \quad \text{Crack initiation stress} \\
\sigma_t & \quad \text{Tensile strength (TS)}
\end{align*}

1 Introduction

The Hoek–Brown failure criterion is widely used in rock mechanics and rock engineering practice for determining the strength of brittle intact rock and rock masses. This nonlinear semiempirical failure criterion was introduced by Hoek and Brown [33], and the following form was suggested for intact rock (see also [17]) (Eq. 1):

$$\sigma = \sigma_3 + \sigma_c \left( \frac{m_i}{\sigma_c} + 1 \right)^{0.5} \quad (1)$$

where $\sigma_1$ and $\sigma_3$ are major and minor principal stress at failure, respectively, $m_i$ is Hoek–Brown material constant, and $\sigma_c$ is the uniaxial compressive strength of intact rock. According to Eq. (1), two independent parameters are necessary, namely the:

- Uniaxial compressive strength ($\sigma_c$)
- Hoek–Brown material constant of the intact rock ($m_i$)
Although several practical, empirical, and probabilistic approaches have been presented in the literature to address uniaxial compressive strength (UCS) [12, 34, 36, 73, 80], the accurate determination of \( m_i \) is still challenging task and is influenced by many factors such as mineral composition, grain size, and cementation of rock. Generally, \( m_i \) presents curve-fitting parameter for Hoek–Brown failure envelope [37]. However, researches by Zuo et al. [84] showed that \( m_i \) is not a curve-fitting parameter but has physical meanings and can be derived from micro-mechanical principles (Hoek and Martin [38]).

Hoek and Brown [33–35] suggested that these values should be determined by numerous triaxial tests, applying different confining pressures (\( \sigma_3 \)) between zero and 0.5 \( \sigma_c \). These laboratory tests are time-consuming, expensive, and in many cases, there are not enough (or suitable) samples. Singh et al. [70], Peng et al. [55], and Shen and Karakus [65] demonstrated that the reliability of \( m_i \) values measured from triaxial test analysis depends on the quality and quantity of test data used in the analysis. They concluded that the range of \( \sigma_3 \) could have a significant influence on the calculation of \( m_i \). It is the reason why several methods were developed for determining the Hoek–Brown constant (\( m_i \)) [72].

There are several techniques available to calculate \( m_i \) values in the absence of triaxial test. These approaches are entitled, Guidelines [32, 33], R-index [10, 33, 52, 59, 60, 62], UCS-based model [65, 74], tensile strength (TS)-based approach [77], and crack initiation stress-based model [10]. These methods are based on the rock lithological classifications and rock properties that can be easily obtained at an early stage of a project, which can be used in preliminary designs of engineering projects when triaxial test data are not available.

Aladejare and Wang [1] published a paper and introduced a new method for the determination of \( m_i \) value. They developed a Bayesian approach for probabilistic characterization of Hoek–Brown constant \( m_i \) through Bayesian integration of information from Hoek’s guideline chart, regression model, and site-specific UCS data. The UCS data used in this paper were obtained from testing granite samples collected from the Forsmark site, Sweden. In addition, several sets of simulated data are used to explore the evolution of \( m_i \) as the number of site-specific data increases.

Wei et al. [78] experimentally investigated the effect of confining pressure \( \sigma_3 \) and critical crack parameter on determination of \( m_i \) value. They applied ultrasonic test and load test results of limestone and verified the exponential impact of \( \sigma_3 \) on limestone, while the negative correlation was observed between critical crack parameter and \( m_i \).

Recently, Wen et al. [79] developed an empirical relation for estimation \( m_i \) from \( \sigma_3 \) and \( \beta \), where \( \sigma_3 \) is minor principal stress and \( \beta \) is an angle between the major principal stress and weak plane based on substantial uniaxial and triaxial compression test data. They considered the effect of anisotropy on the value of Hoek constant (\( m_i \)).

In the present study, however, we focused on the quasi-isotropic intact rocks and utilized the existing methods in the literature for predicting \( m_i \) values. Furthermore, the detailed comparison is drawn between the obtained values of each approach to calculate which method provides the best estimation for the investigated rocks based on the calculated error function. Accordingly, new material constants are proposed for different igneous, sedimentary, and metamorphic rocks.

## 2 Determination of Hoek–Brown constant \( m_i \)

In the absence of triaxial tests, there are several different methods available to estimate the Hoek–Brown constant \( m_i \), which are referred to as the R-index method [33], UCS-based model [65, 74], TS-based model [77], and combination method [3, 66] below. By using these methods, the H-B constant \( m_i \) is obtained for the collected data, the achieved results are compared, and then, the error function was calculated and accordingly considering the lowest error value, the best data fit was presented and finally new material constants introduced.

### 2.1 Guideline method

Hoek and Brown [33] and Hoek [32] provided values of \( m_i \) constants for different types of rocks. The values of \( m_i \) are between 7 and 35; however, several factors that influence these values, such as mineral composition, foliation, grain size (texture), and cementation are among others [10].

The updated values of constant \( m_i \) for intact rock were collected by [10], using the published values of Hoek [32] (Table 1). Possible data ranges are shown by a variation range value immediately following the suggested \( m_i \) value. For example, for sandstones, the \( m_i \) values can vary between 13 and 21, and for slates, between 3 and 11.

### 2.2 Calculation the rigidity of the rock (R-index)

This method was introduced by [33] and also developed by [48, 59–61]. Cai [10] published the paper and showed that Hoek–Brown’s strength parameter (\( m_i \)) could be determined from the ratio of the uniaxial compressive strength (\( \sigma_c \)) and the tensile strength (\( \sigma_t \)), and the suggested relationship is:
As can be seen from Fig. 1, when \( R > 8 \), the error for approximating \( m_i \) (Eq. 2) by \( R \) (Eq. 4) is less than 1.6%.

It has been observed that when the \( R \) is higher than 8, the value of \( m_i \) is nearly equal to Hoek–Brown material constant (\( m_i \)). Note, that according to [38] \( m_i \) is not a curve fitting parameter, but has a physical meaning and can be derived from micro-mechanics principles. The referred \( m_i \) model is express in Eq. (3):

\[
m_i = \frac{\mu c}{\beta t} \tag{3}
\]

where \( c \) and \( t \) are the uniaxial compressive strength (UCS) and tensile strength (TS) of intact rock, respectively. While \( \mu \) is the coefficient of friction for pre-existing sliding crack surfaces, \( \beta \) is an intermediate fracture mechanics parameter that can be obtained from experimental data. It means when \( R > 8 \):

\[
m_i \approx R = \frac{c}{t} \tag{2}
\]

In recent years, Hoek and Brown [34] analyzed several published data and proposed the following approximate relationship between the compressive to tensile strength ratio, \( \frac{c}{t} \), and the Hoek–Brown parameter \( m_i \) (see Fig. 2):

\[
\frac{c}{t} = 0.81 m_i + 7 \tag{5}
\]

\[
m_i = 1.235 \frac{c}{t} - 8.642 \tag{6}
\]

It means that the Hoek–Brown constant (\( m_i \)) can be calculated using the following relationship, using the uniaxial compressive strength (\( c \)) and the tensile strength (\( t \)) data of the intact rock.

### 2.3 UCS-based model

Firstly, Shen and Karakus [65] and later Vásárhelyi et al. [74] also emphasized the difficulties in determining the \( m_i \) values of rocks. They suggested normalizing the Hoek–
Brown constant \( m_i = \frac{m_i}{\sigma_c} \) by using the strength of the rock \( m_i = \frac{m_i}{\sigma_c} \), i.e.:
\[
m_i = \sigma_b^{b+1}
\]
where \( a \) and \( b \) are constants that depend on rock types.

### 2.4 TS-based model

The tensile strength-based calculation method was suggested by Wang and Shen [77]. In this method, the \( m_i \) value is determined from the tensile strength \( \sigma_t \) of the intact rock:
\[
m_i = A_i^B
\]
where \( A \) and \( B \) are material constants that depend on rock types.

### 2.5 Combination method (UCS and TS)

Analyzing the published data of Sheorey [66], Arshadnejad and Nick [3] suggested a new equation to calculate the Hoek–Brown material constant \( m_i \) based on uniaxial compressive strength \( \sigma_c \) and the tensile strength \( \sigma_t \) parameters of the intact rock:
\[
m_i = e^{a(b^{m_i} - 1)}
\]
where \( a \), \( b \), and \( c \) are material constants. The suggested constants are summarized in Table 2, according to Arshadnejad and Nick [3].

### 2.6 Crack initiation stress-based model

According to [10], the Hoek–Brown constant \( m_i \) depends on the confining pressure. For practical estimate of \( m_i \), it was found that for strong, brittle rocks, applicable to high confining zone the following equation could be used:
\[
m_i = 12 \frac{\sigma_c}{\sigma_{ci}}
\]
(10)
For low confinement stress to tension zone, especially for the tension zone the suggested equation is:
\[
m_i = 8 \frac{\sigma_c}{\sigma_{ci}}
\]
(11)
In these equations, \( \sigma_c \) and \( \sigma_{ci} \) are the uniaxial compressive strength and the crack initiation stress, respectively.

### 2.7 Bayesian approach

The proposed approach [1] derives the probability density function (PDF) of \( m_i \) based on the integration of Hoek’s guideline chart, regression model, and site-specific UCS data, under a Bayesian framework. A large number of equivalent samples of \( m_i \) are generated from the PDF using Markov Chain Monte Carlo (MCMC) simulation.
The published values of $m_i$ for volcanic tuffs. The latter one is between 8 and 13.

