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Estimation of Strength Envelope of Rocks in the Athens Schist Formation

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Abstract: *This study evaluates the strength envelope of rock masses from the Athens Schist Formation using the Hoek-Brown failure criterion and RSData simulations. The primary objective of the study is to correlate theoretical data with modeled rock mass strength parameters, which focuses on greywacke, limestone, and sericite sandstone. Hoek-Brown constants (mb, s, and a) were calculated using parameters like UCS, GSI, and mi, demonstrating how geological characteristics like blockiness and joint conditions affect rock strength. According to the analysis, limestone and sericite sandstone had higher strength values, while greywacke, which had the lowest GSI, had the weakest strength characteristics. However, the simulations tended to overestimate some parameters compared to accepted benchmarks, highlighting the drawbacks of modeling with indirect data. The study suggests improving future estimates of rock mass strength and emphasizes the significance of field validation and cautious parameter selection for precise geotechnical analysis.*

Keywords: Rock mass strength, Hoek-Brown failure criterion

1. INTRODUCTION

The Hoek-Brown failure criterion is the relationship between the increasing peak strength of isotropic rock and increasing confining stress. The relationship follows a non-linear graph and is parabolic in form, making it particularly suited for geotechnical applications where rock mass behavior deviates from idealized conditions. Although this criterion was initially developed for intact rocks, Hoek et al. [1] introduced various parameters such as broken rock mb, the exponential term a, and parameters that consider GSI [2] and disturbance factor D [3] to account for blast damage and stress relaxation, which were defined as gaps between theoretical models and field conditions.

The Hoek-Brown failure criterion is one of the widely accepted methodologies for evaluating the strength of the rock, where its applications can be used to assess the stability of the slope, guide excavation methods, and structural design in rock environments. However, geotechnical engineers must distinguish the strength of intact rock samples measured in laboratory conditions against the performance of in-situ rock masses that contain natural discontinuities. It is because intact rock cores may have idealized measurements that differ from field observations, as natural rock masses contain discontinuities such as fractures and joints that control the mechanical behavior of the rock. However, in nature, rocks are rarely intact; they exist as rock masses, characterized by fractures, joints, and other discontinuities that dominate their mechanical response. Moreover, in practice, these forms of discontinuities may govern as failure mechanisms, indicating that the rock mass may fail along a pre-existing weakness plane even if the laboratory tests indicate high intact strength.

The Athens Schist Formation, which was the selected research paper by Hoek et al. [4], exemplifies these challenges. In the case of the Athens Schist Formation, it varies widely in its composition of rocks from strong or medium strong to weak rocks. This affects the overall strength wherein the weakest structural discontinuities (i.e., schist layers), especially near-surface, govern [5]. Near the surface, where weathering is most intense, the rock mass behavior is often controlled by these discontinuities rather than the intact material. Understanding this transition from intact to fractured rock is vital for accurate stability assessments, excavation planning, and support design in engineering projects [6,7].

The primary objective of the paper is to evaluate the rock characteristics of the Athens Schist Formation using the data provided by the researchers and establish the strength envelope through the RSData. To accomplish this objective, the following are set as the sub-objectives of the study.

a) To examine the theoretical data of the rock samples in the study.
b) To determine and simulate the experimental data of the rock samples in the study through RSData.
c) To interpret the strength envelope of the selected rocks from RSData and understand the relationship between different parameters of the rock.

2. MATERIALS

In the study of Marinos and Hoek [5], various rock types present in the Athens Schist Formation were studied. The types of rocks that were chosen for analysis were Limestone, Sericite sandstone, and Greywacke. Among the various rocks that were in the study, these were the samples that were considered, as all of these are sedimentary rocks. It was determined that analyzing the differences between sedimentary rocks would be beneficial in deepening our understanding of each material.

2.1. Limestone

Limestone is a sedimentary rock that is composed of calcium carbonate, which is typically in the form of calcite minerals. It is formed through the accumulation and lithification of organic matter and chemical precipitates in shallow marine environments. It is a rock that is typically blocky, where it consists of angular blocks that are formed due to intersecting discontinuities such as folds, faults, or joints. The discontinuity surface was found to range from fair to poor quality as it is prone to weathering or slickensiding. This form of rock was found to have a high intact strength with a uniaxial compressive strength of 54 MPa and a Hoek-Brown coefficient (m_i) of 10, which is the typical value for carbonate rocks. The GSI for limestone is estimated to range from 40 to 60, which reflects its blocky structure with fair to discontinuous conditions. The shear strength parameters of this rock include a cohesion of 1.9 MPa to 2.7 MPa. Its deformability is reported to range from 5 to 20 GPa, mainly depending on the density of the fracture and the presence of weathering. It primarily exhibits moderate to high strength but is susceptible to weathering and tectonic weakening, which can reduce its stability.

