Selecting Equivalent Strength for Intact Rocks in Heterogeneous Rock Masses

Mahmoud Behnia · Ahmad Rahmani Shahraki · Zabihallah Moradian

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Abstract Many surface and underground structures are constructed in heterogeneous rock formations. These formations have a combination of weak and strong rock layers. Due to the alternation of the weak and strong layers, selecting the equivalent and appropriate geomechanical parameters for these formations is challenging. One of these problems is choosing the equivalent strength (i.e., uniaxial compressive strength) of intact rock for a group of rocks. Based on the volume of weak and strong parts and their strength, the equivalent strength of heterogeneous rocks changes. Marinos and Hoek (Bull Eng Geol Environ 60(2):85–92, 2001) presented the “weighted average method” for defining the uniaxial compressive strength (UCS) of heterogeneous rock masses based on the volume of weak and strong parts. Laubscher (1977) used the volume ratio of the strength of a weak part to a strong part (UCS weak/UCS strong) to determine the equivalent strength. In this study, the two methods are compared and their validity is evaluated by experimental data and numerical analyses. The geomechanical parameters of two heterogeneous formations (Aghajari and Lahbari) in the west of Iran were estimated using these methods. The results of the present study obtained through numerical analyses using particle flow code are compared with those of previous studies and discussed. Laboratory and numerical results show UCS decrease and approach to weak strength with an increasing in volume of weak part. When strength ratio of strong to weak rock increase, equivalent strength decrease more severely. The findings show that Laubscher’s method gives more appropriate results than the weighted average method.

Keywords Heterogeneous rocks · Uniaxial compressive strength · Weighted average method · GSI · Geomechanical parameters · Numerical analysis · PFC

1 Introduction

During the last decades, a number of rock engineering projects such as tunnels, foundations, rock slopes and railways have been constructed in the complicated geological formations known as heterogeneous rocks. Heterogeneous rocks contain at least two different geological types and have different geomechanical properties. Most of these structures are observed in the form of sedimentary and metamorphic rocks. Typically, strong layers range in thickness from a few...
centimeters to several meters. Weak layers are in the same way, but have more alternations and repetition frequencies. Flysch and molasses are characterized by rhythmic alternations of sandstone and pelitic (fine grained) rocks such as siltstones, marls, shales and clay shales. Conglomerates and limestone can also be found in this form (Tsiambaos 2010). Figure 1 shows heterogeneous rock masses with different combinations of sandstone and siltstone (Aghajari and Lahbari Formations) in the west of Iran.

Many studies have been conducted to recognize the geomechanical parameters of these formations. Selecting equivalent and appropriate strength parameters for all rock masses in these rocks is a challenge. Selecting the strength of a strong section is unrealistic and choosing the strength of a weak section is so conservative. Consequently, a useful method for estimating the geomechanical properties of heterogeneous rocks is needed.

Duffaut (1981) published a study on modeling and simulating heterogeneous rock masses, introducing the term “sandwich (single or multiple) rock mass”. Goodman (1993) highlighted the issue that the composition of a more lithological type of rock with different properties creates a complex geotechnical engineering problem. Marinos and Hoek (2001) published a GSI table for heterogeneous rocks and suggested using the weighted average method for UCS and $m_i$ parameters. Lydzba et al. (2003) used a Mathematical software package and studied composite sedimentary rock formation characterized by a periodic layered structure such as sandstone and claystone. He illustrated a decrease in the strength of composite rock with a decrease in sandstone volume. Vlasov and Merzlyakov (2004) used the asymptotic method of the averaging differential equation for composite rock specimens. Mandrone (2006) presented an engineering geological mapping in the Northern Apennines. He categorizes heterogeneous rock masses in study fields into three different groups and points out that, from a technical point of view, different heterogeneous geological formations cannot be distinguished from each other due to the large number of formations and the inherent problem in determining single values for the Hoek–Brown parameters. Marinos et al. (2006) conducted research on the Egnatia motorway in Greece and estimated rock mass properties of heavily sheared Flysch. The results showed that the value of the uniaxial compressive strength of the intact rock was lower than the one assumed for the design. Sensitivity analyses showed that the differences in the unconfined strength value for such tectonically disturbed weak geomaterial are most critical in the evaluation of the deformations of the tunnel.