Comparing the published values of $m_i$ based on Eq. (9) with the guidelines [10, 32, 33] given for igneous rocks, the value of $m_i$ for basalt is between 20 and 30, whereas the minimum published value of $m_i$ for Basalt is 4.31 (see Appendix 1) which does not fall within the expected range. The minimum published value of $m_i$ for basalt is even less than $m_i$ value for volcanic tuffs. The latter one is between 8 and 13. The published values of $m_i$ for granite are between 11.68 and 34.03, but the expected range based on the guidelines is between 29 and 35. The same discrepancy was observed for gabbro. The expected range based on the guideline values is between 24 and 30, whereas the published results are in between 15.31 and 20.74.

For diorite, the value of $m_i$ based on the guidelines is between 20 and 30; however, according to published data, the value of $m_i$ is between 6.1 and 11. For granodiorite, based on the guideline, the value of $m_i$ changes between 26 and 32, while based on published results, it is between 11 and 18.15. For diabase, according to the guidelines, the value of $m_i$ is between 10 and 20; nevertheless, based on published data it is between 15.3 and 20.3. For andesite and rhyolite, the value of $m_i$ based on the guidelines is between 20 and 30; however, the published values are 6.22 and 5.43 for andesite and rhyolite, respectively. For agglomerate, the value of $m_i$ is between 16 and 22, but the published value is 7.92, which does not fit the guideline range.

For sedimentary rocks, the minimum value of $m_i$ for shale is 3.76 which is close to the estimated range of $m_i$ which is between 4 and 8 (see Appendix 2). Also, the maximum published value of $m_i$ for sandstone is 35.11 which is much higher than the estimated range of $m_i$ value and based on guideline which varies between 13 and 21. Moreover, for dolomite, the value of $m_i$ based on guidelines is between 6 and 12, whereas the value of $m_i$ based on published data is between 7.8 and 17.5. For limestone, the value of $m_i$ based on guideline is between 7 and 15; however, based on published data, the value of $m_i$ is between 5.3 and 14.6.

For metamorphic rocks, it is interesting to know that both maximum and minimum published values are for slate with the amounts of 1.42 and 29.54, respectively (see Appendix 3). However, based on guideline the values of $m_i$ for slate changes between 3 and 11. It means that the range of published value for slate does not fit the estimated range given by the guidelines. For gneiss, the value of $m_i$ based on guidelines is between 23 and 33; however, based on published data, the value ranges between 5.3 and 27. For schist, the published value of $m_i$ is 20.42, but the values based on guideline vary between 9 and 15. For quartzite, the published value of $m_i$ is between 7.36 and 22.7; however, based on guideline it is between 17 and 23. Also, the values of $m_i$ were calculated according to [10].

The differences between the published values of $m_i$ and the guideline values are displayed in Table 4 and Fig. 3. As shown, the published values of $m_i$ do not fit well with the guideline. As it is clear from the graph that there is a good consistency between published experimental data for $m_i$ and R-index method, whereas other methods have significant errors in estimation of $m_i$ for all studied rock samples. The obtained results based on different proposed calculation method are presented in Appendices 4, 5, and 6 for igneous, sedimentary, and metamorphic rocks, respectively. It should be noted that the constant parameters were derived from the existing Eqs. 2, 6, 7, 8, and 9, respectively.

### 4.2 Evaluation of R-index model

According to our analyses for determination of $m_i$, in respect to Eq. 2 (R-index method) and Eq. 5, it was observed that $m_i$ value is independent of rock type. The correlations between $m_i$ and the ratio between uniaxial compressive strength (UCS) and tensile strength (TS), which is called R-index method, for different rocks (sandstone, shale, slate, and gneiss) are presented in Fig. 4.
As shown for different rock types, correlation value $R^2 = 1$ and it is not influenced by rock type.

4.3 Evaluation of UCS-based model

The relationship between $m_i$ and uniaxial compressive strength (UCS) for the investigated rock samples (UCS-based method) shows an opposite result, compared to R-index method. It is evident that based on this approach, no correlation was found for the studied rock samples (Fig. 5).

4.4 Evaluation of TS-based model

Based on our analyses for determination of $m_i$ value by applying TS-based method, the established correlations for the investigated rock types were weak except for slate where the value of $R^2 = 0.66$ (Fig. 6).

In order to examine the relationship between $m_i$ and rigidity of rock (R-index method) for different rock groups, analyses were also carried out based on three different rock types (igneous, sedimentary, and metamorphic) and the results are illustrated in Fig. 7. Additionally, the error function was calculated for each rock type. The calculated
Fig. 3 Comparison of published values of $m_i$ [66] with the guidelines [4, 8, 9], R-index, UCS-based, TS-based, and combination methods: a igneous rocks; b sedimentary rocks; c metamorphic rocks
amount of error function represents the value of $\frac{\sigma_f}{f_p}$ as mentioned earlier in Eq. (3).

The obtained results of regression analyses based on proposed approaches for determination of $m_i$ are summarized in Table 5 (according to rock group) and Table 6 (according to different investigated rock samples), and the statistical results are illustrated in Table 7.

In the proposed method by Arshadnejad and Nick [3], (combination method), (i), (j), and (k) are presented as material constants. Specifically explaining, based on their analyses for different rock groups (igneous, sedimentary,
and metamorphic), there are different material constants. See Table 2 for their obtained results.

4.5 Evaluation of combination method (UCS and TS methods)

We analyzed the data set based on Eq. 9 as proposed by [3]. The results are depicted in Fig. 8. The graphs clearly illustrate that the Hoek constant ($m_i$) is independent of rock type. Accordingly, it is worth to mention the point that the intact rocks are known to contain a wide-ranging uncertainty owing to inherent heterogeneities. For rock mass classification in respect to uncertainties, GSI (Geological Strength Index) provides good classification of rock mass category as it relies on structure as well as surface conditions of existing discontinuities which are highly associated with high uncertainties in rock mass. Ván and Vásárhelyi [72] investigated the sensitivity of Hoek material constant for rock mass ($m_b$) in relation to GSI. Based on their measurement, they calculated that 10% deviation in the GSI value; the relative sensitivity of $m_b$ is at least double the uncertainties of the GSI values and may be 7 times higher in case of large disturbance parameters and low and high GSI values.

5 Discussion

When triaxial test data are not available, $m_i$ values can be estimated by six existing methods entitled, guidelines [32, 33], R-index [10, 33, 52, 59, 60, 62], UCS-based model [65, 74], TS-based model [77], crack initiation stress-based model [10], combination based model [3, 66], and Bayesian approach [1] to evaluate the prediction performance of existing methods, large database of triaxial tests for eight common rock types (slate, shale, limestone, quartzdiorite, sandstone, quartzite, gneiss, and granite) from literature was selected and analyzed as indicated in Appendices 1, 2, and 3.

In the present research, to ensure the quantity and quality of data, the statistical analysis with the help of SPSS software was performed on quasi-isotropic rocks. The results are presented in Fig. 9. As shown, normal distribution function and standard deviation were calculated for each rock group. According to Fig. 9, for igneous rock, the calculated standard deviation is 7.21 with the mean value of 15.36, for sedimentary rock is 6.32 with the mean value of 12, and for metamorphic rocks is 10.07 with the mean value of 13.37. Interestingly enough, metamorphic rocks exhibit higher standard deviation, which can be associated with the foliated texture of the investigated metamorphic rocks.

Similarly, Aladejare and Wang [1] investigated the values of $m_i$ for 30,000 equivalent granite samples based on Bayesian approach and realized that the histogram peaks at
a $m_i$ value of around 30, and roughly about 27,479 out of the total 30,000 samples representing about 91.5% are within $m_i$ range of 18 and 48. Therefore, the 90% inter-perceptual range of $m_i$ is roughly between $m_i$ values of 18 and 48 (Fig. 9d). In comparison with our results, however, Wen et al. [79] published an interesting paper about anisotropic rocks, which has drawn our attention to their new empirical relation. The large number of the data set (738) of different rock types was analyzed. They observed that the more anisotropic the rock is, the more significant decrease in $m_i$ value is evident. Using this relation, the H-B strength criterion is modified, and its performance is evaluated in two examples. The results illustrate the improved ability of the modified criterion to determine the strength of metamorphic and sedimentary rocks.

Based on the empirical model by Wen et al. [79], most of the estimated values of $m_i$ are within the upper/lower limit of 90%, which accounts for 96.6% of all the data, and that all the estimated values are within the upper/lower limit of 80%. This result indicates that the developed relation estimates of $m_i$ agree well with the experimental observations, demonstrating that the developed relation has an excellent ability to estimate $m_i$ accurately. The comparison graph between our results and recently published paper by Wen et al. [79] is presented in Fig. 10.

Moreover, Wen et al. [80–82] thoroughly investigated the impact of minor principal stress ($\sigma_3$) on rock ductile–brittle behavior. Based on their measurement, under a low minor principal stress, rocks experience dilatancy and brittleness that causes the exciting microcrack inside the rock to coalesce, which result in an increase in volume; In

![Fig. 7](image URL)
contrast, applying the high minor principal stress, the rock undergoes ductility which leads to microcrack opening.

In the recently published paper by He et al. [27], they suggested that the constant $m_i$ of the H–B criterion can be continuously estimated during drilling. Therefore, a method to estimate the constant $m_i$ from drilling data was proposed. Based on the proposed method for $m_i$ determination, for the granite, slate, the obtained values of $m_i$ in their work were lower than the suggested values for granite.

