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Estimation of the Poisson's Ratio of the Rock Mass

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Abstract

The value of Poisson's ratio is a crucial parameter in rock mechanics and engineering for both intact rock and rock mass. Poisson's ratio has not gotten the attention it merits compared to other essential mechanical characteristics of intact rock and rock mass. Limited relationships exist between rock mass classification systems (such as RMR, RMQR, Q, and GSI) and Poisson's ratio. This paper provides a comprehensive review of models proposed by various researchers for estimating Poisson's ratio for rock mass. The different methods are compared, and new general equations are derived. The results indicate that the Poisson's ratio value of rock mass is inversely proportional to its quality and strength and depends on the Poisson's ratio value of the intact rock. Specifically, a linear equation is obtained using the RMR or GSI system, showing that the Poisson's ratio increases as the quality and strength of the rock mass decrease. The Q system has a logarithmic link between the rock mass quality and Poisson's ratio. It should be noted that the derived equations are applicable only under the assumption of a homogeneous isotropic rock mass.

Keywords

rock mass classification, rock mass, Poisson's ratio, empirical methods

1 Introduction

Compared to other essential mechanical features of rocks, Poisson's ratio is an elastic constant whose relevance is largely overlooked. Various dispersed and varied areas in rock mechanics call for prior knowledge or an estimation of the Poisson's ratio. Although the values of Poisson's ratio for rock masses are required in most rock engineering applications, there are some situations where the values for intact rocks are necessary. In addition, the intact rock value can be considered a limit for Poisson's ratio values that a jointed rock mass may assume.

The ratio of the radial strain and the equivalent axial strain brought on by evenly distributed axial stress is what is meant by the definition of Poisson's ratio of the homogeneous isotropic rock [1]:

$$\nu = -d\varepsilon_{trans} / d\varepsilon_{axial} . \quad (1)$$

Where ν is the Poisson's ratio, ε_{trans} is the transverse strain, ε_{axial} is an axial strain (Negative strain signifies extension, while positive strain denotes contraction). Using strain increments rather than strains is advantageous in plasticity theory, where nonlinear stress-strain curves are also encountered [2].

Theoretically, the Poisson's ratio of an isotropic, linear elastic material is a fixed value ranging from -1 to +0.5. For rock materials, it is always positive and ranges from 0.05 to 0.45. A low Poisson's ratio, such as 0.05–0.25, means rocks fracture easier, whereas a high Poisson's ratio, such as 0.35–0.45, indicates the rocks are harder to fracture [2, 3].

Three different approaches can be used to determine the intact rock's Poisson's ratio (ν_i). [4]:

- secant Poisson's ratio (ν_s),
- average Poisson's ratio (ν_{av}), and
- tangent Poisson's ratio (ν_t).

To study the behavior of the secant Poisson's ratio, the origin of the ratio was kept at the zero-stress position, but the reference point was viewed as a moving point that changes with stress. The average Poisson's ratio reflects the relative change in axial and radial strain at some stress interval's upper and lower limits. The tangent Poisson's ratio calculation is more susceptible to changes in the testing procedure and sample frequency than the secant Poisson's ratio calculation (see Fig. 1) [5].

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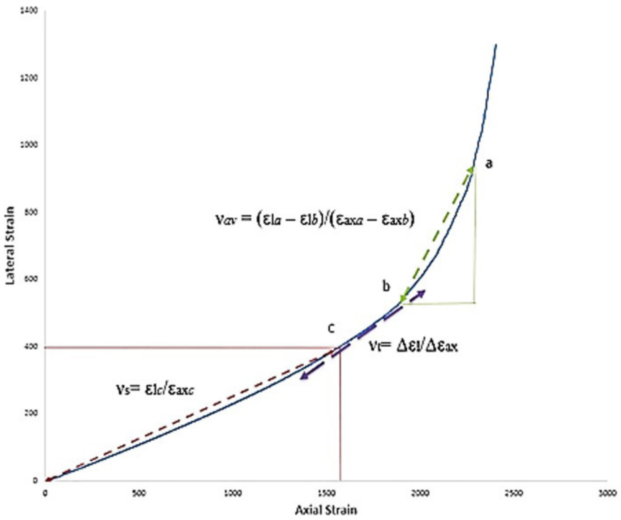


Fig. 1 Schematic calculation of (a) secant Poisson's ratio (v_s), (b) tangent Poisson's ratio (v_t) and (c) average Poisson's ratio (v_{av}) of intact rock [5]

According to the study by Dong et al. [4], the tangent Poisson's ratio fluctuation with stress interval width is displayed in Fig. 2 for two different rocks. Here it is demonstrated that when the width of the stress interval is approximately 1% of UCS, the estimated tangent Poisson's ratios display significant oscillations [2]. The tangent Poisson's ratio fluctuates less while the stress interval is longer; it only becomes stable when the stress interval is 5% of UCS or greater. From the testing standpoint, the tangent Poisson's ratio is essentially the average Poisson's ratio measured across a constrained stress interval, and its calculation is highly unreliable [4]. As a result, both the calculating method and the stress significantly impact Poisson's ratio.

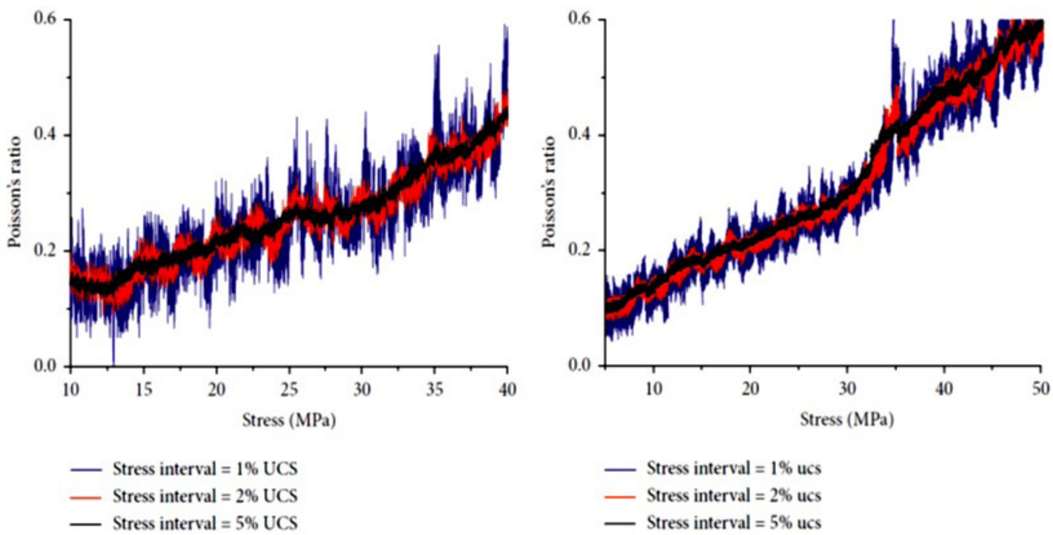
Davarpanah et al. [6] investigated the relationship between secant and tangent Poisson's ratio for intact stratified rocks, analyzing the uniaxial compressive test results of different rocks from different open pit mines in Australia and Papua New Guinea. Their results found strong and consistent correlations with high determination coefficients for different rock types between secant and tangent Poisson's ratio.

The purpose of this work is to review and contrast the many theories about the computation of Poisson's ratio of the rock mass in relation to several empirical rock mass classification systems (such as *RMR*, *RMQR*, *GSI* and *Q* methods). It was assumed that the rock mass is always homogeneous and isotropic material, i.e., the Poisson's ratio is always independent of the direction. The Poisson's rate of the rock mass probably depends on the Poisson's ratio of intact rock.

2 Poisson's ratio of intact rock

Quantifying the intact rock's Poisson's rate value in a laboratory setting using indirect or dynamic approaches is relatively straightforward [7, 8] or directly by static (uniaxial compressive) tests [9]. The purpose of this article is not to compare static and dynamic Poisson's ratios [10, 11], it focuses on the static results, which are essential for the calculation of the Poisson's ratio of the rock mass.

Gercek [12] summarized the normal ranges of values for Poisson's ratio of the most significant rock types in his review study. (Fig. 3). The figure shows that there can be significant variation in Poisson's ratio even for the same type of rock. There are several possible reasons for this – e.g., different loading/strain rates, calculation methods, size effects, temperature, etc.