2.2. Sericite Sandstone

Sericite Sandstone is a type of sandstone present within the Athens Schist Formation, which exhibits a blocky structure consisting of angular blocks. Its name is derived from the presence of sericite, which is a fine-grained muscovite mica that gives it a distinctive foliated appearance. The mineral composition of this type of sandstone typically consists of quartz grains, sericite mica, and trace amounts of chlorite and iron oxides. Its discontinuity conditions range from fair to very poor quality, as it is also prone to weathering and to becoming slickensided. Its intact strength is reported to have a UCS of 37 MPa and a Hoek-Brown coefficient (m_i) of 19, which is characteristic of sandstone compositions. The GSI for sericite sandstone ranges from 40 to 60, which is a reflection of its blocky structure and its discontinuity conditions. The parameters of the rock in terms of shear strength were defined to range from 1.5 MPa to 1.9 MPa and a friction angle of 35° to 39°. Its deformation modulus ranges from 5 to 20 GPa but can be significantly reduced due to foliation and shearing, which reduces its mechanical performance, especially in heavily disturbed zones of the rock mass.

2.3. Greywacke

Greywacke is a variety of sandstone that is characterized by its dark color. The mineral composition of the rock is characterized by poorly sorted angular grains of quartz, feldspar, and small rocks of lithic fragments set in a compact fine clay and muddy matrix [8]. This type of sandstone is most abundant in New Zealand as it comprises a large percentage of their bedrock. It is a hard rock that is gritty to touch, veined, and non-vesicular. Compared to most sandstones, Greywacke contains less amounts of quartz, but more amounts of feldspars, volcanic rock fragments, silt, and clay. Greywacke is commercially used as an aggregate and as an armor rock in seawalls and the construction industry.

If compared to the previous rock samples, greywacke has a considerably weaker UCS of 25 MPa and a Hoek-Brown coefficient (m_i) of 18. The GSI of this rock sample is lower as it ranges from 22 to 38, which indicates a poor rock mass structure and poor surface conditions. The cohesion is 0.6 to 0.8 MPa, and the friction angle range is 29° to 34°. The deformation modulus is lower, which was indicated to fall within the range of 1–10 GPa. Greywacke's strength and deformability are highly influenced by discontinuity conditions, such as weathering and shearing, making it weaker compared to limestone and sericite sandstone.

3. METHODS

The researchers used RSData to graph the principal stress plots and the normal/shear stress plot of limestone, sericite sandstone, and greywacke. The parameters were established based on various studies focusing on the behaviour and parameters of these materials.

Table 1. Hoek Brown Classification and Criterion

Material	UCS	GSI	m_i	m_b	s	a
Limestone	54	50	10	1.677	0.00387	0.506
Serecite Sandstone	37	50	19	3.186	0.00387	0.506
Greywacke	25	30	18	1.478	0.00042	0.522

Table 2. Rock Mass Parameters of Selected Rocks

Material	Tensile Strength	Uniaxial Compressive Stregth	Global Strength	Modulus of Deformation
Limestone	0.125	3.252	9.414	6143.718
Serecite Sandstone	0.045	2.228	8.79	6143.718
Greywacke	0.007	0.43	3.713	1627.662

Table 3. Rock Mass Parameters of Selected Rocks (cont.)

Material	$\sigma_{3,max}$	Cohesion	Friction Angle
Limestone	1.119	0.641	50.452
Serecite Sandstone	1.112	0.563	53.154
Greywacke	0.029	0.313	44.108