Table 5 Calculated values of $m_i$ by different methods (Eqs. 2, 5, 7, 8, 9, 10)

| Rock type     | R-index method | UCS-based method | TS-based method | Combination method |
|---------------|----------------|------------------|-----------------|-------------------|
|               | $m_i = a\left(\frac{c}{r}\right) + b$ | $m_i = c\frac{\sigma_i}{\tau}$ | $m_i = g_i^h$ | $m_i = e^{\left(\frac{\sigma_i}{\tau}\right)}$ |
|               | $a$ | $b$ | $c$ | $d$ | $R^2$ | $e$ | $f$ | $R^2$ | $g$ | $h$ | $R^2$ | $i$ | $j$ | $k$ | $R^2$ |
| Igneous       | 1   | 0.17 | 1   | 0.81 | 6.88 | 1   | 0.29 | 0.73 | 0.19 | 29.14 | –0.3 | 0.04 | 1.08 | 2   | 0.34 | 0.99 |
| Sedimentary   | 1   | 0.17 | 1   | 0.81 | 6.88 | 1   | 15.16 | –0.07 | 0.7 | 21.81 | –0.34 | 0.38 | 1.08 | 2   | 0.34 | 0.99 |
| Metamorphic   | 1   | 0.37 | 1   | 0.82 | 6.76 | 1   | 5.96 | 0.07 | 0.35 | 36.91 | –0.6 | 0.52 | 0.95 | 2   | 0.4  | 0.99 |
| All types     | 1   | 0.21 | 1   | 0.81 | 6.86 | 1   | 10.98 | 0.004 | 0.64 | 22.8 | –0.34 | 0.32 | 1.07 | 2   | 0.37 | 0.99 |

Table 6 Determination of $m_i$ based on existing methods

| Rock type     | Origin      | Name          | R-index method | UCS-based method | TS-based method |
|---------------|-------------|---------------|----------------|------------------|-----------------|
|               |             |               | $m_i = a\left(\frac{c}{r}\right) + b$ | $m_i = c\sigma_i^r$ | $m_i = E^l$ |
|               |             |               | $a$ | $b$ | $R^2$ | $c$ | $d$ | $R^2$ | $e$ | $f$ | $R^2$ |
| Igneous       | Plutonic    | Granite       | 1   | 0.08 | 1   | 0.0005 | 1.87 | 0.46 | 436.97 | –1.17 | 0.89 |
|               | Quartzdiorite|               | 1   | 0.12 | 1   | 2.72  | 0.24 | 0.3  | –          | –      | –    |
| Sedimentary   | Clastic     | Sandstone     | 1   | 0.15 | 1   | –     | –    | –    | 20.19 | –0.25 | 0.23 |
|               |             | Shale         | 1   | 0.28 | 1   | –     | –    | –    | 17.78 | –0.37 | 0.47 |
| Biochemical   | Limestone   |               | 1   | 0   | 1   | 2.18 | 0.33 | 0.1  | 29.45 | –0.52 | 0.35 |
| Metamorphic   | Gneiss      |               | 1   | 0.21 | 1   | 0.29 | 0.68 | 0.54 | –          | –      | –    |
|               | Quartzites  |               | 1   | 0.14 | 1   | 0.12 | 0.86 | 0.91 | –          | –      | –    |
|               | Slate       |               | 1   | 0.42 | 1   | –     | –    | –    | 33.31 | –0.65 | 0.67 |

Table 7 Statistical results of predicted $m_i$ values using different approaches

| Rock type     | Estimation method | Predicted $m_i$ | Min | Max | Ave | SD |
|---------------|-------------------|-----------------|-----|-----|-----|----|
| Igneous       | R-index           | 4.31 | 34.08 | 15.36 | 7.21 |
|               | UCS method        | 6.17 | 31.69 | 16.36 | 6.15 |
|               | TS method         | 7.21 | 16.02 | 11.98 | 2.41 |
|               | Combination method| 4.1  | 36.95 | 14.3  | 7.65 |
| Sedimentary   | R-index           | 3.76 | 35.11 | 12   | 6.32 |
|               | UCS method        | 17.82 | 23.51 | 20.3 | 1.12 |
|               | TS method         | 5.23 | 30.4  | 12.58 | 5.15 |
|               | Combination method| 3.65 | 38.53 | 10.95 | 6.47 |
| Metamorphic   | R-index           | 1.43 | 32.33 | 13.37 | 10.07 |
|               | UCS method        | 7.2  | 22.46 | 14.99 | 6.74 |
|               | TS method         | 3.83 | 48.42 | 9.4  | 6.92 |
|               | Combination method| 1.98 | 34.29 | 13.18 | 10.44 |
and sandstone from [33], and they were higher than the suggested value for slate and limestone.

To establish the correlations for specific rock types, Shen and Karakus [65], Wang and Shen [77] considered five of the most common rock types (coal, granite, limestone, marble, and sandstone) from the database in the Rocscience [61], in which there are at least 12 groups of data with 115 triaxial tests available. Results illustrate that four rock types have trends of decreasing $m_i$ with increasing $r_i$; however, such a correlation for limestone was not observed. It is worth noting that this finding is also in agreement with our obtained results for limestone. This may be due to the fact that limestone has a wide array of test data with different compositions and cementations; for example, there are different guidelines-based $m_i$ values for three types of limestone, crystalline ($m_i = 12 \pm 3$), sparitic ($m_i = 10 \pm 2$), and micritic ($m_i = 9 \pm 2$), in the Hoek guidelines [32]. Therefore, the data sets for limestone are quite widely scattered compared with those for the other four rock types.

The observed value of $m_i$ for limestone is between 5.3 and 14.6; In contrast, according to guideline, the $m_i$ value of limestone is between 7 and 15, and according to R-index method $m_i$ is between 1.42 and 30.97; however, such a correlation for limestone was not observed. It is worth noting that this finding is also in agreement with our obtained results for limestone. This may be due to the fact that limestone has a wide array of test data with different compositions and cementations; for example, there are different guidelines-based $m_i$ values for three types of limestone, crystalline ($m_i = 12 \pm 3$), sparitic ($m_i = 10 \pm 2$), and micritic ($m_i = 9 \pm 2$), in the Hoek guidelines [32]. Therefore, the data sets for limestone are quite widely scattered compared with those for the other four rock types.

The observed value of $m_i$ for slate is between 1.42 and 30.97; however, based on guideline, the $m_i$ value of slate is between 3 and 11, and based on R-index method $m_i$ is between 1.59 and 31.23. So, R-index method gives the best estimate of $m_i$ value among the others. However, based on [65], UCS-based method provides a better prediction of $m_i$ value than the guidelines-based and R-index methods and according to [77], TS-based model exhibits the best performance for granites, limestone, and marble.

Additionally, the observed value of $m_i$ for slate is between 1.42 and 30.97; however, based on guideline, the $m_i$ value of slate is between 3 and 11, and based on R-index method $m_i$ is between 1.59 and 31.23. So, R-index method gives the best estimate of $m_i$ value among the others. The obtained values of $m_i$ were 6.28, 5.1, 12.8, and 13.7, respectively.

Moreover, the observed value of $m_i$ for shale is between 3.76 and 25.31, but, according to guideline, the $m_i$ value of shale is between 4 and 8, and according to R-index method $m_i$ is between 3.7 and 24.9, according to UCS-based method $m_i$ is between 17.82 and 22.1, based on TS-based model $m_i$ is between 6.52 and 29.87, and based on combination method $m_i$ is between 3.65 and 24.3. Therefore, R-index

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**Fig. 8** Calculated values of $m_i$ based on combination method for: **a** igneous rocks; **b** sedimentary rocks; **c** metamorphic rocks; **d** all rocks.

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method gives the best estimate of \( m_i \) value among the others.

Furthermore, the observed value of \( m_i \) for sandstone is between 3.97 and 35.1; nevertheless, according to guideline, the \( m_i \) value of sandstone is between 13 and 21, according to R-index method \( m_i \) is between 3.9 and 35, according to UCS-based method \( m_i \) is between 17.82 and 22.23, and based on TS-based method \( m_i \) is between 5.48 and 29.87, and based on combination method \( m_i \) is between 3.83 and 38.5. As a result, R-index method gives the best estimate of \( m_i \) value among the others. Nevertheless, based on [77], UCS-based model gives the best prediction for sandstone.

As well as that, the observed value of \( m_i \) for quartzite is between 7.36 and 30.1, while, according to guideline, the \( m_i \) value of quartzite is between 17 and 23, according to R-index method \( m_i \) is between 7.36 and 30.14, according to UCS-based method \( m_i \) is between 8.45 and 21.1, based on TS-based method \( m_i \) is between 5.66 and 10.43, and based on combination method \( m_i \) is between 6.55 and 31.10. Hence, R-index method gives the best estimate of \( m_i \) value among the others.

In addition, the observed value of \( m_i \) for gneiss is between 5.34 and 32.33, whereas, according to guideline, the \( m_i \) value of gneiss is between 23 and 33, according to R-index method \( m_i \) is between 5.3 and 32.3, according to UCS-based method \( m_i \) is between 8.07 and 22.46, based on TS-based method \( m_i \) is between 4.68 and 11.44, and based on combination method \( m_i \) is between 4.92 and 34.28. Therefore, R-index method gives the best estimate of \( m_i \) value among the others.
Finally, the observed value of $m_i$ for granite is between 11.68 and 34.03; on the other hand, according to guideline, the $m_i$ value of granite is between 29 and 35, according to R-index method $m_i$ is between 11.7 and 34.1, according to UCS-based method $m_i$ is between 8.92 and 22.8, based on TS-based method $m_i$ is between 7.42 and 15.42, and based on combination method $m_i$ is between 10.22 and 36.95. Thus, R-index method gives the best estimate of $m_i$ value among the others.