(a) (b)

Fig. 2 Tangent Poisson's ratios of two types of hard rocks with varying stress intervals; (a) Marble specimens, (b) Red sandstone specimens [4]

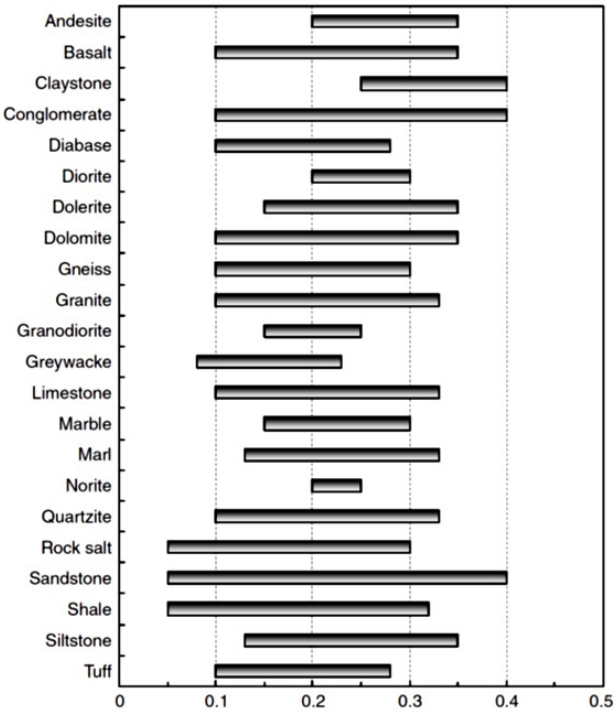


Fig. 3 Typical ranges of values for Poisson's ratio of some intact rock types [12]

A thorough analysis of Poisson's ratios for common oxides, silicate minerals, and rocks is given in Ji et al.'s publication [13]. They published and analyzed several laboratory results that carried out different confining pressure (up to 200 MPa) and temperatures (20–1500°C).

First, Kumar [14] looked into how Poisson's ratio affected the characteristics of the intact rock. He highlighted the significance of this material constant in the theory of rocks. According to his results, there is a linear relationship between Young's modulus (E), uniaxial compressive strength (σ_c), tensile strength (σ_t) and the Poisson's ratio (v):

- Young's modulus increases with decreasing Poisson's ratio;
- Compressive strength increases with increasing Poisson's ratio;
- Tensile strength decreases with increasing Poisson's ratio.

It is essential to highlight that the obtained correlation coefficients were quite low. Recent years have seen the development of multiple relationships to compute the Poisson's ratio of the complete rock from various mechanical factors, such as stiffness index, cohesiveness, and internal friction angle [15]. According to the different theories, Poisson's ratio decreases in case of increasing rigidity. Lógó and Vásárhelyi [16] conducted a theoretical study to examine the relationship between the stiffness of the rock and its Poisson's ratio for entire rock. They assumed that the ratio of the uniaxial compressive strength (σ_c) to the tensile strength (σ_t) could be used to compute the Poisson's ratio of the complete rock:

$$v_i = \frac{1}{\sqrt{\frac{\sigma_c}{|\sigma_t|} + 1}} . \tag{2}$$

Note that, based on the analysis of Davarpanah et al. [17], the ratio of the compressive strength (σ_c) and tensile strength (σ_t) is equal to the Hoek-Brown material constant of the intact rock (m_i).

Aydan et al. [18] carried out several uniaxial compressive tests in squeezing rocks in Japan; it was found that the Poisson's ratio of the intact rocks tends to approach 0.5 as the uniaxial strength approach zero. As the strength increases, it tends to converge a value between 0.2 and 0.25. The relationship between Poisson's ratio (v_i) and uniaxial compressive strength (σ_c) (MPa) of intact rock can be fitted to the following expression (Eq. (3)) and illustrated in Fig. 4 [19].

$$v_i = 0.25\left(1 + e^{-0.2\sigma_c}\right) \tag{3}$$

Arslan et al. [20] and Kumar et al. [21] studied the relationship between the unconfined compressive strength and the Poisson's rate. When numerous rock types (including gypsum [20] and basalt, granite, schist, limestone, sandstone, and shale [21] were analyzed, they discovered that the Poisson's rate linearly increased with increasing uniaxial compressive strength (σ_c), expressed in MPa (Fig. 5).

$$v_i = A + B\sigma_c \tag{4}$$

The constants A and B depend on the type of rock. The published material constants are summarized in Table 1 (note: the original equation of Kumar [14] was

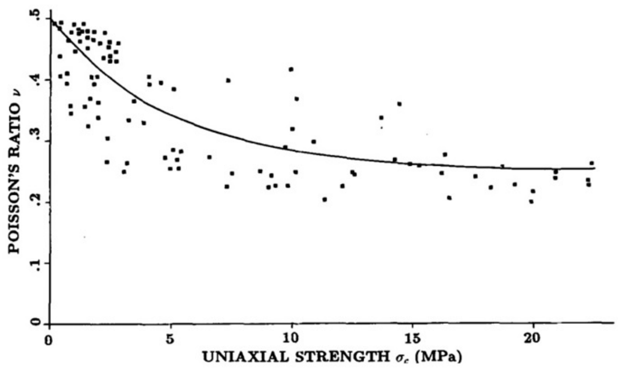


Fig. 4 Poisson's ratio of squeezing rocks in Japan in the function of the uniaxial compressive strength [19]

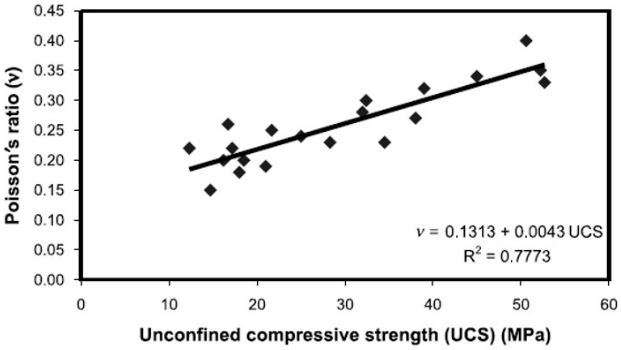


Fig. 5 Unconfined compressive strength (UCS) versus Poisson's ratio of gypsum rock [20]

Table 1 Summary of Poisson's ratio (ν) and uniaxial compressive strength (σ_c) relationships (Eq. (4)) [a][14]; [b][20] [c][21], [d][22]

Rock	A	B	σ_c
General[a]	0.0289	0.00262	-
Gypsum[b]	0.1313	0.0043	10–55
Basalt[c]	0.235	0.0002	170–415
Granite[c]	0.246	0.0002	70–276
Schist[c]	0.160	0.00057	30–105
Limestone[c]	0.186	0.0016	35–170
Sandstone[c]	0.136	0.00227	28–138
Shale[c]	0.208	0.00606	7–40
Shale[d]	0.293	-0.00324	11–55

based on 27 independent laboratory test results of different rocks and used psi – here, we recalculated it to MPa). Fig. 5 shows the measured results for gypsum rock [20]. According to the results of Arslan et al. [20] and Kumar et al. [21], the Poisson's rate is increasing with increasing uniaxial compressive strength (UCS). Shalabi et al. [22] got the opposite results: increasing the uniaxial compressive strength, the Poisson's ratio linearly decreases.

The study to examine the connection between Poisson's ratio and confining pressure was conducted by Xu et al. [23] and Lógó and Vásárhelyi [24]. It was discovered that the relationship between this material constant and confining pressure should be linear (Fig. 6).

According to the investigations of Carneiro and Puga [25], the Poisson's ratio of the isotropic homogeneous material also depends on the temperature (Fig. 7).

Despite being a crucial mechanical factor in rock engineering design, Poisson's ratio receives less research due to its challenging measurement. There aren't many recommendations for calculating the Poisson's ratio value in the rock mass classification system because there aren't many in situ data available. Therefore, it's crucial to calculate the Poisson's ratio of the rock mass's quality.