Liang et al. (2007) studied bedded salt rocks and pointed that UCS is governed by the weakest material. Tziallas et al. (2013) estimated the rock strength of layered samples made of sandstone and siltstone with different ratios (Fig. 2). They conducted laboratory tests on six types of specimens with different percentages of siltstone, and then evaluated the UCS and Young Modulus of these samples.

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Fig. 1 Heterogeneous rock masses composed of sandstone and siltstone (a Aghajari, b Lahbari formations)
According to the results, the strength of the specimen decreased with increasing the siltstone percentage. Mohamed et al. (2008) did a series of laboratory tests on the heterogeneous formations of Kenny Hill. Their specimens were made of sandstone with shale interlayers in different ratios. The results showed that the shale played a critical role in the composition. The increase in the shale percentage caused a decrease in the overall strength of the specimens whose strength was close to that of the shale.

Budetta and Nappi (2011) described an application of the geological strength index (GSI) method to the San Mauro formation, which is characterized by sandstones alternating with argillaceous marls. They used the weighted average method and classified the geomechanical formation to four classes based on the Sandstone/Pelite ratio and three GSI ranges. They mentioned that, due to the Flysch complex structure, better results could be obtained on small areas using a large number of field surveys. Marinos (2014) used the special geological strength index (GSI) chart for heterogeneous rock masses, and presented a range of geotechnical parameters for every flysch type. He presented the standardization tunnel behavior for every rock mass type of flysch, based on its site-specific geotechnical characteristics such as structure, intact rock strength, persistence and complexity of discontinuities. Pepe et al. (2015) used the GSI method for highly heterogeneous Flysch and noted that the highly heterogeneous rock composition plays a key role in determining the overall mechanical behavior. The increase in the amount of weak rock in comparison to that of strong rock can lead to an isotropic behavior. More details on heterogeneous rock structures and their classifications can be found in Marinos (2010) and Tziallas et al. (2013).

Yue et al. (2016) studied calibration of stiffness and strength for layered rock. They mentioned that “the overall strength of layered rocks is useful for predicting their stability or failure under production conditions, which may contribute to vertical height containment of hydraulic fractures in an unconventional reservoir”. In their study, they used PFC3D simulations to evaluate the contributions of layers properties (e.g., number, thickness, and sequence) on the average strength of a layered reservoir. Their simulation results showed that the stiffness and strength of a layered rock was affected by the proportions and ratios of hard and weak layers.

Most of the studies on composite and heterogeneous rocks have indicated that the overall strength of rock is influenced by the weak part. The strength and volume of weak rocks control geomechanical parameters, hence the heterogeneous GSI table developed by Marinos and Hoek (2001). However, some studies on heterogeneous rocks have indicated that estimating and selecting the equivalent and appropriate strength of these materials are challenging and require further research.

Although previous investigations studied the strength of composite samples, but due to need of faster and convenient estimation of this parameter in the engineering project, the existing methods (Laubscher, weighted average) should be compared with laboratory and numerical results and the ability of them must be check. Therefore, in this study, the methods for estimating the equivalent strength in heterogeneous formations (Laubscher 1977), and weighted average methods are reviewed. In addition, the methods are compared together using the
laboratory results from previous research and numerical result of PFC, the geomechanical parameters of Aghajari and Lahbari formations in the west of Iran are evaluated and compared with the laboratory and numerical results of modeling by PFC.

2 Geomechanical Parameters of Heterogeneous Rocks

Hoek and Brown (1997) proposed a criterion for estimating rock mass properties. The Hoek and Brown criterion assumes that rock mass is isotropic and needs three parameters (i.e., UCS, GSI and $m_i$) for evaluating rock mass geomechanical parameters. Marinos and Hoek (2001) and (2005) extended this criterion to estimate the properties of heterogeneous rock masses such as Flysch. Marinos et al. (2007) updated the GSI table for heterogeneous rocks. Marinos classified Flysch into eleven types and described each one. These types are based on the siltstone/sandstone ratio and their disturbance due to tectonic activity. Many studies have used this table for evaluating the GSI of heterogeneous formations.