6 Conclusion

This paper comprehensively reviewed the proposed methods for determination of $m_i$ value using the triaxial data set published by [66]. New linear and nonlinear correlations were found. New material constants were suggested for igneous, sedimentary, and metamorphic rocks such as granite, quartzdiorite, sandstone, shale, limestone, gneiss, quartzite, and slate. Furthermore, the error function was calculated for each rock type. According to our analyses, R-index approach with new material constants provides the best fit for all the studied lithotypes including igneous, sedimentary, and metamorphic rocks. Moreover, it is worth mentioning that comparison graph between out achieved results for quasi-isotropic rocks and anisotropic rocks was developed. The data scattering of quasi-isotropic rocks differs from the anisotropic rocks in that quasi-isotropic rocks exhibit normal distribution in narrower range between 1.43 and 35.11, whereas anisotropic rocks display wider range of data distribution between 1 and 80.

The combination methods (UCS) and (TS) provide the best fit for investigated rock data, when the determination coefficient and error function are considered. For various rock types such as igneous, sedimentary, and metamorphic rocks, the different approaches resulted in non-uniform correlations. For instance, TS-based approach works well for the granite and gives estimation fit with $R^2 = 0.89$. For quartzites, UCS-based approach displays the best approximation with $R^2 = 0.91$, and for slate, TS-based model exhibits the best correlation with $R^2 = 0.67$.

R-index method, the value of $m_i$ is not influenced by rock type. In other words, this method gives the best estimation for all the investigated rock types and is independent of rock type. However, in all the other approaches, the rock type plays a significant role in correlation values and results.

Fig. 10 Comparison between $m_i$ values estimated via the proposed relation and measured values for different rock types (red rhombus symbol is related to quasi-isotropic intact igneous rocks; green triangle symbol is related to quasi-isotropic intact sedimentary rocks; blue cross symbol is related to quasi-isotropic intact metamorphic rocks; and small orange square symbol is related to anisotropic intact rocks (Wen et al. [79])) (color figure online)
### Appendix 1: Published values of triaxial parameters for Hoek–Brown criterion using data set for igneous rocks [66]

| No | Rock name      | \(\sigma_c\) (MPa) | \(\sigma_t\) (MPa) | \(m_i\) | \(\frac{\sigma_c}{\sigma_t}\) | \(\frac{\sigma_t}{\sigma_c}\) | Source                  |
|----|----------------|---------------------|---------------------|--------|-----------------|-----------------|--------------------------|
| 1  | Agglomerate tuff | 92                  | 11.43               | 7.926  | 8.05            | 0.09            | Betourney et al. [6]     |
| 2  | Tuff            | 125.2               | 5.44                | 22.963 | 23.01           | 0.18            | Wang and Kemeny [76]     |
| 3  | Andesite        | 201.9               | 31.64               | 6.225  | 6.38            | 0.03            | Betourney et al. [6]     |
| 4  | Basalt          | 79.1                | 17.45               | 4.313  | 4.53            | 0.05            | Betourney et al. [6]     |
| 5  | Diabase         | 322.9               | 15.85               | 20.324 | 20.37           | 0.06            | Betourney et al. [6]     |
| 6  | Diabase         | 532                 | 34.6                | 15.310 | 15.38           | 0.03            | Brace [8]                |
| 7  | Diorite         | 67.8                | 10.82               | 6.103  | 6.27            | 0.09            | Betourney et al. [6]     |
| 8  | Diorite         | 124.3               | 18.57               | 6.548  | 6.69            | 0.05            |                         |
| 9  | Diorite         | 279.7               | 25.21               | 11.004 | 11.09           | 0.04            | Mogi [50]                |
| 10 | Gabbro          | 379.1               | 25.1                | 15.033 | 15.10           | 0.04            | Broch [9]                |
| 11 | Gabbro          | 226.9               | 10.92               | 20.738 | 20.78           | 0.09            |                         |
| 12 | Granite         | 241.3               | 11.34               | 21.227 | 21.28           | 0.09            | Betourney et al. [6]     |
| 13 | Granite         | 318.2               | 10.31               | 30.816 | 30.86           | 0.10            | Brace [8]                |
| 14 | Granite         | 260                 | 18.56               | 13.936 | 14.01           | 0.05            | Franklin and Hoek [20]   |
| 15 | Granite         | 220.6               | 8.28                | 26.589 | 26.64           | 0.12            | Heard et al. [28]        |
| 16 | Granite         | 193.1               | 13.83               | 13.884 | 13.96           | 0.07            | Johnson et al. [43]      |
| 17 | Granite         | 115.7               | 9.83                | 11.681 | 11.77           | 0.10            |                         |
| 18 | Granite         | 163.5               | 10.92               | 14.900 | 14.97           | 0.09            |                         |
| 19 | Granite         | 306.5               | 23.24               | 13.115 | 13.19           | 0.04            | Mogi [50]                |
| 20 | Granite         | 337.7               | 15.45               | 21.812 | 21.86           | 0.06            | Mogi [51]                |
| 21 | Granite         | 93.8                | 2.75                | 34.034 | 34.11           | 0.36            | Schwartz [63]            |
| 22 | Granodiorite    | 334.9               | 21.06               | 15.837 | 15.90           | 0.05            | Betourney et al. [6]     |
| 23 | Granodiorite    | 113.1               | 10.16               | 11.043 | 11.13           | 0.10            | Betourney et al. [6]     |
| 24 | Granodiorite    | 259.1               | 14.23               | 18.150 | 18.21           | 0.07            | Dayre and Giraud [13]    |
| 25 | Lamprophyre     | 116.3               | 14.02               | 8.174  | 8.30            | 0.07            | Betourney et al. [6]     |
| 26 | Quartzdiorite   | 174.7               | 9.53                | 18.274 | 18.33           | 0.10            | Betourney et al. [6]     |
| 27 | Quartzdiorite   | 173.4               | 14.47               | 11.903 | 11.98           | 0.07            |                         |
| 28 | Quartzdiorite   | 98.6                | 7.35                | 13.343 | 13.41           | 0.14            |                         |
| 29 | Quartzdiorite   | 273.8               | 15.71               | 17.371 | 17.43           | 0.06            | Broch [9]                |
| 30 | Quartzdiorite   | 209.7               | 9.98                | 20.965 | 21.01           | 0.10            |                         |
| 31 | Quartzdiorite   | 300.2               | 23.57               | 12.658 | 12.74           | 0.04            | Franklin and Hoek [20]   |
| 32 | Rhyolite        | 106.4               | 18.96               | 5.430  | 5.61            | 0.05            | Betourney et al. [6]     |

### Appendix 2: Published values of triaxial parameters for Hoek–Brown criterion using data set for sedimentary rocks [66]