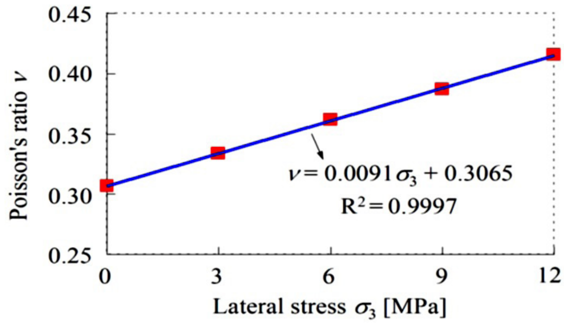


Fig. 6 Poisson's ratio as a function of confining pressure [22]

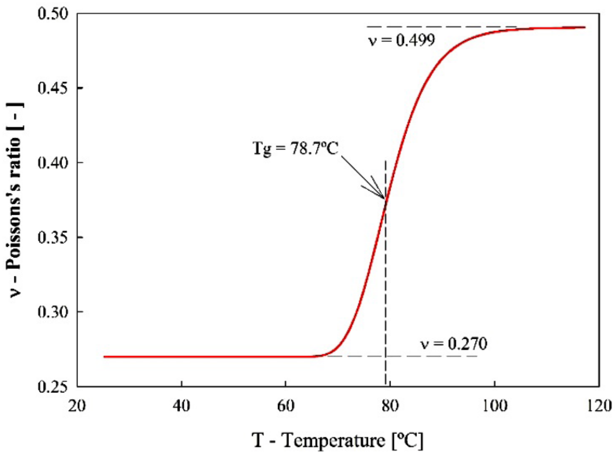


Fig. 7 Poisson's ratio as a function of temperature [24]

3 Empirical rock mass classification systems

For the following rock mass categories, computations have currently been created. Rehman et al. [26] conducted the review research. They evaluated the various rock mass categorization systems for determining the mechanical characteristics (internal friction angle and cohesiveness), deformation modulus, and Poisson's ratio. The following rock mass classification systems are employed, focusing on the Poisson's ratio of the rock mass:

- Rock Mass Rate – *RMR* [27, 28]
- Rock Mass Quality Rate – *RMQR*-value [29]
- Rock Mass Quality (*Q*-value) [30]
- Geological Strength Index – *GSI* [31, 32, 33]

3.1 Rock Mass Rate (RMR)

Bieniawski [27, 28] published the details of a rock mass classification called the Geomechanics Classification or the Rock Mass Rating (*RMR*) system:

$$RMR = R1 + R2 + R3 + R4 + R5 + R6\ . \tag{5}$$

The maximum value of *RMR* is 100 (intact rock). The following six parameters are used to classify a rock mass using the *RMR* system:

R1. Uniaxial compressive strength of intact rock material (0–15),
R2. Rock Quality Designation (RQD) (5–20),
R3. Spacing of discontinuities (5–20),
R4. Condition of discontinuities (0–30),
R5. Groundwater conditions (0–15),
R6. Orientation of discontinuities. (0–12).

Using the *RMR* system, the different mechanical parameters (such as deformation moduli, basic friction angle and cohesion, and rock mass strength) can be calculated. In this paper, the strength of the rock mass will be used for predicting Poisson's ratio of the rock mass.

Firstly, Yudhbir et al. [34] proposed the following equation for the estimation of rock mass strength based on *RMR* [28]:

$$\frac{\sigma_{rm}}{\sigma_c} = e^{\left(\frac{7.65(RMR-100)}{100}\right)} . \tag{6}$$

Using huge number of in situ measurements, Kalamaras and Bieniawski [35] suggested the following relationship (note the similar equation was suggested by [36]:

$$\frac{\sigma_{rm}}{\sigma_c} = e^{\left(\frac{7.65(RMR_{89}-100)}{24}\right)} . \tag{7}$$

According to the theory of Asef et al. [37], the strength of the rock mass is independent of the strength of the intact rock. They published for estimation of rock mass strength based on RMR_{76} [27]:

$$\sigma_{rm} = 0.5 \times e^{0.06 RMR_{76}} . \tag{8}$$

3.2 Rock Mass Quality Rating (RMQR)

Although the *RMQR* method is not yet widely used, it is important to present it as it provides an exact relationship between the Poisson's ratio and the quality of the rock mass [29].

The *RMQR* approach uses a combination of relevant rock mass metrics, all accessible rock mass classifications, sound mechanical reasoning and produces a quantitative measure for the physical state of the rock mass relative to intact rock. Using the geomechanical characteristics of intact rock, this approach can determine the geomechanical properties of rock masses [29]. Six essential elements make up the rock mass characterization known as the rock mass quality rating (*RMQR*):

$$RMQR = R1 + R2 + R3 + R4 + R5 + R6 . \tag{9}$$

R1. Degradation Degree (D.D.) (0–15),
R2. Discontinuity Set Number (DSN) (0–20),
R3. Discontinuity Spacing (D.S.) (0–20),
R4. Discontinuity Condition (D.C.) (0–30),
R5. Groundwater Seepage Condition (GWSC) (0–9),
R6. Groundwater Absorb Condition (GWAC) (0–6).

The *RMQR* value is between 0 (very poor or weak rock mass) and 100 (solid or intact rock material). Analyzing several of Japan's rock mechanical projects, the following relationship was suggested between *RMR* value and *RMQR* value [29]:

$$RMQR = 100 \frac{RMR}{RMR + 1.1(100 - RMR)} . \tag{10}$$

It means the *RMQR* value is nearly equal to the *RMR* value (within the experimental error).

3.3 Rock Mass Quality (Q-value)

One of the most popular and widely used rock mass classification systems in rock engineering for underground excavations, tunnels, and rock slope design is the Rock Mass Quality (Q-system) classification system, developed and created by Barton et al. [30, 38]. In reality, the Q-system is far more than six parameters, as the geology has to be understood before the application can be optimal. It began as a quantitative categorization system for estimates of tunnel support based on the evaluation of rock mass quality using the following equation:

$$Q = \left(\frac{RQD}{J_n}\right) x \left(\frac{J_e}{J_a}\right) x \left(\frac{J_w}{SRF}\right) . \tag{11}$$

Q-value resembles a logarithmic scale of quality with its six orders of magnitude from approximately 10^{-3} (extraordinary poor) to 10^{3} (extraordinary good, i.e., intact rock) (possible value ranges are in parenthesis):

- *RQD*: Rock Quality Designation (5–100)
- J_n: number of joint sets (0.5–20)
- J_r: Roughness of the most unfavorable joint or discontinuity (0.5–4)
- J_a: Degree of alteration or filling along the weakest joint (0.75–20)
- J_w: water inflow (0.05–1)
- *SRF*: stress reduction factor (2.5–10)

The meaning of the parameters used to determine the value of Q can be seen from the following comments:

- The first quotient (RQD/J_n) roughly represents the rock mass's block size.
- The second quotient (J_r/J_a) describes the frictional characteristics of the rock mass.
- Active stress is indicated by the third quotient (J_w/SRF). The third quotient, the most challenging empirical element, has generated discussion in several papers and conferences. As a representative of four different types of rock masses – weakness zones, swelling rock, deformable (ductile) rock masses, and stress influences – it merits special consideration.

The Q approach can be used to assess the strength of the rock mass similarly to other systems for categorizing rock masses. Barton [39] suggested the following equation for estimating rock mass strength based on Q values, using Q-value to determine the strength of the rock mass. In this equation, the strength of the rock mass is unrelated to the strength of the rock:

$$\sigma_{rm} = 5 \times \gamma \times Q_c^{0.33} \left(MPa \right) . \tag{12}$$

Later, Bhasin and Grimstad [40] suggested a new relationship for determining the rock mass strength (σ_{rm}) in the function of Q-value, applying the strength of the intact rock (σ_c):

$$\frac{\sigma_{rm}}{\sigma_c} = \frac{7}{100} \gamma \times Q_c^{1/3} . \tag{13}$$

In both equations, γ is the unit weight in t/m^3 and is assumed to be 2.4 t/m^3 in our calculations.

3.4 Geological Strength Index (GSI)

The qualities of the intact rock pieces and their freedom to slide and rotate under various stress conditions affect a jointed rock mass's strength. The geometrical shape of the unbroken rock fragments and the state of the surfaces separating the fragments govern this freedom. Stronger rock masses will be produced by angular rock fragments with clean, rough discontinuity surfaces than by rounder particles surrounded by worn and changed material. When paired with the intact rock parameters, the Geological Strength Index (*GSI*), created and published by Hoek and co-authors [31, 32, 33], provides a number that may be used to calculate the loss in rock mass strength under various geological situations.