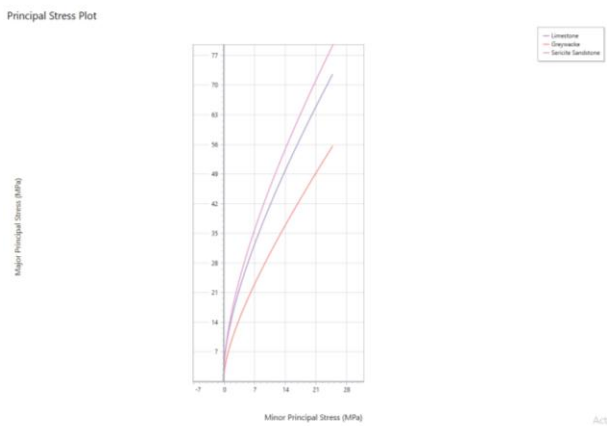

Fig. 1. Principal Stress Plot of Selected Rocks

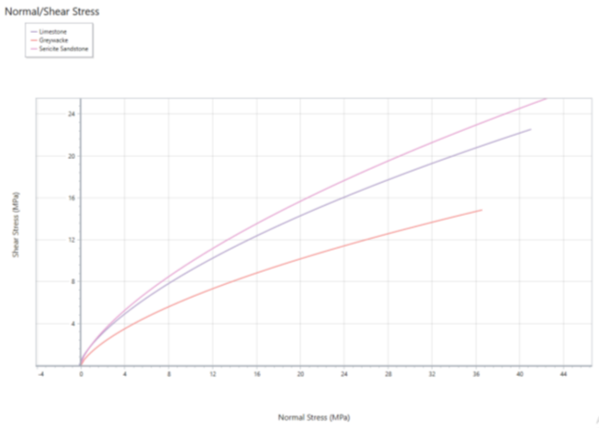

Fig. 2. Normal/Shear Stress Plot of Selected Rocks

4. DISCUSSION

4.1. Parameters

Hoek & Brown utilized the GSI classification as an influencing factor on a rock mass's mechanical properties, that is, the rock's structure or blockiness and the condition of its joints [9]. The classification of GSI was found to play a role in the rock mass behavior of the three selected lithologies, where it was found that the intact properties of the rocks in terms of their UCS and m_i—have a direct impact on the derived Hoek-Brown parameters of m_b, s, and a, which revealed differences when compared to their respective principal stress and normal stress plots as seen in Figures 4 and 5. This indicates that the plots' differences may be directly tied to their geological characteristics.

The parameter m_i is derived from the triaxial test of the sample rock where the unconfined compressive strength of intact rock, σ_{ci}, is measured and fitted into a curve, and therefore results in the rock mass of intact rock. Meanwhile, the mass of broken rock, m_b, is a reduced value m_i after having taken into account the GSI value of the rock sample, as this covers the blockiness and condition of the joints in the rock. The constant a accounts for the strength values of rocks in poorer conditions put under relatively low normal stresses [10].

In comparison to a Mohr-Coulomb plot where the failure is represented by a straight line falling adjacent to the Mohr stress circles, the Hoek-Brown trendline follows a curve that tries to take into following the shape of the curves of the stress circles using the constants m_b, s , and a . This implies that it creates a more accurate visual representation of graphing a rock sample's failure criteria relative to the sample's major and minor stresses.

Constants m_b , s , and a are calculated using the following equations:

$$m_b = m_i \, exp[(GSI - 100) \, / \, (28 - 14D)] \qquad \text{Eq. 1}$$

$$s = exp[(GSI - 100) \, / \, (9 - 3D)] \qquad \text{Eq. 2}$$

$$a = \frac{1}{2} + \frac{1}{6}(e^{-GSI/15} - e^{-20/3}) \qquad \text{Eq. 3}$$

As seen in Table 1, both limestone and sericite sandstone have the same GSI value, resulting in the same s and a constant value. On the other hand, all values have different m_i values, which means varying m_b values. Figure 2 also depicts that greywacke, although having a higher value for the constant a, resulted in a slightly more linear curve compared to both limestone and sericite sandstone.

4.2. Influence of physical properties of rock on strength values

Ultimately, the influence of the rock's GSI value will affect all the strength values, as seen in Tables 2 and 3. The Geological Strength Index (GSI) chart developed by Hoek and Marinos [11] offers a visual framework for calculating the GSI value of jointed rock masses based on two important variables: surface conditions and structure. From "Intact or Massive" (strong, unfractured rock) to "Laminated/Sheared" (heavily fractured or foliated rock with little to no interlocking), the structure column classifies rock masses according to the degree of interlocking and blockiness. Surface condition descriptors range from "Very Poor" (heavily weathered, soft, or clay-filled joints) to "Very Good" (rough, fresh surfaces with tight interlocking). To help engineers estimate the mechanical behavior of rock masses without conducting direct testing, these two axes intersect to define GSI values.