| No | Rock name      | \(\sigma_c\) (MPa) | \(\sigma_t\) (MPa) | \(m_i\) | \(\frac{\sigma_c}{\sigma_t}\) | \(\frac{\sigma_t}{\sigma_c}\) | Source                  |
|----|----------------|---------------------|---------------------|--------|-----------------|-----------------|--------------------------|
| 1  | Dolomite       | 145.3               | 18.2                | 7.859  | 7.98            | 0.05            | Brace [8]                |
| 2  | Dolomite       | 524.5               | 64.22               | 8.044  | 8.17            | 0.02            |                         |
| No | Rock name | $\sigma_r$(MPa) | $\sigma_t$(MPa) | $m_1$ | $\frac{\sigma_r}{m_1}$ | $\frac{m_1}{\sigma_r}$ | Source |
|----|-----------|-----------------|-----------------|-------|---------------------|-----------------|--------|
| 3  | Dolomite  | 218.7           | 12.46           | 17.493| 17.55               | 0.08            | Mogi [60] |
| 4  | Limestone | 65.9            | 4.47            | 14.663| 14.74               | 0.22            | Betourney et al. [6] |
| 5  | Limestone | 128.8           | 9.85            | 12.992| 13.08               | 0.10            |        |
| 6  | Limestone | 94.9            | 13.15           | 7.076 | 7.22                | 0.07            | Franklin and Hoek [20] |
| 7  | Limestone | 53.6            | 7.84            | 6.686 | 6.84                | 0.12            |        |
| 8  | Limestone | 217.9           | 39.62           | 5.319 | 5.50                | 0.02            | Gnirk and Cheathan [22] |
| 9  | Limestone | 45              | 6.26            | 7.038 | 7.19                | 0.16            | Horino and Ellickson [39] |
| 10 | Limestone| 54.7            | 9.3             | 5.714 | 5.88                | 0.10            |        |
| 11 | Limestone| 58.7            | 10.63           | 5.345 | 5.52                | 0.09            |        |
| 12 | Limestone| 58              | 9.56            | 5.905 | 6.07                | 0.10            |        |
| 13 | Limestone| 63.4            | 8.65            | 7.197 | 7.33                | 0.11            |        |
| 14 | Limestone| 49.2            | 6.09            | 7.957 | 8.08                | 0.16            |        |
| 15 | Limestone| 100.3           | 9.45            | 10.517| 10.61               | 0.10            | Stowe [71] |
| 16 | Sandstone| 85.2            | 9.87            | 8.520 | 8.63                | 0.10            | Aldritch [2] |
| 17 | Sandstone| 75.5            | 8.72            | 8.543 | 8.66                | 0.11            |        |
| 18 | Sandstone| 149.9           | 6.51            | 22.996| 23.03               | 0.15            | Betourney et al. [6] |
| 19 | Sandstone| 129.9           | 18.15           | 7.017 | 7.16                | 0.05            | Borecki et al. [7] |
| 20 | Sandstone| 112.9           | 14.68           | 7.561 | 7.69                | 0.07            |        |
| 21 | Sandstone| 109             | 8.0             | 13.367| 13.44               | 0.12            | Dlugosz et al. [14] |
| 22 | Sandstone| 21.7            | 0.88            | 24.537| 24.66               | 1.13            | Dunikowski [16] |
| 23 | Sandstone| 152.4           | 16.54           | 9.110 | 9.21                | 0.06            | Everling [18] |
| 24 | Sandstone| 74.2            | 5.98            | 12.33 | 12.41               | 0.17            | Franklin and Hoek [20] |
| 25 | Sandstone| 74.6            | 4.28            | 17.378| 17.43               | 0.23            |        |
| 26 | Sandstone| 211.7           | 18.09           | 11.618| 11.70               | 0.05            |        |
| 27 | Sandstone| 41.5            | 2.92            | 14.123| 14.21               | 0.34            | Glushko and Kirnichanskiy [21] |
| 28 | Sandstone| 65.4            | 5.79            | 11.206| 11.30               | 0.17            | Gowd and Rummel [23] |
| 29 | Sandstone| 93.9            | 3.78            | 24.761| 24.84               | 0.26            | Gustkewicz [24] |
| 30 | Sandstone| 42.6            | 1.22            | 35.014| 34.92               | 0.82            |        |
| 31 | Sandstone| 150.6           | 14.8            | 10.079| 10.18               | 0.07            | Harelend et al. [25] |
| 32 | Sandstone| 75.4            | 5.25            | 14.288| 14.36               | 0.19            |        |
| 33 | Sandstone| 93.3            | 9.74            | 9.474 | 9.58                | 0.10            |        |
| 34 | Sandstone| 10             | 0.4             | 25.314| 25.00               | 2.53            | Harza Engg Co. [26] |
| 35 | Sandstone| 163             | 10.41           | 15.602| 15.66               | 0.10            | Hoshino et al. [40] |
| 36 | Sandstone| 173.7           | 14.9            | 11.570| 11.66               | 0.07            | Hossaini and Vutukuri [41] |
| 37 | Sandstone| 236.1           | 56.05           | 3.975 | 4.21                | 0.02            | Ilintsksaya et al. [42] |
| 38 | Sandstone| 76.9            | 6.26            | 12.191| 12.28               | 0.16            | Kovári and Tisa [44] |
| 39 | Sandstone| 72.1            | 5.48            | 13.082| 13.16               | 0.18            |        |
| 40 | Sandstone| 110.7           | 7.26            | 15.174| 15.25               | 0.14            | Kuntys [45] |
| 41 | Sandstone| 98.8            | 8.09            | 12.125| 12.21               | 0.12            | Kwasniewski [46] |
| 42 | Sandstone| 103.6           | 10.63           | 9.643 | 9.75                | 0.09            |        |
| 43 | Sandstone| 104.2           | 13.39           | 7.652 | 7.78                | 0.07            |        |
| 44 | Sandstone| 44.2            | 3.39            | 12.972| 13.04               | 0.29            | Misra [49] |
| 45 | Sandstone| 61             | 5.75            | 10.510| 10.61               | 0.17            |        |
| 46 | Sandstone| 48.2            | 2.87            | 16.759| 16.79               | 0.35            |        |
| 47 | Sandstone| 99.5            | 7.39            | 13.379| 13.46               | 0.13            |        |
| 48 | Sandstone| 162.1           | 16.47           | 9.741 | 9.84                | 0.06            |        |
| 49 | Sandstone| 102.1           | 5.82            | 17.498| 17.54               | 0.17            |        |
| 50 | Sandstone| 110.3           | 6.33            | 17.382| 17.42               | 0.16            |        |
| 51 | Sandstone| 86.7            | 4.38            | 19.734| 19.79               | 0.23            |        |
| No | Rock name   | $\sigma_r$(MPa) | $\sigma_t$(MPa) | $m_i$   | $\frac{\sigma_r}{m_i}$ | $\frac{\sigma_t}{m_i}$ | Source                  |
|----|-------------|-----------------|-----------------|---------|------------------------|------------------------|-------------------------|
| 52 | Sandstone   | 72.7            | 3.8             | 19.065  | 19.13                  | 0.26                   | Murrel [53]             |
| 53 | Sandstone   | 28.9            | 3.93            | 7.216   | 7.35                   | 0.25                   | Ramamurthy [56]         |
| 54 | Sandstone   | 111.9           | 14.21           | 7.748   | 7.87                   | 0.07                   | Ramez [57]              |
| 55 | Sandstone   | 116.4           | 5.86            | 19.813  | 19.86                  | 0.17                   | Rao et al. [58]         |
| 56 | Sandstone   | 104.9           | 5.88            | 17.793  | 17.84                  | 0.17                   |                        |
| 57 | Sandstone   | 119.2           | 7.18            | 16.551  | 16.60                  | 0.14                   |                        |
| 58 | Sandstone   | 54.8            | 1.56            | 35.107  | 35.13                  | 0.64                   | Schwartz [63]           |
| 59 | Sandstone   | 70.8            | 7.68            | 9.115   | 9.22                   | 0.13                   | Sheorey et al. [67]     |
| 60 | Sandstone   | 64.8            | 5.02            | 12.824  | 12.91                  | 0.20                   | Singh et al. [69]       |
| 61 | Sandstone   | 62.9            | 9.64            | 6.370   | 6.52                   | 0.10                   | Vutukuri and Farough Hossani [75] |
| 62 | Sandstone   | 45              | 3.04            | 14.754  | 14.80                  | 0.33                   | Wilhelm and Somerton [83] |
| 63 | Siltstone   | 65.2            | 6.73            | 9.582   | 9.69                   | 0.15                   | Hobbs [30]              |
| 64 | Shale       | 220.6           | 33.85           | 6.364   | 6.52                   | 0.03                   | McLamore and Gray [47]  |
| 65 | Shale       | 184.7           | 25.29           | 7.164   | 7.30                   | 0.04                   |                        |
| 66 | Shale       | 154             | 17.56           | 8.655   | 8.77                   | 0.06                   |                        |
| 67 | Shale       | 84.5            | 5.35            | 15.737  | 15.79                  | 0.19                   |                        |
| 68 | Shale       | 185             | 26.47           | 6.848   | 6.99                   | 0.04                   |                        |
| 69 | Shale       | 190.2           | 27.28           | 6.830   | 6.97                   | 0.04                   |                        |
| 70 | Shale       | 175             | 21.34           | 8.078   | 8.20                   | 0.05                   |                        |
| 71 | Shale       | 193.9           | 26.86           | 7.082   | 7.22                   | 0.04                   |                        |
| 72 | Shale       | 112             | 23.52           | 4.555   | 4.76                   | 0.04                   |                        |
| 73 | Shale       | 107.9           | 26.9            | 3.762   | 4.01                   | 0.03                   |                        |
| 74 | Shale       | 78.8            | 15.73           | 4.808   | 5.01                   | 0.06                   |                        |
| 75 | Shale       | 57.4            | 11.15           | 4.959   | 5.15                   | 0.09                   |                        |
| 76 | Shale       | 66.8            | 13.15           | 4.886   | 5.08                   | 0.07                   |                        |
| 77 | Shale       | 93.2            | 22.07           | 3.986   | 4.22                   | 0.04                   |                        |
| 78 | Shale       | 99.3            | 21.88           | 4.318   | 4.54                   | 0.04                   |                        |
| 79 | Shale       | 58              | 8.08            | 7.043   | 7.18                   | 0.12                   |                        |
| 80 | Shale       | 80.4            | 13.76           | 5.672   | 5.84                   | 0.07                   | Sheorey et al. [67]     |
| 81 | Shale       | 66.9            | 4.21            | 15.826  | 15.89                  | 0.24                   | Singh [68]              |
| 82 | Shale       | 25.9            | 2.23            | 11.509  | 11.61                  | 0.44                   |                        |
| 83 | Shale       | 28.7            | 3.72            | 7.568   | 7.72                   | 0.26                   |                        |
| 84 | Shale       | 10              | 0.4             | 25.314  | 25.00                  | 2.53                   |                        |
| 85 | Coal        | 14.1            | 0.93            | 15.1232 | 15.16                  | 1.07                   | Hobbs [29]              |
| 86 | Coal        | 23.6            | 2.26            | 10.334  | 10.44                  | 0.44                   |                        |
| 87 | Coal        | 58.9            | 13.27           | 4.213   | 4.44                   | 0.07                   |                        |
| 88 | Coal        | 36.5            | 4.13            | 8.728   | 8.84                   | 0.24                   |                        |
| 89 | Coal        | 30.3            | 3.45            | 8.673   | 8.78                   | 0.29                   |                        |
| 90 | Coal        | 40.1            | 3.96            | 10.034  | 10.13                  | 0.25                   |                        |
| 91 | Coal        | 28.2            | 1.63            | 17.300  | 17.30                  | 0.61                   |                        |
| 92 | Coal        | 26.2            | 2.1             | 12.401  | 12.48                  | 0.47                   |                        |
| 93 | Coal        | 10.8            | 0.59            | 18.403  | 18.31                  | 1.70                   |                        |
| 94 | Coal        | 10.6            | 0.38            | 28.021  | 27.89                  | 2.64                   |                        |
| 95 | Coal        | 32.3            | 3.17            | 10.101  | 10.19                  | 0.31                   |                        |
| 96 | Coal        | 31.3            | 3.47            | 8.915   | 9.02                   | 0.28                   |                        |
| 97 | Coal        | 18.7            | 1.46            | 12.763  | 12.81                  | 0.68                   |                        |
| 98 | Coal        | 15.6            | 0.61            | 25.643  | 25.57                  | 1.64                   |                        |
| 99 | Coal        | 35.6            | 3.97            | 8.871   | 8.97                   | 0.25                   |                        |
|100 | Coal        | 33              | 3.13            | 10.420  | 10.54                  | 0.32                   |                        |
# Appendix 3: Published values of triaxial parameters for Hoek–Brown criterion using data set for metamorphic rocks [66]