The main challenge for estimating the geomechanical parameters of heterogeneous rocks is selecting the appropriate parameters of intact rock (i.e., $\sigma_{ci}$ and $m_i$) for the Hoek and Brown criterion. Heterogeneous rocks are layered and consist of different materials with different strengths. However, we need an equivalent strength for designing of structures in these rocks. The properties of the strong part doesn’t represent the rock mass characteristics. In addition, selecting the weak part underestimates the rock mass strength and is a conservative selection. Consequently, for calculating the strength of intact rock, Schmidt hammer, point load and uniaxial compressive tests are recommended. Schmidt hammer has large dispersion, and the point load test is not suitable for soft rocks. Consequently, uniaxial compressive strength is the best method to estimate the strength of intact rock. Sample preparation should be carefully considered in this method.

The constant $m_i$ depends on the frictional characterization of the constituent minerals. The constant is determined by the Triaxial test or obtained from the qualitative description of the rock material. Hoek and Brown described the constant $m_i$ for different rock types (Marinos and Hoek 2001). This parameter, compared to GSI and UCS, has less impact on strength parameters.

Marinos et al. (2007) suggested the weighted average method to obtain the equivalent UCS for heterogeneous rocks (Table 1).

Laubscher introduced a chart for estimating intact rock strength (IRS) where the rock mass contains weak and strong zones (Fig. 3). He introduced this method for the In-site Rock Mass Rating system (IRMR) and the Mining Rock Mass Rating system (MRMR) as an extension of the Bieniawski’s RMR system for mining applications. One of the parameters examined by this method is UCS. For example, if the strength ratio of the weak part to the strong part is 30%, and 30% of the total volume of the rock mass is weak, the equivalent strength is equal to 55% of the strength of the strong part (Read and Stacey 2009).

3 Case Study: Konjancham Tunnels

3.1 Geological Features of the Study Area

To study the existing methods and to compare their accuracy in calculating geomechanical parameters, laboratory and field data of two formations (Aghajari and Lahbari) in the west of Iran were used. The formations consisted of heterogeneous rock masses with alternations of siltstone and sandstone layers. The Aghajari formation, in its type section, consisted of 2966-m alternation layers of brown to gray calcareous sandstones, red marls with gypsum interlayers, and red siltstones (Motiei 1993). The Lahbari Member refers to a rock unit that is essentially the same as the one previously called the lower Bakhtiari. However, the criteria used for defining the Lahbari Member differ from those used to define the lower Bakhtiari (James’ and Wynd 1965). In the Aghajari formation, about 40% of the total volume was sandstone, whereas sandstone composed 20% of the total volume in the Lahbari formation. Tunnel KT 1 (4.96 km long) and tunnel KT 2 (12 km long) were excavated by TBM in Aghajari and Lahbari formations, respectively (Fig. 4). Weak and Strong layers were different in volume and percentage along the tunnels.
3.2 Field Data

To obtain the essential data on these formations and rock masses in direction of the tunnels and to perform the laboratory tests, five boreholes (total length = 183 m) were drilled in the Aghajari formation and nine boreholes (total length = 645 m) were drilled in the Lahbari formation. The selected samples were delivered to a rock mechanics laboratory. The

| Flysch type | Suggested proportions of $\sigma_{ci}$ and $m_i$ for estimating rock mass properties of Flysch (Marinos et al. 2007) |
|-------------|---------------------------------------------------------------------------------------------------------------|
| I, III      | Use values for sandstone beds                                                                                 |
| II, VI, XI  | Use values for siltstone or shale                                                                              |
| IV          | Thin beds: Reduce sandstone values by 10% and use full values for siltstone thick beds: use equivalent values for siltstone and sandstone beds |
| V, VII, VIII| Reduce sandstone values by 20% and use full values for siltstone                                                |
| IX          | Use equivalent values for siltstone and sandstone beds according to their participation                         |
| X           | Reduce sandstone values by 40% and use full values for siltstone                                              |

Fig. 3 Laubscher’s chart: evaluating an equivalent IRS value in heterogeneous rock samples of intact rock (Laubscher 1977)
values of Rock quality designation (RQD) and their distribution for Aghajari and Lahbari formations are shown in Fig. 5. As can be seen, the RQD value for the Lahbari formation is higher than that for the Aghajari formation. This is due to increase in sandstone and consequently increasing discontinuities in the Aghajari formation. The histogram of discontinuities spacing of Lahbari and Aghajari formations is presented in Fig. 6.