There are several possibilities for calculating the Geological Strength Index. These calculation methods were compared by [41, 42]. Their investigation shows that the *GSI* application in a fractured granitic rock environment can be imprecise. Various *GSI* determination techniques can produce substantially disparate *GSI* values for the same rock mass. Fig. 8 illustrates the *GSI* method for blocky rock masses [43].

The Hoek-Brown failure criterion includes *GSI* as one of the input parameters [33]. An empirically derived relationship known as the Hoek-Brown failure criterion explains a nonlinear increase in the peak strength of homogeneous isotropic rock with increasing confining stress. The strength of the rock mass can be determined using the Hoek-Brown failure criterion and the Geological Strength Index (*GSI*) [33, 44]:

$$\sigma_{rm} = \sigma_c \times s^a , \tag{14}$$

$$s = \exp\left(\frac{GSI - 100}{9 - 3D} \right) , \tag{15}$$

$$a = \frac{1}{2} + \frac{1}{6} \times \left(e^{\frac{-GSI}{15}} - e^{\frac{-20}{3}} \right) . \tag{16}$$

Where *GSI* is the Geological Strength Index (0–100), and *D* is a factor which depends upon the degree of disturbance to which the rock mass has been subjected by blast

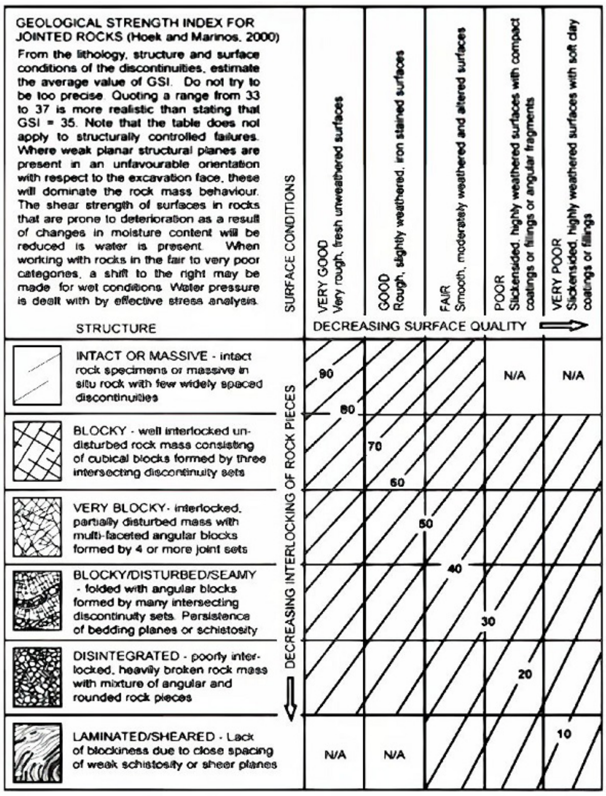


Fig. 8 Characterization of blocky rock masses based on interlocking and joint conditions [42]

damage and stress relaxation (0: undisturbed, 1: very disturbed rock mass) [33]. In this paper, we assumed to be 0 (undisturbed rock mass).

4 Estimation of the Poisson's ratio of the rock mass – using the theory of Aydan et al.'s

It was assumed [19, 26] that Eq. (3) can be used for the calculation of the Poisson's ratio of the rock mass (v_{rm}) indirectly of the strength of the rock mass (σ_{rm}):

$$v_{rm} = 0.25\left(1 + e^{-0.2\sigma_{rm}}\right). \tag{17}$$

Note that this is an assumption that the change in the property of the rock mass is the same as the change in the property of the intact rock.

The rock mass strength (σ_{rm}) can be determined using empirical rock mass classification systems, such as *RMR*, *GSI* or *Q*-values.

4.1 RMR based calculation methods

4.1.1 Dependent on the strength of the intact rock

Incorporating Eq. (6) in Eq. (17), the Poisson ratio of rock mass with different RMR values as a function of rock mass strength is depicted (Fig. 9). As shown, considering the different values of *RMR*, increasing the uniaxial compressive strength of rock mass, the Poisson's ratio decreasing. In respect to the range of *RMR* values, for *RMR* bigger than 60, the curve shows the smoother decrease in Poisson's ratio from 0.5 to 0.25 as uniaxial compressive strength (σ_{rm}) increases; however, for *RMR* values less than 60, we can see the immediate decrease in Poisson's ratio from 0.5 to 0.25, when compressive strength of rock mass is less than 5 MPa. Then it follows the steady state when the compressive strength of rock mass is greater than 5 MPa.

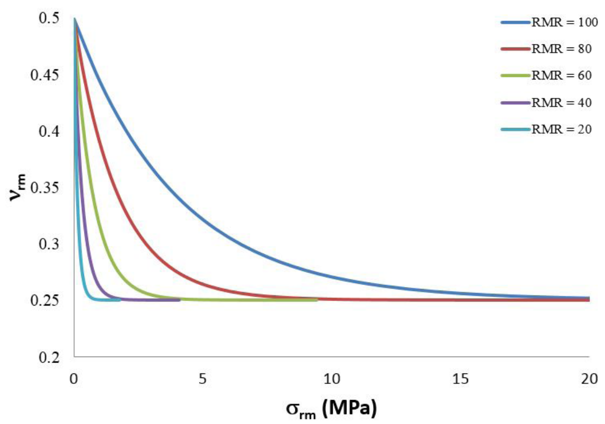


Fig. 9 Poisson's ratio of rock mass (nrm) as a function of the rock mass strength for different values of *RMR* (Eq. (6))

Using the same Eqs. (7) and (17) the Poisson's ratio of the rock mass (v_{rm}) is plotted as a function of uniaxial compressive strength of the intact rock (σ_c) and the Rock Mass Rate (*RMR*) values (see Fig. 10). One can see that the Poisson's ratio is varies sensitive for very poor and poor rock quality (*RMR* < 40). In the case of fair rock mass quality (40 < *RMR* < 60), it is 0.25 for strong rocks.

4.1.2 Independent of the strength of the intact rock

The Poisson's ratio of rock mass as a function of the *RMR* is displayed (Fig. 11) by inserting Eq. (8) into Eq. (17). The Poisson's ratio increases almost linearly below *RMR* = 60 and remains constant between 60 and 100 (v_{rm} = 0.25), as shown. Theoretically, the rock mass's Poisson's ratio is 0.45 if *RMR* = 10.

4.2 GSI based calculation methods

The strength of a rock mass can be determined using the Geological Strength Index (GSI) value. Its Poisson's ratio can be shown as a function of its strength (Fig. 12), using

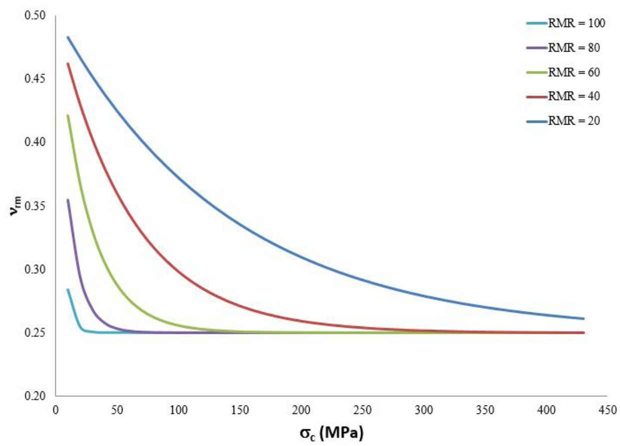


Fig. 10 Poisson's ratio of rock mass (v_{rm}) as a function of uniaxial compressive strength for different values of *RMR* (Eq. (6))