| No | Rock name | $\sigma_{i}$(MPa) | $\sigma_{f}$(MPa) | $m_{i}$ | $\frac{\sigma_{f}}{\sigma_{i}}$ | $\frac{m_{i}}{m_{f}}$ | Source |
|----|-----------|------------------|------------------|-------|-----------------|----------------|--------|
| 1  | Schist    | 133.6            | 6.59             | 20.246| 20.27           | 0.15           | Barat [5]|
| 2  | Slate     | 148.6            | 18.64            | 7.844 | 7.97            | 0.05           | Attewell and Sandford [4]|
| 3  | Slate     | 108.7            | 28.66            | 3.528 | 3.79            | 0.03           |        |
| 4  | Slate     | 53.4             | 27.5             | 1.428 | 1.94            | 0.03           |        |
| 5  | Slate     | 62.3             | 21.7             | 1.980 | 2.87            | 0.03           |        |
| 6  | Slate     | 98               | 41.56            | 1.933 | 2.36            | 0.02           |        |
| 7  | Slate     | 129.4            | 39.96            | 2.930 | 3.24            | 0.02           |        |
| 8  | Slate     | 178.3            | 19.97            | 8.819 | 8.93            | 0.05           |        |
| 9  | Slate     | 57.8             | 1.86             | 30.965| 31.08           | 0.54           | Donath [15]|
| 10 | Slate     | 14.5             | 0.64             | 22.700| 22.66           | 1.57           |        |
| 11 | Slate     | 44.2             | 4.6              | 9.504 | 9.61            | 0.22           |        |
| 12 | Slate     | 68.1             | 4.03             | 16.853| 16.90           | 0.25           |        |
| 13 | Slate     | 155.1            | 10.85            | 14.217| 14.29           | 0.09           |        |
| 14 | Slate     | 167.6            | 12.22            | 13.644| 13.72           | 0.08           | Fayed [19]|
| 15 | Slate     | 242              | 39.35            | 5.988 | 6.15            | 0.02           | McLamore and Gray [47]|
| 16 | Slate     | 181.9            | 40.14            | 4.311 | 4.53            | 0.02           |        |
| 17 | Slate     | 99.2             | 30.5             | 2.945 | 3.25            | 0.03           |        |
| 18 | Slate     | 106.3            | 31.44            | 3.085 | 3.38            | 0.03           |        |
| 19 | Slate     | 124              | 27.16            | 4.345 | 4.57            | 0.04           |        |
| 20 | Slate     | 162.6            | 34.66            | 4.479 | 4.69            | 0.03           |        |
| 21 | Slate     | 220.3            | 44.09            | 4.797 | 5.00            | 0.02           |        |
| 22 | Gneiss    | 315.1            | 17.58            | 17.865| 17.92           | 0.06           |        |
| 23 | Gneiss    | 75.3             | 13.63            | 5.343 | 5.52            | 0.07           |        |
| 24 | Gneiss    | 221.7            | 13.61            | 16.233| 16.29           | 0.07           | Broch [9]|
| 25 | Gneiss    | 195.4            | 29.86            | 6.389 | 6.54            | 0.03           |        |
| 26 | Gneiss    | 197.7            | 22.29            | 8.759 | 8.87            | 0.04           |        |
| 27 | Gneiss    | 106.4            | 11.17            | 9.423 | 9.53            | 0.09           |        |
| 28 | Gneiss    | 272.8            | 11.32            | 24.061| 24.10           | 0.09           | Horino and Ellickson [39]|
| 29 | Gneiss    | 234.8            | 7.8              | 30.063| 30.10           | 0.13           |        |
| 30 | Gneiss    | 222.2            | 7.54             | 29.438| 29.47           | 0.13           |        |
| 31 | Gneiss    | 224.8            | 7.66             | 29.301| 29.35           | 0.13           |        |
| 32 | Gneiss    | 212.5            | 6.57             | 32.329| 32.34           | 0.15           |        |
### Appendix 4: Measured and calculated values of $m_i$ based on different methods for igneous rocks

| No | Rock name  | $m_i$(measured) | $\frac{c_i}{\sigma}$ | $m_i$(R-index (Cai)) | $m_i$(UCS based) | $m_i$(TS based) | $m_i$(Hoek–Brown (2019)) | $m_i$(combination method) |
|----|-------------|-----------------|-----------------------|----------------------|-----------------|-----------------|--------------------------|--------------------------|
| 1  | Agglomerate tuff | 7.93            | 8.05                  | 7.92                 | 7.69            | 14.03           | 1.26                     | 7.00                     |
| 2  | Tuff        | 22.96           | 23.01                 | 22.97                | 21.27           | 12.20           | 19.67                    | 21.88                    |
| 3  | Andesite    | 6.23            | 6.38                  | 6.22                 | 13.54           | 10.34           | -0.79                    | 5.63                     |
| 4  | Basalt      | 4.31            | 4.53                  | 4.31                 | 6.90            | 12.36           | -3.06                    | 4.10                     |
| 5  | Diabase     | 20.32           | 20.37                 | 20.32                | 18.99           | 12.72           | 16.42                    | 18.84                    |
| 6  | Diabase     | 15.31           | 15.38                 | 15.31                | 6.17            | 10.06           | 10.27                    | 13.61                    |
| 7  | Diorite     | 6.10            | 6.27                  | 6.11                 | 9.55            | 14.26           | -0.93                    | 5.53                     |
| 8  | Diorite     | 6.55            | 6.69                  | 6.54                 | 21.32           | 12.13           | -0.41                    | 5.88                     |
| 9  | Diorite     | 11.00           | 11.09                 | 11.00                | 22.50           | 7.21            | 5.01                     | 9.62                     |
| 10 | Gabbro      | 15.03           | 15.10                 | 15.04                | 14.73           | 11.08           | 9.94                     | 13.34                    |
| 11 | Gabbro      | 20.74           | 20.78                 | 20.73                | 15.40           | 14.22           | 16.92                    | 19.29                    |
| 12 | Granite     | 21.23           | 21.28                 | 21.23                | 16.25           | 14.06           | 17.53                    | 19.86                    |
| 13 | Granite     | 30.82           | 30.86                 | 30.83                | 19.50           | 12.13           | 29.32                    | 32.14                    |
| 14 | Granite     | 13.94           | 14.01                 | 13.94                | 8.92            | 11.68           | 8.59                     | 12.29                    |
| 15 | Granite     | 26.59           | 26.64                 | 26.60                | 22.13           | 10.57           | 24.13                    | 26.39                    |
| 16 | Granite     | 13.88           | 13.96                 | 13.89                | 21.92           | 8.86            | 8.53                     | 12.24                    |
| 17 | Granite     | 11.68           | 11.77                 | 11.69                | 21.15           | 9.96            | 5.84                     | 10.22                    |
| 18 | Granite     | 14.90           | 14.97                 | 14.91                | 21.67           | 9.61            | 9.78                     | 13.21                    |
| 19 | Granite     | 13.12           | 13.19                 | 13.11                | 22.64           | 7.42            | 7.58                     | 11.52                    |
| 20 | Granite     | 21.81           | 21.86                 | 21.81                | 22.80           | 8.53            | 18.24                    | 20.52                    |
| 21 | Granite     | 34.03           | 34.11                 | 34.08                | 20.84           | 15.42           | 33.31                    | 36.95                    |
| 22 | Granite breccia | 15.84          | 15.90                 | 15.84                | 16.21           | 14.54           | 10.92                    | 14.13                    |
| 23 | Granodiorite | 11.04           | 11.13                 | 11.04                | 9.10            | 13.14           | 5.05                     | 9.65                     |
| 24 | Granodiorite | 18.15           | 18.21                 | 18.15                | 12.20           | 13.20           | 13.76                    | 16.49                    |
### Appendix 5: Measured and calculated values of $m_i$ based on different methods for sedimentary rocks