According to the geological and structural mapping of rock masses and based on the GSI chart (Marinos et al. 2007), geological strength index was evaluated.
3.3 Petrographic Analysis

The micro-petrographic description of rocks for engineering purposes includes determining all parameters which cannot be obtained from a macroscopic examination of a rock sample. These parameters include mineral composition, grain size, texture, weathering degree, porosity and micro fracturing (ISRM 1977). Using macroscopic descriptions and thin section analyses, the following three main rock types have been distinguished: sandstone, siltstone and clay siltstone.

Clay Siltstone has very fine grained clastic texture and clay minerals such as muscovite (Fig. 8a). Fine grained texture with coarse crystalline minerals such as quartz, feldspar and calcite has been found in siltstone (Fig. 8b).

Sandstone consists of calcite cement with coarse crystalline minerals such as quartz, plagioclase, and chlorite, and rock fragments such as chert and quartz (Fig. 8c).

3.4 Laboratory Data

The site investigation plan consisted of field surveys and laboratory tests for siltstone and sandstone rocks. The UCS of sandstone and siltstone were estimated by uniaxial compressive tests. Siltstone samples were prevented from weathering and decomposition and loss of their natural moisture by wax to deliver of them to the rock mechanics laboratory. Because of the reaction of siltstone with water in the saturation process the samples were saturated under confined pressure in the soil triaxial cell. The results of rock mechanical tests on the samples are presented in Table 2.

Due to the frequency of sandstone and siltstone layers and their variable thickness, geomechanical parameters varied along the tunnels. Consequently, the equivalent parameters for rock masses were used for the stability analysis of the tunnels. The reinforcement systems such as segment thickness in mechanized excavation cannot vary with alternating soft and hard layers in a short length. Thus, selecting the equivalent strength for intact rock is a challenging problem.

For selecting the appropriate amount of UCS, the weighted average method and the Laubscher’s method were used. The Aghajari formation consists of about 40% sandstone and 60% siltstone, and Lahbari formation consists of 20% sandstone and 80% siltstone. According to the strength of siltstone and sandstone and the GSI of the formations, the UCS for the Aghajari and Lahbari formations evaluated by the weighted average method were 9.8 and 6.4 MPa, respectively; The UCS for the Aghajari and Lahbari formations evaluated by the Laubscher’s method were 4.6 and 3.6 MPa, respectively. For both formations, the selected $m_i$ value was 7.
GEOLOGICAL STRENGTH INDEX (GSI) FOR HETEROGENEOUS ROCK MASSES SUCH AS FLYSCH
(V. Marinos, 2007)

Heterogeneous rock masses are made those with alternating layers of clearly different lithology types with significant differences in their strength properties. For flysch, a typical formation with heterogeneous rock masses, these alternations are consisting of sandstones and siltstones. Clay shales may be present. From a description of the lithology, structure and surface conditions of discontinuities (particular of the bedding planes), choose a box in the chart. The selection of the structure should be based on the tectonic disturbance (undisturbed, slightly disturbed, strongly disturbed - folded, desintegrated, sheared), the proportion of siltstone against sandstones and the expressed or not stratiﬁcation inside the siltstone layers. In the type IV and V when the thickness of sandstone beds exceed 50 cm an increase of the GSI value by 5 is suggested. From type IV and the following types, the stratiﬁcation planes are perceptible inside the siltstone mass. Locate the position in the box that corresponds to the conditions and estimate the average value GSI from the contours. The determination of the structure and the condition of discontinuities may range between two adjacent ﬁelds. Note that the Hoek - Brown criterion does not apply to structurally controlled failures. Where unfavourably oriented continuous weak planar discontinuities are present, these will dominate the behavior of the rock mass. The strength of some rock masses is reduced by the presence of groundwater and this can be allowed for by a slight shift to the right in the columns for fair, poor and very poor conditions. Water pressure does not change the value of GSI and it is dealt with by using effective stress analysis.

STRUCTURE AND COMPOSITION

**TYPE I.** Undisturbed, with thick to medium thickness sandstone beds with sporadic thin ﬁlms of siltstone. In shallow tunnels or slopes where conﬁnement is poor the mode of the failure has a kinematic character controlled by the bedding planes and GSI is meaningless.