According to the GSI chart, the GSI value of 50 for limestone and sericite sandstone implies that the characteristics of both rocks are very blocky with good to fair surface quality. This is compared to the GSI value of 30 seen in greywacke, where it is interpreted as disturbed rock with fair to poor surface quality. Characteristically speaking, a heavily jointed rock that features a blocky structure will present weaker strength values. This is consistent with the plots generated in Figure 1 and Figure 2, as the greywacke's curve line presents a weaker trend and a lesser representation of strength values. This continues to the strength values in Tables 2 and 3, where the values generated by the parameters of greywacke produce significantly lower strength values despite it having a higher m_i value compared to limestone.

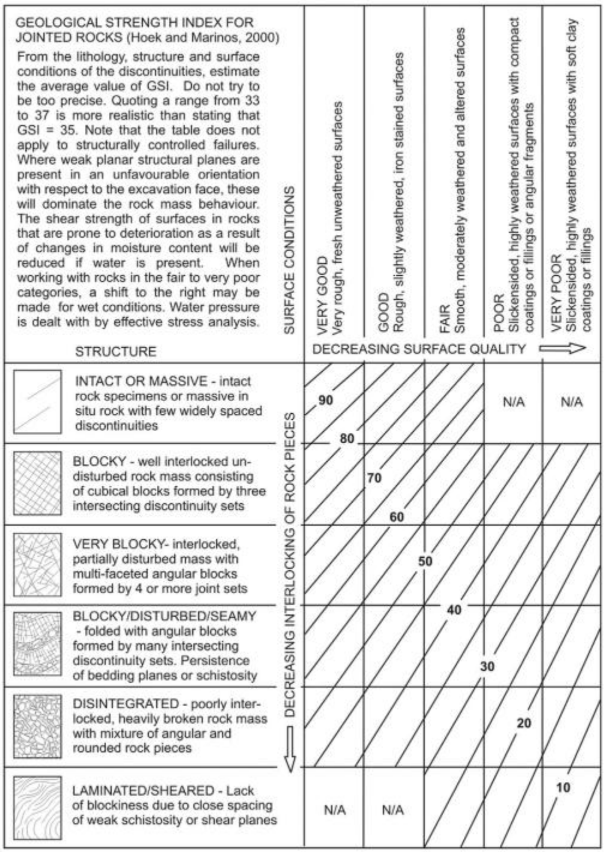

Fig. 3. Basic GSI chart.

4.3. Accuracy of strength estimation using GSI vs. actual test data

If we compare the results of the rock mass quality of the tested rock samples against the estimated values by Hoek and Brown [12] for average quality rock masses and poor quality rock masses, various findings can be found regarding the accuracy of the strength estimation of the rock samples.

Typical properties for this average quality rock mass may be as follows:

Intact rock strength	σ_{ci}	80 MPa
Hoek-Brown constant	m_i	12
Geological Strength Index	GSI	50
Friction angle	ϕ'	33°
Cohesive strength	c'	3.5 MPa
Rock mass compressive strength	σ_{cm}	13 MPa
Rock mass tensile strength	σ_{tm}	-0.15
Deformation modulus	E_m	9000 MPa
Poisson's ratio	ν	0.25
Dilation angle	α	$\phi'/8 = 4°$
Post-peak characteristics		
Broken rock mass strength	σ_{fcm}	8 MPa
Deformation modulus	E_{fm}	5000 MPa

Fig 4. Typical Properties of Average Quality Rock Mass (Hoek & Brown, 1997) [11]

Based on the GSI chart, limestone and sericite sandstone can be classified as average quality rock masses; meanwhile, greywacke can be defined as a very poor quality rock mass. Based on the established estimated values by Hoek and Brown, it was evident that there were discrepancies between the simulation results against the expected results. This was present for the limestone sample as there were discrepancies from the expected values for average quality rock masses, with the simulated friction angle of 50.45° being greater than the expected value of 33°, and the deformation modulus was less than 9000 MPa. However, it is interesting that the cohesion falls within the expected range, as typical cohesion values fall between 0.5 MPa to 3.5 MPa. Similar findings can also be found for Sericite Sandstones, where its cohesion of 0.563 MPa is also within the range for the average quality rock masses, but also has an overestimated angle of internal friction of 53.15°.