| No. | Rock name   | $m_i$(measured) | $\frac{a_i}{b_i}$ | $m_i$(R-index (Cai)) | $m_i$(UCS based) | $m_i$(TS based) | $m_i$(Hoek–Brown (2019)) | $m_i$(combination method) |
|-----|-------------|-----------------|-------------------|---------------------|-----------------|-----------------|--------------------------|--------------------------|
| 1   | Dolomite    | 7.86            | 7.99              | 7.86                | 21.49           | 8.06            | 1.18                     | 6.95                     |
| 2   | Dolomite    | 8.04            | 8.17              | 8.04                | 23.51           | 5.23            | 1.41                     | 7.10                     |
| 3   | Dolomite    | 17.49           | 17.55             | 17.50               | 22.12           | 9.18            | 12.95                    | 15.81                    |
| 4   | Limestone   | 16.66           | 14.74             | 14.67               | 20.33           | 13.05           | 9.49                     | 12.99                    |
| 5   | Limestone   | 12.99           | 13.08             | 13.00               | 21.31           | 9.95            | 7.44                     | 11.41                    |
| 6   | Limestone   | 7.08            | 7.22              | 7.08                | 20.86           | 9.02            | 0.24                     | 6.31                     |
| 7   | Limestone   | 6.69            | 6.84              | 6.69                | 20.04           | 10.77           | -0.23                    | 6.00                     |
| 8   | Limestone   | 5.32            | 5.50              | 5.32                | 22.11           | 6.18            | -1.88                    | 4.90                     |
| 9   | Limestone   | 7.04            | 7.19              | 7.05                | 19.80           | 11.63           | 0.20                     | 6.29                     |
| 10  | Limestone   | 5.71            | 5.88              | 5.71                | 20.07           | 10.15           | -1.41                    | 5.22                     |
| 11  | Limestone   | 5.35            | 5.52              | 5.34                | 20.17           | 9.70            | -1.85                    | 4.92                     |
| 12  | Limestone   | 5.91            | 6.07              | 5.90                | 20.15           | 10.06           | -1.18                    | 5.37                     |
| 13  | Limestone   | 7.20            | 7.33              | 7.19                | 20.28           | 10.41           | 0.38                     | 6.41                     |
| 14  | Limestone   | 7.96            | 8.08              | 7.96                | 19.92           | 11.74           | 1.30                     | 7.03                     |
| 15  | Limestone   | 10.52           | 10.61             | 10.52               | 20.94           | 10.10           | 4.41                     | 9.19                     |
| 16  | Sandstone   | 8.52            | 8.63              | 8.52                | 20.70           | 9.95            | 1.98                     | 7.49                     |
| 17  | Sandstone   | 8.54            | 8.66              | 8.54                | 20.53           | 10.38           | 2.01                     | 7.51                     |
| 18  | Sandstone   | 23.00           | 23.03             | 22.98               | 21.54           | 11.47           | 19.68                    | 21.89                    |
| 19  | Sandstone   | 7.02            | 7.16              | 7.02                | 21.32           | 8.07            | 0.16                     | 6.26                     |
| 20  | Sandstone   | 7.56            | 7.69              | 7.56                | 21.11           | 8.68            | 0.82                     | 6.71                     |
| 21  | Sandstone   | 13.37           | 13.44             | 13.37               | 21.06           | 10.64           | 7.89                     | 11.75                    |
| 22  | Sandstone   | 24.54           | 24.66             | 24.62               | 18.81           | 22.79           | 21.69                    | 23.87                    |
| 23  | Sandstone   | 9.11            | 9.21              | 9.11                | 21.56           | 8.33            | 2.69                     | 7.98                     |
| 24  | Sandstone   | 12.33           | 12.41             | 12.33               | 20.50           | 11.81           | 6.62                     | 10.80                    |
| 25  | Sandstone   | 17.38           | 17.43             | 17.37               | 20.51           | 13.25           | 12.80                    | 15.68                    |
| 26  | Sandstone   | 11.62           | 11.70             | 11.62               | 22.06           | 8.08            | 5.75                     | 10.16                    |
| 27  | Sandstone   | 14.12           | 14.21             | 14.14               | 19.69           | 15.11           | 8.84                     | 12.48                    |
| 28  | Sandstone   | 11.21           | 11.30             | 11.21               | 20.32           | 11.94           | 5.25                     | 9.79                     |
| 29  | Sandstone   | 24.76           | 24.84             | 24.80               | 20.84           | 13.83           | 21.91                    | 24.10                    |
| No | Rock name | $m_r$(measured) | $m_r$(R-index (Cai)) | $m_r$(UCS based) | $m_r$(TS based) | $m_r$(Hoek–Brown (2019)) | $m_r$(combination method) |
|----|-----------|----------------|----------------------|------------------|----------------|--------------------------|--------------------------|
| 30 | Sandstone | 35.01 | 34.92 | 34.89 | 19.72 | 20.38 | 34.31 | 38.20 |
| 31 | Sandstone | 10.08 | 10.18 | 10.08 | 21.55 | 8.66 | 3.88 | 8.81 |
| 32 | Sandstone | 14.29 | 14.36 | 14.29 | 20.53 | 12.35 | 9.03 | 12.62 |
| 33 | Sandstone | 9.47 | 9.58 | 9.47 | 20.83 | 9.99 | 3.14 | 8.30 |
| 34 | Sandstone | 25.31 | 25.00 | 24.96 | 17.82 | 29.87 | 22.11 | 24.30 |
| 35 | Sandstone | 15.60 | 15.66 | 15.59 | 21.66 | 9.77 | 10.62 | 13.89 |
| 36 | Sandstone | 11.57 | 11.66 | 11.57 | 21.76 | 8.64 | 5.70 | 10.12 |
| 37 | Sandstone | 3.98 | 4.21 | 3.97 | 22.23 | 5.48 | -3.46 | 3.82 |
| 38 | Sandstone | 12.19 | 12.28 | 12.20 | 20.55 | 11.63 | 6.47 | 10.68 |
| 39 | Sandstone | 13.08 | 13.16 | 13.08 | 20.46 | 12.17 | 7.54 | 11.49 |
| 40 | Sandstone | 15.17 | 15.25 | 15.18 | 21.09 | 11.05 | 10.11 | 13.48 |
| 41 | Sandstone | 12.13 | 12.21 | 12.13 | 20.92 | 10.65 | 6.38 | 10.62 |
| 42 | Sandstone | 9.64 | 9.75 | 9.64 | 20.99 | 9.70 | 3.35 | 8.44 |
| 43 | Sandstone | 7.65 | 7.78 | 7.65 | 21.00 | 8.96 | 0.93 | 6.78 |
| 44 | Sandstone | 12.97 | 13.04 | 12.96 | 19.77 | 14.35 | 7.40 | 11.38 |
| 45 | Sandstone | 10.51 | 10.61 | 10.51 | 20.22 | 11.97 | 4.41 | 9.19 |
| 46 | Sandstone | 16.76 | 16.79 | 16.73 | 19.89 | 15.20 | 12.02 | 15.03 |
| 47 | Sandstone | 13.38 | 13.46 | 13.39 | 20.93 | 10.99 | 7.92 | 11.77 |
| 48 | Sandstone | 9.74 | 9.84 | 9.74 | 21.66 | 8.35 | 3.47 | 8.52 |
| 49 | Sandstone | 17.50 | 17.54 | 17.49 | 20.97 | 11.92 | 12.94 | 15.80 |
| 50 | Sandstone | 17.38 | 17.42 | 17.37 | 21.08 | 11.58 | 12.79 | 15.67 |
| 51 | Sandstone | 19.73 | 19.79 | 19.74 | 20.73 | 13.14 | 15.71 | 18.20 |
| 52 | Sandstone | 19.07 | 19.13 | 19.08 | 20.47 | 13.80 | 14.89 | 17.48 |
| 53 | Sandstone | 7.22 | 7.35 | 7.22 | 19.19 | 13.64 | 0.41 | 6.43 |
| 54 | Sandstone | 7.75 | 7.87 | 7.75 | 21.10 | 8.78 | 1.05 | 6.86 |
| 55 | Sandstone | 19.81 | 19.86 | 19.81 | 21.16 | 11.90 | 15.79 | 18.28 |
| 56 | Sandstone | 17.79 | 17.84 | 17.78 | 21.01 | 11.88 | 13.30 | 16.11 |
| 57 | Sandstone | 16.55 | 16.60 | 16.54 | 21.20 | 11.09 | 11.78 | 14.83 |
| 58 | Sandstone | 35.11 | 35.13 | 35.10 | 20.07 | 18.73 | 34.57 | 38.53 |
| 59 | Sandstone | 9.12 | 9.22 | 9.11 | 20.44 | 10.84 | 2.70 | 7.99 |
| 60 | Sandstone | 12.82 | 12.91 | 12.83 | 20.31 | 12.54 | 7.24 | 11.26 |
| 61 | Sandstone | 6.37 | 6.52 | 6.37 | 20.27 | 10.03 | -0.61 | 5.74 |
| 62 | Sandstone | 14.75 | 14.80 | 14.74 | 19.80 | 14.90 | 9.57 | 13.05 |
| 63 | Siltstone | 9.58 | 9.69 | 9.58 | 20.32 | 11.34 | 3.28 | 8.39 |
| 64 | Shale | 6.35 | 6.52 | 6.36 | 22.13 | 6.52 | -0.62 | 5.74 |
| 65 | Shale | 7.16 | 7.30 | 7.17 | 21.86 | 7.20 | 0.34 | 6.38 |
| 66 | Shale | 8.66 | 8.77 | 8.66 | 21.58 | 8.16 | 2.15 | 7.61 |
| 67 | Shale | 15.74 | 15.79 | 15.73 | 20.69 | 12.27 | 10.79 | 14.02 |
| 68 | Shale | 6.85 | 6.99 | 6.85 | 21.86 | 7.09 | -0.04 | 6.13 |
| 69 | Shale | 6.83 | 6.97 | 6.83 | 21.90 | 7.02 | -0.06 | 6.11 |
| 70 | Shale | 8.08 | 8.20 | 8.08 | 21.77 | 7.64 | 1.45 | 7.13 |
| 71 | Shale | 7.08 | 7.22 | 7.08 | 21.93 | 7.06 | 0.24 | 6.31 |
| 72 | Shale | 4.56 | 4.76 | 4.55 | 21.10 | 7.39 | -2.78 | 4.29 |
| 73 | Shale | 3.76 | 4.01 | 3.76 | 21.05 | 7.05 | -3.71 | 3.65 |
| 74 | Shale | 4.81 | 5.01 | 4.81 | 20.59 | 8.48 | -2.48 | 4.50 |
| 75 | Shale | 4.96 | 5.15 | 4.95 | 20.14 | 9.54 | -2.31 | 4.61 |
| 76 | Shale | 4.89 | 5.08 | 4.88 | 20.35 | 9.02 | -2.39 | 4.55 |
| 77 | Shale | 3.99 | 4.22 | 3.99 | 20.83 | 7.55 | -3.45 | 3.83 |
| 78 | Shale | 4.32 | 4.54 | 4.32 | 20.93 | 7.57 | -3.06 | 4.10 |
| No | Rock name | $m_i$ (measured) | $\frac{v}{v_i}$ | $m_i$ (R-index (Cai)) | $m_i$ (UCS based) | $m_i$ (TS based) | $m_i$ (Hoek–Brown (2019)) | $m_i$ (combination method) |
|----|-----------|-----------------|----------------|------------------------|------------------|------------------|-----------------------------|----------------------------|
| 79 | Shale     | 7.04            | 7.18           | 7.04                   | 20.15            | 10.65            | 0.19                        | 6.28                       |
| 80 | Shale     | 5.67            | 5.84           | 5.67                   | 20.62            | 8.88             | -1.45                       | 5.18                       |
| 81 | Shale     | 15.83           | 15.89          | 15.83                  | 20.36            | 13.32            | 10.91                       | 14.12                      |
| 82 | Shale     | 11.51           | 11.61          | 11.53                  | 19.05            | 16.57            | 5.65                        | 10.08                      |
| 83 | Shale     | 7.57            | 7.72           | 7.59                   | 19.18            | 13.90            | 0.85                        | 6.73                       |
| 84 | Shale     | 25.31           | 25.00          | 24.96                  | 17.82            | 29.87            | 22.11                       | 24.30                      |
| 85 | Coal      | 15.12           | 15.16          | 15.10                  | 18.25            | 22.37            | 10.01                       | 13.40                      |
| 86 | Coal      | 10.33           | 10.44          | 10.35                  | 18.92            | 16.49            | 4.20                        | 9.04                       |
| 87 | Coal      | 4.21            | 4.44           | 4.21                   | 20.17            | 8.99             | -3.18                       | 4.02                       |
| 88 | Coal      | 8.73            | 8.84           | 8.72                   | 19.51            | 13.41            | 2.23                        | 7.66                       |
| 89 | Coal      | 8.67            | 8.78           | 8.67                   | 19.26            | 14.27            | 2.16                        | 7.62                       |
| 90 | Coal      | 10.03           | 10.13          | 10.03                  | 19.64            | 13.61            | 3.82                        | 8.77                       |
| 91 | Coal      | 17.30           | 17.30          | 17.24                  | 19.16            | 18.45            | 12.64                       | 15.54                      |
| 92 | Coal      | 12.40           | 12.48          | 12.40                  | 19.06            | 16.91            | 6.71                        | 10.86                      |
| 93 | Coal      | 18.40           | 18.31          | 18.25                  | 17.92            | 26.14            | 13.88                       | 16.59                      |
| 94 | Coal      | 28.02           | 27.89          | 27.86                  | 17.89            | 30.40            | 25.67                       | 28.03                      |
| 95 | Coal      | 10.10           | 10.19          | 10.09                  | 19.34            | 14.69            | 3.89                        | 8.82                       |
| 96 | Coal      | 8.92            | 9.02           | 8.91                   | 19.30            | 14.24            | 2.45                        | 7.82                       |
| 97 | Coal      | 12.76           | 12.81          | 12.73                  | 18.62            | 19.16            | 7.11                        | 11.16                      |
| 98 | Coal      | 25.64           | 25.57          | 25.53                  | 18.38            | 25.85            | 22.82                       | 25.02                      |
| 99 | Coal      | 8.87            | 8.97           | 8.86                   | 19.48            | 13.60            | 2.39                        | 7.77                       |
| 100| Coal      | 10.42           | 10.54          | 10.45                  | 19.37            | 14.75            | 4.33                        | 9.13                       |
| 101| Coal      | 9.09            | 9.20           | 9.09                   | 19.57            | 13.41            | 2.68                        | 7.97                       |
| 102| Coal      | 12.94           | 12.93          | 12.86                  | 18.51            | 19.78            | 7.27                        | 11.28                      |
| 103| Coal      | 14.48           | 14.52          | 14.45                  | 18.68            | 19.68            | 9.22                        | 12.77                      |
| 104| Coal      | 9.78            | 9.88           | 9.78                   | 19.35            | 14.50            | 3.51                        | 8.55                       |
| 105| Coal      | 11.79           | 11.84          | 11.76                  | 19.01            | 16.86            | 5.92                        | 10.28                      |
| 106| Coal      | 15.38           | 15.45          | 15.39                  | 19.19            | 17.60            | 10.37                       | 13.68                      |
| 107| Coal      | 17.58           | 17.63          | 17.57                  | 18.50            | 22.05            | 13.04                       | 15.88                      |