**TYPE II.** Undisturbed massive siltstone (stratiﬁcation planes are imperceptible) with sporadic thin interlayers of sandstones

**TYPE III.** Moderately disturbed sandstones with thin ﬁlms of interlayers of siltstone

**TYPE IV.** Moderately disturbed rockmass with sandstone and siltstone similar amounts

**TYPE V.** Moderately disturbed siltstones with sandstone interlayers

**TYPE VI.** Moderately disturbed siltstones with sparse sandstone interlayers

**TYPE VII.** Strongly disturbed, folded rock mass that retains its structure, with sandstone and siltstone in similar extend

**TYPE VIII.** Strongly disturbed, folded rock mass, with siltstones and sandstone interlayers. The structure is retained and deformation - shearing is not strong

**TYPE IX.** Desintegrated rockmass that can be found in wide zones of faults or/and of high weathering. In this type mainly brittle material is present with some disturbed siltstones between rock pieces

**TYPE X.** Tectonically deformed intensively folded faulted siltstone or clay shale with broken and deformed sandstone layers forming an almost chaotic structure

**TYPE XI.** Tectonically strongly sheared siltstone or clayey shale forming a chaotic structure with pockets of clay. Thin layers of sandstone are transformed into small rock pieces. Ultimately the ground behavior is that of a soil

**N/A** Means geologically impossible combination. In the non-shadowed areas, such rockmasses are not impossible to find but it is very unusual

**Direction of tectonic disturbance and deformation of equivalent rockmass lithology**

**DECREASE OF THE QUALITY OF DISCONTINUITIES**
Fig. 7  GSI selected for the LA (Lahbari) and AG (Aghajari) formations along with the GSI table for heterogeneous rocks (Marinos et al. 2007)

Fig. 8  Thin sections of the rock sample: a clay siltstone, b siltstone and c sandstone

Table 2  Laboratory results for sandstone and siltstone

| Formations            | Rock type | Quantity | Density (gr/cm$^3$) | Porosity (%) | Mechanical parameters |
|-----------------------|-----------|----------|--------------------|--------------|-----------------------|
|                       |           |          | Dry     | Sat.    |                       | Number of test | UCS (Mpa) | mi | Ei (GPa) |
| Aghajari and Lahbari  | Siltstone | Mean     | 2.29    | 2.44    | 17.16                  | 38            | 3     | 4  | 1.1      |
|                       |           | SD       | 0.10    | 0.06    | 3.35                   |               |        |    |          |
|                       | Sandstone | Mean     | 2.31    | 2.44    | 16.51                  | 20            | 20    | 9  | 5        |
|                       |           | SD       | 0.14    | 0.03    | 5.30                   |               |        |    |          |

Fig. 9  Hoek and Brown curves for rock masses and formations obtained through the weighted average method and the Laubscher’s method
3.5 Geomechanical Parameters

Figure 9 shows the curve of Hoek and Brown criteria for two formations, different rock types and various calculation methods. Table 3 presents the geomechanical parameters of rock masses in these formations. The parameters depend on the sandstone/siltstone ratio and the selected method.

The results show that the weighted average method provides higher values than the Laubscher’s method. The results of the weighted average method and the Laubscher’s method are close to the results of the strong part (sandstone) and the weak part (siltstone), respectively. Consequently, there is a significant difference between the values obtained through the weighted average method and those obtained through the Laubscher’s chart.

To choose the appropriate curve between the results of the two presented methods, some experimental investigations are reviewed. Afterwards, the results of the investigations are compared with those of the numerical analysis by PFC for a laboratory simulation test, and discussed.

4 Numerical Analysis

For more results and better comparison between the laboratory result and the equivalent UCS concluded from the average method and the Laubscher method, we decided to conduct tests such as laboratory tests with a similar ratio of the strength of the strong part to the strength of the weak part. We also conducted numerical analyses by PFC2D, developed by the ITASCA Consulting Group. Potyondy and Cundall summarized how the approach was developed and provided an example application using the PFC for a tunnel in massive granite (Cho et al. 2007).