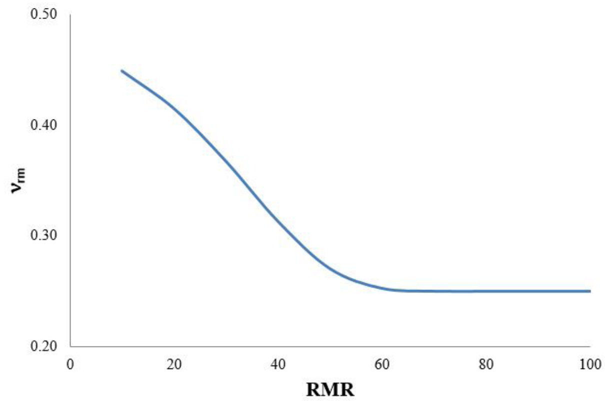


Fig. 11 Poisson's ratio of rock mass (v_{rm}) as a function of the *RMR*, independent of the strength of intact rock (Eq. (9))

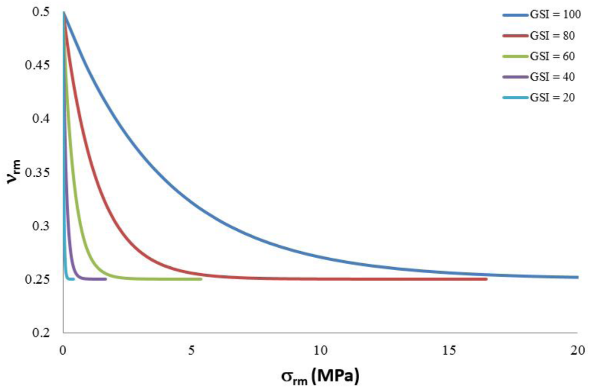


Fig. 12 Poisson's ratio of the rock mass (v_{rm}) as a function of rock mass strength (σ_{rm}) for different values of GSI (Eq. (15))

Eqs. (14)–(17). Like the relationship between Poisson's ratio and uniaxial compressive strength for different *RMR* values, different values of *GSI* can also reveal that an increase in uniaxial compressive strength results in a decrease in Poisson's ratio. The curve indicates a uniform decrease of Poisson's ratio from 0.5 to 0.25 for *GSI* values greater than 60. However, for *GSI* values less than 60, the Poisson's ratio sharply declines from 0.5 to 0.25 when the strength of the rock mass is less than 5 MPa and remains steady when the strength of the rock mass is greater than 5 MPa.

Fig. 13 shows the Poisson's ratio of the rock mass as a function of the uniaxial compressive strength of the intact rock and the *GSI* value, using Eqs. (8) and (17). The plot demonstrates that the Poisson's ratio is highly responsive to very poor and poor rock quality, characterized by a *GSI* value below 40. For fair rock mass quality, with a *GSI* value ranging between 40 and 60, the Poisson's ratio is 0.25 for strong rocks.

4.3 Rock mass quality (Q-value)

4.3.1 Independent of the strength of the intact rock

By incorporating Eq. (13) in Eq. (17), Poisson's ratio of the rock mass based on *Q* is shown in Fig. 14. The Poisson's ratio decreases if the rock quality increases – above good rock quality (Q > 10) is nearly constant, it is around 0.25.

4.3.2 Dependent of the strength of the intact rock

To describe this relationship, Bhasin and Grimstad [40] devised Eq. (11) (where denotes the unit weight in t/m^3). This work showed how the intact rock strength impacts rock mass strength estimation. As the strength of the rock mass grows, Poisson's ratio declines based on various *Q* values. The graph for Poisson's ratio exhibits a smoother reduction from 0.5 to 0.25 as the strength of the rock mass increases when the *Q* value is more than 50. The Poisson's ratio, however, decreases sharply from 0.5 to 0.25 for rock masses with lower strengths (less than 5 MPa) when the *Q* value is below 50, and then it stabilizes for rock masses with higher strengths (beyond 5 MPa). (Fig. 15)

Using Eqs. (11) and (15), the graph in Fig. 16 shows the link between the uniaxial compressive strength of the intact rock and the *Q* value, as well as Poisson's ratio of

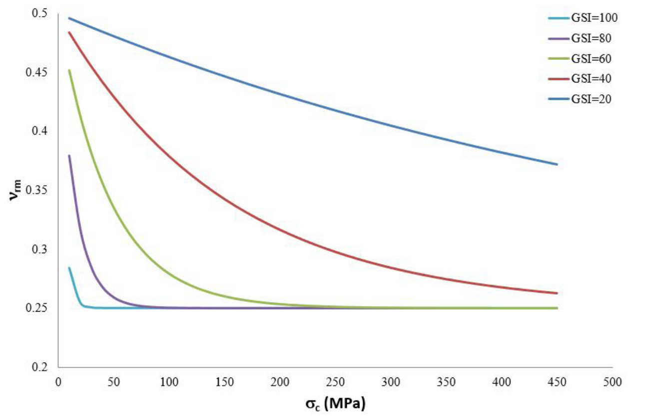


Fig. 13 Poisson's ratio of the rock mass (v_{rm}) as a function of uniaxial compressive strength (σ_c) for different values of *GSI* (Eq. (15))

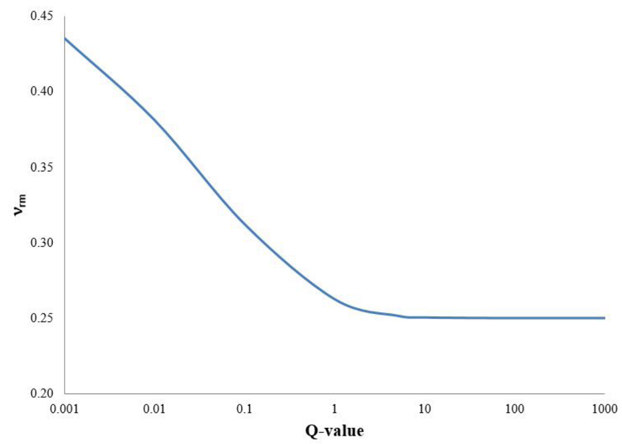


Fig. 14 Poisson's ratio of the rock mass (v_{rm}) based on *Q* value (Eq. (12))

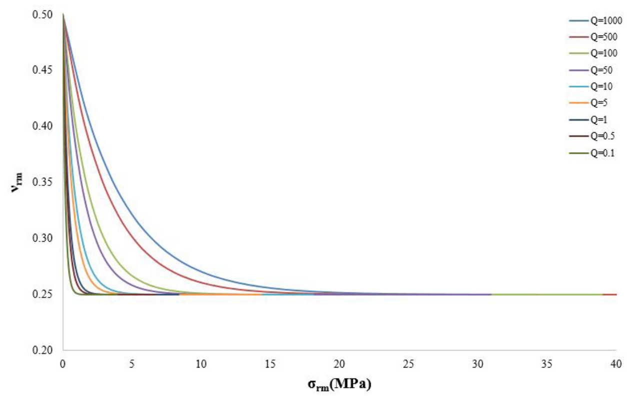


Fig. 15 Poisson's ratio of the rock mass (v_{rm}) as a function of rock mass strength (σ_{rm}) for different *Q* values (Eq. (13))

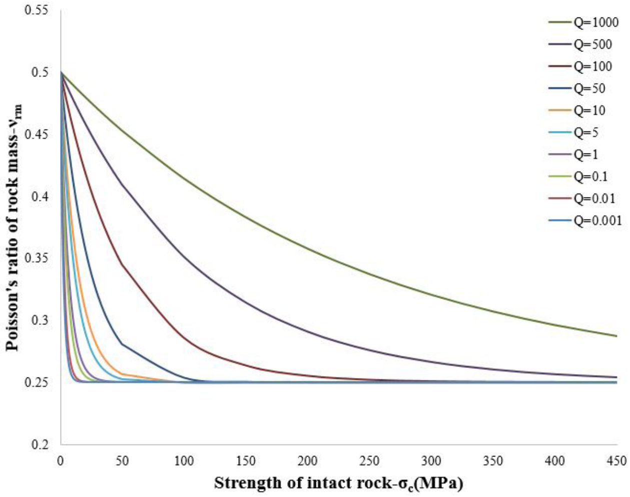


Fig. 16 Poisson's ratio of the rock mass (ν_{rm}) as a function of uniaxial compressive strength (σ_c) for different Q values

the rock mass. In particular for Q values under 10, the data shows the significant impact of extremely poor and poor rock quality on the Poisson's ratio. On the other hand, the Poisson's ratio is 0.25 for powerful rocks with fair rock mass quality, where Q is in the range of 10 to 100.