Appendix 6: Measured and calculated values of $m_i$ based on different methods for metamorphic rocks
| No | Rock name | $m_i$ (measured) | $\frac{c}{n}$ | $m_i$ (R-index (Cai)) | $m_i$ (UCS based) | $m_i$ (TS based) | $m_i$ (Hoek–Brown (2019)) | $m_i$ (combination method) |
|----|-----------|-----------------|--------------|----------------------|-----------------|-----------------|----------------------|-----------------------------|
| 9  | Slate     | 30.97           | 31.08        | 31.04                | 7.93            | 25.31           | 29.58                | 32.44                       |
| 10 | Slate     | 22.70           | 22.66        | 22.61                | 7.20            | 48.42           | 19.23                | 21.46                       |
| 11 | Slate     | 9.50            | 9.61         | 9.50                 | 7.78            | 14.60           | 3.18                 | 8.32                        |
| 12 | Slate     | 16.85           | 16.90        | 16.84                | 8.02            | 15.82           | 12.14                | 15.13                       |
| 13 | Slate     | 14.22           | 14.29        | 14.22                | 8.49            | 8.66            | 8.94                 | 12.56                       |
| 14 | Slate     | 13.64           | 13.72        | 13.64                | 8.54            | 8.06            | 8.23                 | 12.01                       |
| 15 | Slate     | 5.99            | 6.15         | 5.99                 | 22.27           | 6.19            | -1.08                | 5.44                        |
| 16 | Slate     | 4.31            | 4.53         | 4.31                 | 21.83           | 6.15            | -3.07                | 4.10                        |
| 17 | Slate     | 2.95            | 3.25         | 2.94                 | 20.92           | 6.76            | -4.64                | 2.96                        |
| 18 | Slate     | 3.09            | 3.38         | 3.09                 | 21.03           | 6.69            | -4.48                | 3.09                        |
| 19 | Slate     | 4.35            | 4.57         | 4.35                 | 21.25           | 7.03            | -3.02                | 4.13                        |
| 20 | Slate     | 4.48            | 4.69         | 4.48                 | 21.66           | 6.47            | -2.87                | 4.23                        |
| 21 | Slate     | 4.80            | 5.00         | 4.80                 | 22.13           | 5.95            | -2.49                | 4.49                        |
| 22 | Gneiss    | 17.87           | 17.92        | 17.87                | 8.93            | 6.46            | 13.41                | 16.19                       |
| 23 | Gneiss    | 5.34            | 5.52         | 5.34                 | 8.07            | 7.54            | -1.84                | 4.92                        |
| 24 | Gneiss    | 16.23           | 16.29        | 16.23                | 8.71            | 7.55            | 11.40                | 14.52                       |
| 25 | Gneiss    | 6.39            | 6.54         | 6.39                 | 8.63            | 4.68            | -0.59                | 5.76                        |
| 26 | Gneiss    | 8.76            | 8.87         | 8.76                 | 8.64            | 5.59            | 2.27                 | 7.69                        |
| 27 | Gneiss    | 9.42            | 9.53         | 9.42                 | 8.27            | 8.51            | 3.08                 | 8.25                        |
| 28 | Gneiss    | 24.06           | 24.10        | 24.06                | 22.46           | 9.49            | 21.00                | 23.19                       |
| 29 | Gneiss    | 30.06           | 30.10        | 30.07                | 22.23           | 10.78           | 28.39                | 31.06                       |
| 30 | Gneiss    | 29.44           | 29.47        | 29.44                | 22.14           | 10.91           | 27.61                | 30.18                       |
| 31 | Gneiss    | 29.30           | 29.35        | 29.31                | 22.16           | 10.85           | 27.46                | 30.01                       |
| 32 | Gneiss    | 32.33           | 32.34        | 32.31                | 22.07           | 11.44           | 31.14                | 34.29                       |
| 33 | Gneiss    | 26.01           | 26.06        | 26.02                | 22.34           | 10.01           | 23.42                | 25.64                       |
| 34 | Gneiss    | 23.23           | 23.26        | 23.21                | 22.35           | 9.61            | 19.97                | 22.17                       |
| 35 | Gneiss    | 31.39           | 31.40        | 31.37                | 22.17           | 11.08           | 29.98                | 32.91                       |
| 36 | Gneiss    | 29.70           | 29.73        | 29.70                | 22.43           | 10.28           | 27.93                | 30.54                       |
| 37 | Quartzite | 7.36            | 7.49         | 7.36                 | 8.45            | 6.11            | 5.8                  | 6.54                        |
| 38 | Quartzite | 30.10           | 30.14        | 30.10                | 9.40            | 5.66            | 28.43                | 31.11                       |
| 39 | Quartzite | 15.72           | 15.78        | 15.71                | 8.70            | 7.46            | 10.77                | 14.00                       |
| 40 | Quartzite | 12.93           | 13.00        | 12.92                | 21.10           | 10.43           | 7.35                 | 11.34                       |
| 41 | Marble    | 7.65            | 7.77         | 7.65                 | 20.85           | 9.27            | 0.92                 | 6.77                        |
| 42 | Marble    | 8.53            | 8.64         | 8.52                 | 20.80           | 9.72            | 1.98                 | 7.50                        |
| 43 | Marble    | 6.08            | 6.23         | 6.07                 | 21.35           | 7.66            | -0.97                | 5.50                        |
| 44 | Marble    | 6.25            | 6.41         | 6.25                 | 21.00           | 8.37            | -0.76                | 5.65                        |
| 45 | Marble    | 7.15            | 7.28         | 7.14                 | 21.07           | 8.62            | 0.31                 | 6.37                        |
| 46 | Marble    | 7.09            | 7.22         | 7.08                 | 19.94           | 11.24           | 0.24                 | 6.32                        |
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