In numerical modelling by computer programs such as FLAC and UDEC, macro mechanical properties (e.g., Young modulus, passion ratio, uniaxial compressive strength, friction angle etc.) are directly used for modeling. In PFC2D, aid is the calibration of micro-contact parameters to match the macro-scale response with selecting the appropriate micromechanical parameters. A model can be built to be consistent with using the uniaxial compressive test and the Brazilian test. In the process of estimating these parameter, the parameters are first created using a PFC program and then changed to micro parameters to achieve the optimum results close to the experimental results. For modelling, we selected two different materials with different strength properties and the strength ratio of 2.4. These two model (A and B) are composed by cement and kaolinite with different ratio of material weight for different strength and stiffness behavior by Tien et al. (2006). The strength ratio in the laboratory study by Tziallas et al. was 2.2. The aim of these modelling was providing fairly similar samples and a better investigation so that the numerical results and the laboratory results could be compared more effectively and discussed. The mechanical properties of the two materials (i.e., A and B) are shown in Table 4.

Models were made using a computer program according to the uniaxial compressive strength test. For calibrating samples most easily and classifying them into layers with different volume ratios, we prepared cylindrical samples that were 100 mm long and 50 mm in diameter. First, we made two samples with 100% volume of A and B structures. Then, we prepared eight other samples with different specified volume ratios of the weak structure (B) (Fig. 10).

| Rock/formation type        | $\sigma_{ci}$ (MPa) | $\sigma_r$ (MPa) | $\sigma_z$ (MPa) | $\sigma_{cm}$ (MPa) | $E_m$ (MPa) | $C$ (MPa) | $\Phi$ ($) |
|----------------------------|---------------------|------------------|------------------|--------------------|------------|----------|-----------|
| Sandstone                  | 20                  | -0.05            | 1.20             | 3.32               | 4472.1     | 0.96     | 29.2      |
| Aghajari weighted method   | 9.8                 | -0.1             | 1.39             | 2.09               | 7423.6     | 0.58     | 31.8      |
| Aghajari Laubscher’s method| 4.6                 | -0.05            | 0.65             | 0.98               | 5086.0     | 0.27     | 31.8      |
| Lahbari weighted method    | 6.4                 | -0.03            | 0.51             | 1.06               | 3373.6     | 0.31     | 29.0      |
| Lahbari Laubscher’s method | 3.6                 | -0.02            | 0.29             | 0.59               | 2530.2     | 0.18     | 29.0      |
| Siltstone                  | 3.0                 | -0.05            | 0.42             | 0.53               | 4107.3     | 0.16     | 26.9      |
Results of the uniaxial compressive strength of the samples are presented in Fig. 11 and Table 5. The results show the failure process of samples are similar to previous studies on failure process of composite samples like Liang et al. (2007). When the sample only made of A or B material, the total failure was occurred in the whole of the sample. With increasing the weak part in the sample to 25%, the micro cracks mostly are initiated in the weak part and after that the failure occurred only in the weak part.

According to Fig. 12, samples made of the strong structure (A) had the maximum strength. As the volume ratio of the weak part in the samples increased, the UCS decreased gradually until it reached the minimum (i.e., the sample with 100% of the weak structure). Figure 13 shows the effect of increasing the volume ratio of the weak structure in the samples.

As can be seen in Fig. 13, the strength of sample A, completely made of the strong structure, was 103.53 MPa. As the volume of the weak structure in the sample increased by 5%, the equivalent strength decreased and reached 81.31 MPa. The strength of sample B, completely made of the weak structure, was 43.51 MPa. As evident by numerical modelling, as the volume ratio of the weak structure increased,

Table 4 Mechanical properties of the materials A (hard) and B (weak) (Tien et al. (2006))

| Material | $\sigma_c$ (MPa) | $\tau$ (MPa) | $E$ (GPa) | Passion’s ratio | Friction angle(°) | Dry density (KN/m3) |
|----------|-----------------|--------------|-----------|-----------------|---------------------|---------------------|
| A        | 104.2           | 9.6          | 21.7      | 0.23            | 29                  | 21.5                |
| B        | 43.3            | 3.9          | 11.9      | 0.21            | 25                  | 17.6                |

Fig. 10 Three samples with different volume ratios of the weak part (10, 40 and 90%, respectively)

Fig. 11 Failure of and crack initiation in all samples with different volume ratios of the weak part

Fig. 12 Three samples with different volume ratios of the weak part (10, 40 and 90%, respectively)
equivalent UCS decreased sharply, confirming the laboratory results. The strength of the model with 20% of the weak structure was 46.11 MPa, similar to that of the model with 100% of the weak structure. As the volume of the weak structure in the samples was more than 20%, no significant change was seen in the equivalent UCS. Effectively, the equivalent UCS remained relatively stable, the same as the strength of the weak sample (B).