5 Estimation of the Poisson's ratio of the rock mass – using linear theory

The Poisson's ratio, as shown by Arslan et al. [20] and Kumar et al. [21], linearly depends on the rock's strength (Eq. (10)). Hence it may also be computed from the rock mass's strength:

$$\nu_i = A + B\sigma_{rm}, \tag{18}$$

wher A and B are rock type material constants (see Table 1).

Suppose the Poisson's ratio of the rock mass is calculated using Eq. (18). In that case, the strength increases as the rock mass quality improves (regardless of the applicable classification system). As a result, the Poisson's ratio of the rock mass rises. This goes against everything we've learned thus far: Poisson's rock mass ratio falls as rock mass quality rises (and vice versa). Calculating the rock mass's Poisson ratio is impossible using Eq. (18).

6 Estimation of the Poisson's ratio using RMR and RMQR value

6.1 Calculation without Poisson's ratio of intact rock

First, Tokashiki and Aydan [45] suggested a direct way of calculating the Poisson's ratio from the Rock Mass Rate data. They argue that the Poisson's ratio of the rock mass depends only on the RMR value and is independent of the Poisson's ratio of the intact rock, taking the following form:

$$\nu_{rm} = 0.5 - 0.2\frac{RMR}{RMR + 0.2\left(100 - RMR\right)}. \tag{19}$$

This equation is plotted in Fig. 17. The plotted curve shows that the Poisson's ratio of the intact rock ($RMR = 100$) is 0.3, while the soil like material ($RMR = 0$) is 0.5.

6.2 Calculation with Poisson's ratio of intact rock

Later, this equation was developed. According to Aydan et al. [19, 29], The Poisson's ratio of the rock mass is also influenced by the Poisson's ratio of the intact rock (i).

$$\frac{\nu_{rm}}{\nu_i} = 2.5 - 1.5\frac{RMR}{RMR + \left(100 - RMR\right)} \tag{20}$$

Analyzing the measured data of different rock engineering projects in Japan, Aydan et al. [29] determined that β it is between 0.3 and 3.0 (the average value is 1.0 – see Fig. 18). Note, the data for $RMQR$ values less than 50 are mainly from those of rock masses exhibiting squeezing behavior [29].

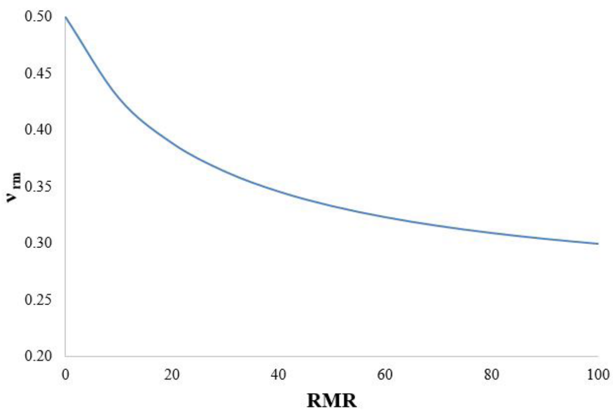


Fig. 17 Poisson's ratio of the rock mass (ν_{rm}) in the function of Rock Mass Rate (RMR) (Eq. (19))

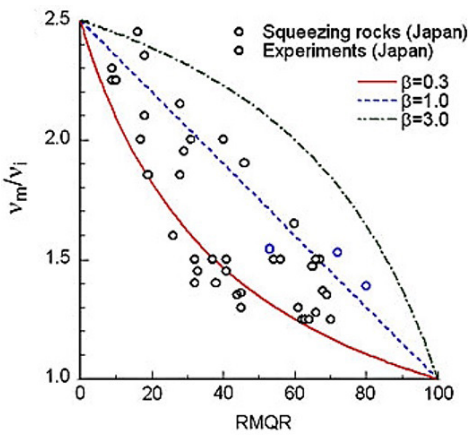


Fig. 18 Comparison of experimental data for Poisson's ratio of rock mass with the empirical relation [29] (Eq. (19))

Vásárhelyi and Kovács [46] analyzed Eq. (20). Plotting the Poisson's ratio of the rock mass in the function of *RMR*, one can see by decreasing the quality of the rock mass, the Poisson's ratio is increasing. However, theoretically, Poisson's ratio changes between 0.1 and 0.5. Therefore, the proposed equation doesn't provide a realistic estimation when the Poisson's ratio of intact rock is more significant than 0.3 (see Fig. 19).

In Fig. 20, the change in Poisson's ratio of the rock mass as a function of *RMR* is shown when the intact rock has Poisson's ratio equal to 0.2 for β values of 0.3, 1 and 3, using Eq. (20).

7 Poisson's ratio in the function of the Geological Strength Index (GSI)

When the *GSI* was initially developed, it became necessary to calculate the rock mass's Poisson ratio. In a table provided by Hoek et al. [32], the value of the rock mass's Poisson ratio rises as the *GSI* value falls (see Fig. 21).

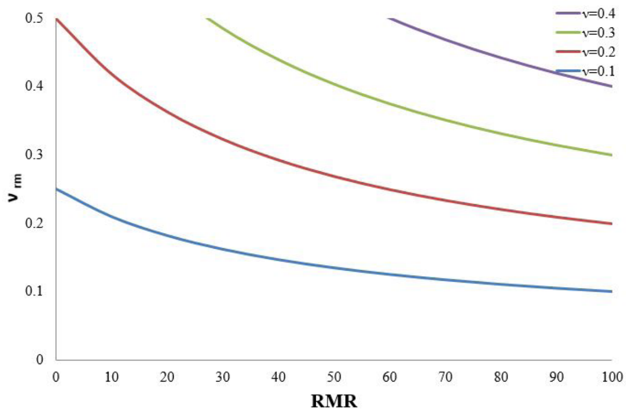


Fig. 19 Poisson's ratio of the rock mass (v_{rm}) as a function of *RMR* (Eq. (20))

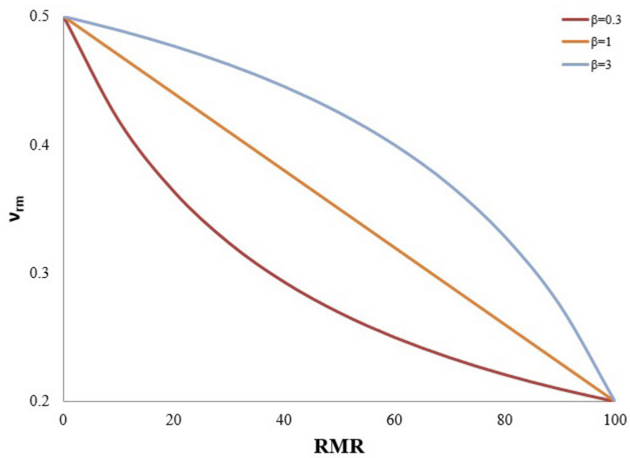


Fig. 20 Poisson's ratio (v_{rm}) in the function of *RMR* in case of different β constants (Eq. (20)), the Poisson's ratio of the intact rock is 0.2

GENERALISED HOEK-BROWN CRITERION

$$\sigma_1' = \sigma_3' + \sigma_c \left(m_b \frac{\sigma_3'}{\sigma_c} + s \right)^a$$

σ_1' = major principal effective stress at failure
σ_3' = minor principal effective stress at failure
σ_c = uniaxial compressive strength of *intact* pieces of rock
m_b, s and a are constants which depend on the composition, structure and surface conditions of the rock mass