Typical properties for this very poor quality rock mass may be as follows:

Intact rock strength	σ_{ci}	20 MPa
Hoek-Brown constant	m_i	8
Geological Strength Index	GSI	30
Friction angle	ϕ'	24°
Cohesive strength	c'	0.55 MPa
Rock mass compressive strength	σ_{cm}	1.7 MPa
Rock mass tensile strength	σ_{tm}	-0.01 MPa
Deformation modulus	E_m	1400 MPa
Poisson's ratio	ν	0.3
Dilation angle	α	zero
Post-peak characteristics		
Broken rock mass strength	σ_{fcm}	1.7 MPa
Deformation modulus	E_{fm}	1400 MPa

Fig 5. Typical Properties of Poor Quality Rock Mass (Hoek & Brown, 1997) [11]

In simulating the parameters of greywacke, which can be classified as having a poor quality rock mass. It was found that certain parameters meet the threshold for the expected values for poor-quality rocks, such as the GSI set in the simulation. However, most of the parameters were found to be not within the expected range. This indicates that the data set for greywacke may be overestimated, as most of the parameters exceed the expected ranges, such as the friction angle and cohesive strength of the rock samples. These discrepancies may be due to various factors, such as the set parameters during the establishment of the strength envelope. As mentioned earlier, existing research on the types of rock samples was used as the means to determine the parameters, specifically the GSI, UCS, and mi values of limestone, sericite sandstone, and greywacke. It is because for weak, heavily fractured, and weathered rock masses, determining shear strength parameters, namely cohesion and internal friction angle, is difficult to obtain using a standard triaxial test. For these types of rock masses, it is costly to find and prepare suitable samples. Hence, indirect methods of obtaining these parameters are utilized. Typical approaches for indirectly obtaining the friction angle are commonly derived from other parameters of the rock, such as strength, deformability, and index properties [13]. However, the use of these parameters may have resulted in the curve-fitting estimation for the strength envelopes being overestimated. Hoek and Brown recommended considering the impact of blast damage or weathering, which can impact the GSI of the in-situ rock samples by 5 to 10 points, which can lower the strength parameters of each rock sample. Lastly, other factors, such as the isotropic behavior for foliated rocks, may need to be included in the simulation as their strength varies with the loading direction.

5. CONCLUSION AND RECOMMENDATIONS

Overall, the research paper was able to accomplish its main objective of assessing the strength envelopes of the selected rock samples, where it indicated varying results in terms of the simulated data as the relationship between the strength parameters to the GSI, UCS, and m_i was established. The relationship of these parameters was implied by the formulas for constants m_i, s, and a, which highlights that GSI has a heavy influence in determining the values for these constants as well as calculating the strength values for each rock. This was evident in the established GSI of Greywacke (30), resulting in significantly lower strength values compared to limestone and sericite sandstone. The primary reason for this relationship is that GSI, being the measure for the blockiness and the condition of joints in a rock, ultimately determines the strength of rocks. The more weathering occurred in a rock, and/or the worse surface conditions are for that rock, the lower the GSI value and, therefore, the weaker in rock strength. Meanwhile, the evaluation of the simulated results indicates that there was overestimation that occurred if compared against the typical values for both average quality rock and poor quality rock mass. The overestimation may be due to the used data that may not be accurate as the conditions of the rock samples may have been primarily idealized or are not considered to represent the actual site conditions of the rock fully—this includes misjudgements in the assignment of parameters, especially if blast damage, weathering, or the anisotropic behavior of the rock samples were not accounted for during the simulation process.

To further improve the accuracy of future simulations, several recommendations are suggested. One of these suggestions is to validate and revise the assigned set of parameters by conducting field assessments or using discontinuity mappings, which were discussed by Hoek and Brown [12]. Next, another consideration that could be taken is that during the simulation phase of the fitting of the Hoek-Brown envelope, it is critical that the confining stresses used not exceed 25% of the UCS of the established rock. Next, the derivation of the Mohr-Coulomb parameters is strongly recommended, as understanding how the parameters were developed could result in a more comprehensive analysis of the simulated data. Other means of validation also include cross-validation through other rock mass classification systems, such as the Rock Mass Rating or the Q-system, to ensure that the assessment of the rock mass is consistent. Lastly, it is important to have a conservative approach in simulating data, where the parameters may need to be reduced to be within the range of Hoek and Brown's expected values for rock mass, where it is recommended that 75% of the actual parameters be used, such as in the derived cohesion. If these steps are utilized, it would result in a more accurate and robust estimation of strength envelopes, as it would result in more realistic data for geotechnical applications.

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