### 5 Discussion

To make a fair decision, we should compare the Laubscher’s method and the laboratory and numerical methods with similar strength ratios. The strength ratio of the laboratory and numerical results was 2.22 and 2.38, respectively. We selected 2.4 as the strength ratio of the Laubscher’s method. All three ratios were very similar and the results could be compared together and
analyzed. We first briefly review the laboratory results and then compare them with the numerical and Laubscher’s results.

The strength ratio of sandstone to siltstone in the study by Tziallas et al. (2013) was 2.2. As can be seen in Fig. 14, strength decreases rapidly at the first part of the curve, and the strength of the sample is close to that of the siltstone when there is 37% of siltstone. No significant reduction is observed at the second part of the curve, and the strength of the samples is equal to that of the siltstone. The parameter $m_i$ decreased as the siltstone part increased. This is similar to the alteration of the uniaxial compressive strength ($\sigma_{ci}$) when there was a percentage of siltstone in the sample (Tziallas et al. 2013). Mohamed et al. (2008) studied the effect of different percentages of shale in sandstone samples. The strength ratio of sandstone to shale was 4.43. In samples with 10% of shale, the strength decreased approximately 70%.

An increase in the compressive strength ratio of rocks (hard/weak strength) resulted in more decrease in the equivalent compressive strength as the percentage of the low-strength material increased. The results of the studies by Tziallas et al. (2013) and Mohamed et al. (2008) are presented and compared in Fig. 15.

The data obtained through the Laubscher’s method indicate that strength decreases as the weak volume ratio increases (Fig. 16). Careful attention reveals that

![Fig. 14 UCS reduction as siltstone percentage increases (Tziallas et al. 2013)](image-url)

![Fig. 15 Anticipated behavior of heterogeneous materials with $\sigma_{ci}/\sigma_{ci}$ hard ratios and different weak material percentages reported by Tziallas et al. and Mohamed et al.](image-url)
the initial and final sections of the graphs for the three methods are much similar. Comparing the results of the Laubscher’s method and the laboratory test indicate that the strength ratio of the strong rock to the weak rock and siltstone percentage changed (Fig. 17). The results show that the total strength of the sample decreases as the siltstone percentage increases, confirming the laboratory results. However, the strength of the materials used in the laboratory tests decreased rapidly. The decrease in the strength of the materials used in the laboratory tests was greater than that of the materials used in the Laubscher’s method. Accordingly, the parameters evaluated by the weighted average method were higher than the actual results. The weighted average method underestimated the effect of the weak sections. However, the laboratory tests and the numerical analysis results showed that the weak sections had a significant impact on the strength and fracture behavior of rock, and controlled the overall rock mass behavior. Fracture type that occurs in the numerical models is similar to the laboratory samples. It is obvious that with increasing of weak part, fractures and cracks propagate in the weak part of samples both in the laboratory samples (Fig. 2) and numerical models (Fig. 11). Thus, the geomechanical parameters evaluated by the

**Fig. 16** Results of the three methods: laboratory method, numerical method and Laubscher’s method

**Fig. 17** Estimated values of $\sigma_{ci}$ in different strength ratios and siltstone percentages via the Laubscher’s chart
Laubscher’s method were more consistent with the laboratory and numerical results. Consequently, this method is proposed to be used for heterogeneous rock masses.

6 Conclusions

Selecting the appropriate geomechanical parameters for layered rock masses and heterogeneous rocks is important. The GSI chart presented by Hoek and Marinos is used for describing heterogeneous geology formations, but estimating the equivalent strength of intact rock by the weighted average method, recommended by Hoek and Marinos, does not represent rock masses. On the other hand, the equivalent UCS, derived from the Laubscher’s method, is more reasonable compared to laboratory and numerical results. Particularly, previous studies have also noted the influence of the weak layer on the total strength, being in line with the results of the present study.

However, the methods for selecting the equivalent parameters for heterogeneous rocks need to be investigated further. Furthermore, additional tests for layered samples with different ratios of the strength and weak material percentages are needed to achieve acceptable results and methods.

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