STRUCTURE	SURFACE CONDITION	VERY GOOD Very rough, unweathered surfaces	GOOD Rough, slightly weathered, iron stained surfaces	FAIR Smooth, moderately weathered or altered surfaces	POOR Slickensided, highly weathered surfaces with compact coatings or fillings containing angular rock fragments	VERY POOR Slickensided, highly weathered surfaces with soft clay coatings or fillings
BLOCKY - very well interlocked undisturbed rock mass consisting of cubical blocks formed by three orthogonal discontinuity sets	m_b/m_i s a E_m ν GSI	0.60 0.190 0.5 75,000 0.2 85	0.40 0.062 0.5 40,000 0.2 75	0.26 0.015 0.5 20,000 0.25 62	0.16 0.003 0.5 9,000 0.25 48	0.08 0.0004 0.5 3,000 0.25 34
VERY BLOCKY - interlocked, partially disturbed rock mass with multifaceted angular blocks formed by four or more discontinuity sets	m_b/m_i s a E_m ν GSI	0.40 0.062 0.5 40,000 0.2 75	0.29 0.021 0.5 24,000 0.25 65	0.16 0.003 0.5 9,000 0.25 48	0.11 0.001 0.5 5,000 0.25 38	0.07 0 0.53 2,500 0.3 25
BLOCKY/SEAMY - folded and faulted with many intersecting discontinuities forming angular blocks	m_b/m_i s a E_m ν GSI	0.24 0.012 0.5 18,000 0.25 60	0.17 0.004 0.5 10,000 0.25 50	0.12 0.001 0.5 6,000 0.25 40	0.08 0 0.5 3,000 0.3 30	0.06 0 0.55 2,000 0.3 20
CRUSHED - poorly interlocked, heavily broken rock mass with a mixture of angular and rounded blocks	m_b/m_i s a E_m ν GSI	0.17 0.004 0.5 10,000 0.25 50	0.12 0.001 0.5 6,000 0.25 40	0.08 0 0.5 3,000 0.3 30	0.06 0 0.55 2,000 0.3 20	0.04 0 0.60 1,000 0.3 10

Fig. 21 Estimating different constants for generalized Hoek-Brown failure criterion based upon rock mass structure and discontinuity surface conditions [32]. Note that the values in this table are for an undisturbed rock mass

The Poisson rate for the rock mass is displayed in the table as 0.2 above *GSI* 70, 0.25 between 30 and 70, and 0.3 below 30.

Based on theoretical background, Vásárhelyi [47] calculated the Poisson's ratio value for the rock mass (v_{rm}). He discovered a linear relationship: the Poisson's ratio of the rock mass (v_{rm}), which measures the quality of the rock mass, rises as the rock mass's geological strength index, or *GSI*, declines. Besharatinezhad et al. [48] studied the effect of *GSI* and Poisson's ratio of the intact rock (v_i) on the critical height of vertical rock mass slope. They concluded that as Poisson's ratio of the intact rock (v_i) decrease, the critical height of vertical rock mass slope increases [48].

Two correlations were suggested by Vásárhelyi [47] for estimating the Poisson's ratio of the rock mass (v_{rm}):

- If the Poisson's ratio of the intact rock (v_i) is known:

$$v_{rm} = -0.002GSI + v_i + 0.2 . \quad (21)$$

- In the case of Hoek-Brown material constant (m_i) of the intact rock is known:

$$v_{rm} = -0.002GSI - 0.003m_i + 0.457 . \quad (22)$$

Estimated Poisson's rate value of the rock mass in the function of Geological Strength Index (*GSI*) in case of different Hoek-Brown constants is plotted in Fig. 22. As illustrated, increasing the *GSI* and Hoek-Brown constant mi values, the Poisson's ratio of rock mass is decreasing.

Vásárhelyi and Kovács [46] compared the estimated Eqs. (21) and (22). One can see there is a linear relationship between the Poisson's ratio and the rock mass quality, using the *GSI* system: increasing the *GSI* value the Poisson's ratio of the rock mass is decreasing (Fig. 23).

It should be noted that the *GSI* can be determined by knowing both the *RMR* and the *Q* value [49, 50, 51].

8 Poisson's ratio in the function of Rock Mass Quality (Q value)

There is currently no empirical experience on the relationship between the *Q*-value and the Poisson's rate, so our calculations were derived from the *RMR* value. According to the published equations by [49] considering the following equation:

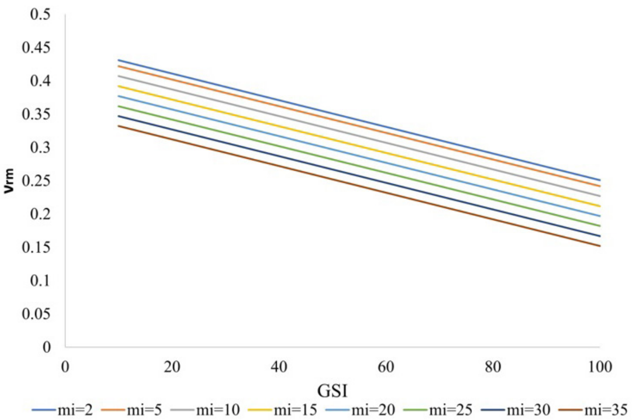


Fig. 22 Poisson's ratio (v_{rm}) in function of *GSI* in case of different Hoek-Brown constants (Eq. (22))

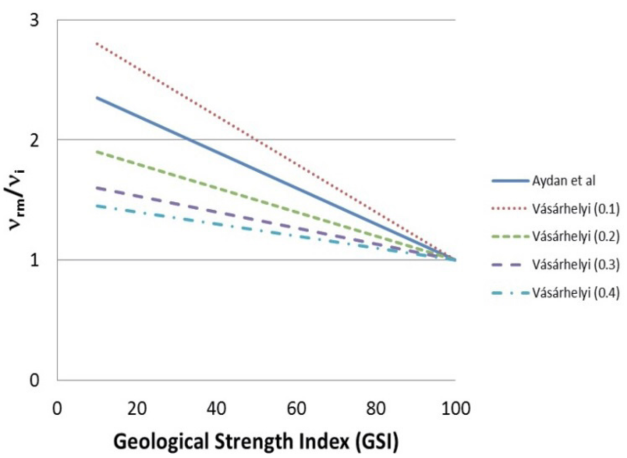


Fig. 23 Comparison of the calculation methods: [17, 45, 46]

$$RMR = \alpha \times \ln(Q) + c \, . \tag{23}$$

Where α and c depend on the features of the investigated site [47]. Note that the logarithmic relationship between the two classifications is theoretically derivable.

According to the publications [49, 51], parameters α and c range from 5 to 15 (the average is 9.78) and from 38 to 60.8 (the average is 47.35), respectively. Between the *Q*-system and *RMR*, in various settings for rock mass quality investigations, writers produced a number of empirical correlation equations that cover a wide variety of applications for the data. Parameters α and c depend on the engineering geological conditions type of project [47]. Using Eq. (23), Bieniawski [28] suggested the following relationship between the two different rock mass classification systems:

$$RMR = 9\ln(Q) + 44 \, . \tag{24}$$

As mentioned above, there are many similar equations [46]. Our present calculations are based on this equation.

8.1 Calculation without Poisson's ratio of intact rock

According to Eq. (19), the Poisson's rock mass rate can be calculated independently from the Poisson's rate of the intact rock. Substituting Eq. (24) for Eq. (19), the Poisson's rate can be calculated from the *Q*-value, and the following equation can be used (it is plotted in Fig. 24):

$$v_{rm} = 0.5 - \frac{1.8\ln(Q) + 8.8}{7.2\ln(Q) + 55.2} \, . \tag{25}$$

8.2 Calculation with Poisson's ratio of intact rock

Eq. (26) can be obtained by assuming the parameter $\beta = 1$ and referring to the relationship proposed by [18, 28] in

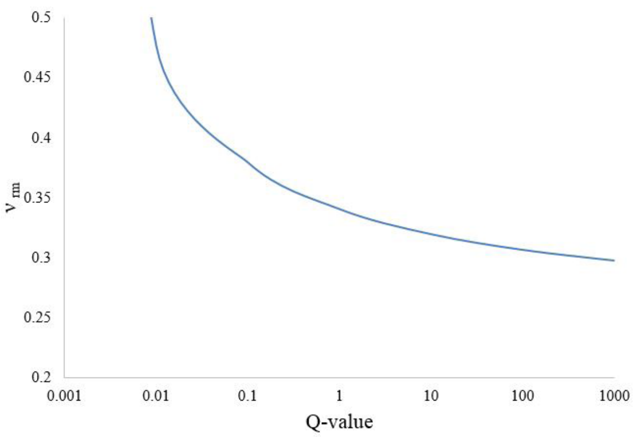


Fig. 24 The Poisson's ratio of the rock mass in the function of *Q*-value – independently the Poisson's ratio of the intact rock (Eq. (25))

Eq. (20), as stated in the text. In this formula, Poisson's ratio of the rock mass is dependent on the Poisson's ratio of the intact rock:

$$\frac{v_{rm}}{v_i} = 2.5 - 1.5\frac{RMR}{100} . \quad (26)$$

Substituting Eq. (23) into Eq. (26):

$$\frac{v_{rm}}{v_i} = 2.5 - 1.5\left(\frac{aln(Q)+c}{100}\right). \quad (27)$$

By substituting Eq. (24) in Eq. (27), the new relationship is formulated as below (Eq. (28)). It shows that the ratio between Poisson's ratio of rock mass over Poisson's ratio of intact rock has a logarithmic relationship with Q system.

$$\frac{v_{rm}}{v_i} = 2.5 - 1.5\left(\frac{9\ln(Q)+44}{100}\right) = -0.135\ln(Q)+1.84 \quad (28)$$

Using Eq. (28), Poisson's ratio of rock mass over Poisson's ratio of intact rock $\left(\frac{v_{rm}}{v_i}\right)$ as a function of Q is plotted in Fig. 25.

Poisson's ratio of the rock mass as a function of Q is presented (Fig. 26). theoretically, Poisson's ratio fluctuates between 0.1 and 0.5; nonetheless, a weaker rock mass should have a higher Poisson's ratio than 0.5. Thus, the proposed equation does not provide a realistic estimation when the Poisson's ratio of intact rock is more than 0.3.

The Poisson's ratio of the rock mass can be determined using Vásárhelyi's theory [47]. By utilizing Eq. (21) and assuming $RMR = GSI$ for Eq. (21), the result can be formulated in Eq. (29) and plotted in Fig. 27. The theory proposes that the Poisson's ratio of the rock mass can be calculated by employing the Q value and the Poisson's ratio of intact rock in the following form:

$$v_{rm} = -0.017\ln(Q) + v_i + 0.12 . \quad 29)$$

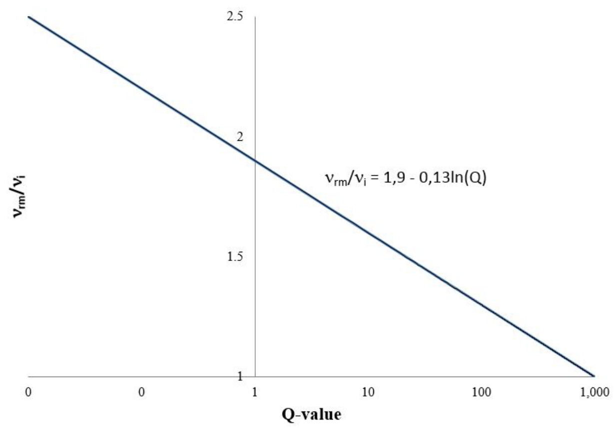


Fig. 25 Ratio Poisson's ratio of rock mass and the intact rock as a function of Q - using Eq. (28)

9 Discussion and conclusions

This research reviews the published equations by different scholars to provide the best estimation for Poisson's ratio of the rock mass. The accurate estimation of Poisson's rock mass ratio relies on the precise estimation of Poisson's ratio of intact rock and rock mass quality.

The association between RMR, GSI, Q and uniaxial compressive strength and Poisson's ratio of rock mass is presented in Figs. 9 to 16 based on our analyses and data from the literature, respectively. As shown, increasing the rock mass quality and uniaxial compressive strength leads to decreasing in Poisson's ratio of the rock mass. In this research, Poisson's rock mass ratio is calculated first directly based on rock mass strength and then based on rock mass classification systems. According to RMR based, GSI based, and Q based calculations (Eqs. (6)–(16)), as the rock mass strength increase, the Poisson's ratio of rock mass decreases. Poisson's rate of the rock mass can be calculated independently from the Poisson's rate of the intact rock (Eq. (25)). According to Eq. (25), as the Q-value increases, the Poisson's ratio of rock mass decreases.

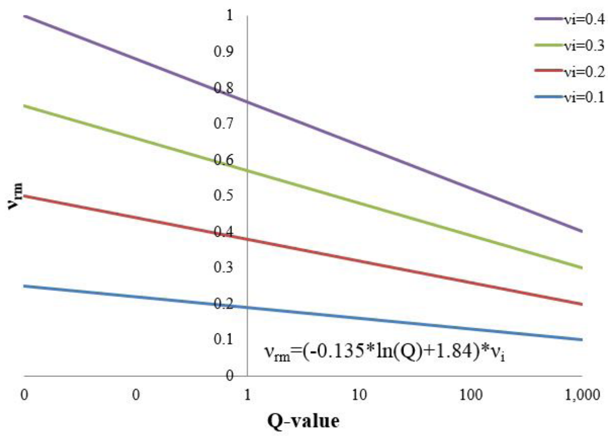


Fig. 26 Poisson's ratio of the rock mass as a function of Q-value (Eq. (28))

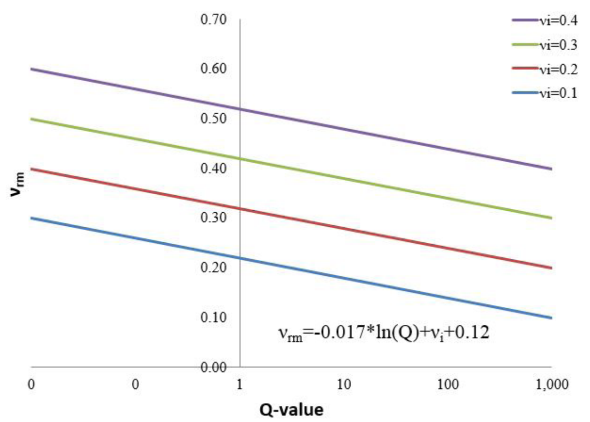


Fig. 27 Poisson's ratio of the rock mass as a function of Q (Eq. (29))

This finding agrees with the published equation by [45], which indicates that by increasing GSI and decreasing the Poisson's ratio of intact rock, the Poisson's ratio of rock mass decrease. According to Eq. (28), the Poisson's rock mass ratio depends on Poisson's ratio of intact rock and has a logarithmic relationship with *Q* system.

Lógó and Vásárhelyi [52] carried out a parametric study on the connection between Poisson's ratio, *GSI* and environmental stress. Their results proved that decreasing the *GSI* value increases the value of Poisson's ratio. If the value of the environmental stress (σ_3) increases, the Poisson's ratio also increases (see Fig. 28).

There are several rock mass classification methods in the rock engineering practice. Analyzing and comparing the different empirical and semi-empirical methods, Table 2 consists of the suggested equations both independent and dependent of the Poisson's ratio of the intact rock (v_i).

As it was mentioned previously, the Poisson's ratio of the rock mass depends on several environmental effects (e.g., in situ stress, temperature, water content, stress state, etc.), so it should be necessary to measure it. A new procedure for determination of the Poisson's rate of a rock mass was developed by [53].

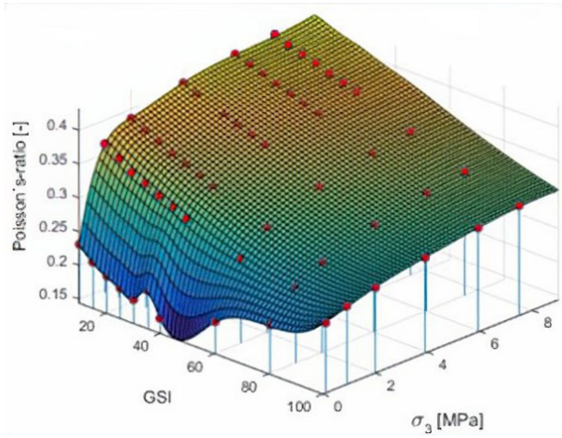


Fig. 28 Relationship between Geological Strength Index (*GSI*) value, Poisson's ratio and environmental stress (σ_3) [52]

Table 2 Suggested equations in case of different rock mass classification systems

Rock mass classification system	v_i independent	v_i dependent
RMR/*RMQR*	$0.5-\frac{0.2RMR}{0.8RMR+20}$	$\left(2.5-1.5\frac{RMR}{100}\right)v_i$
GSI	$-0.003\ \mathrm{GSI}+0.5$	$-0.002\ GSI+v_i+0.2$
Q	$0.5-\frac{1.8\ln(Q)+8.8}{7.2\ln(Q)+55.2}$	$(-0.135\ \ln(Q)+1.84)\ v_i$

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