

Correlation of the Rock Mass Rating (RMR) System with the Unified Soil Classification System (USCS): Introduction of the Weak Rock Mass Rating System (W-RMR)

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Abstract Underground gold mines in Nevada are exploiting increasingly deeper ore bodies comprised of weak to very weak rock masses. The Rock Mass Rating (RMR) classification system is widely used at underground gold mines in Nevada and is applicable in fair to good-quality rock masses, but is difficult to apply and loses reliability in very weak rock mass to soil-like material. Because very weak rock masses are transition materials that border engineering rock mass and soil classification systems, soil classification may sometimes be easier and more appropriate to provide insight into material behavior and properties. The Unified Soil Classification System (USCS) is the most likely choice for the classification of very weak rock mass to soil-like material because of its accepted use in tunnel engineering projects and its ability to predict soil-like material behavior underground. A correlation between the RMR and USCS systems was developed by comparing underground geotechnical RMR mapping to laboratory testing of bulk samples from the same locations, thereby assigning a numeric RMR value to the USCS classification that can be used in spreadsheet calculations and geostatistical analyses. The geotechnical classification system presented in this paper including a

USCS–RMR correlation, RMR rating equations, and the Geo-Pick Strike Index is collectively introduced as the Weak Rock Mass Rating System (W-RMR). It is the authors' hope that this system will aid in the classification of weak rock masses and more usable design tools based on the RMR system. More broadly, the RMR–USCS correlation and the W-RMR system help define the transition between engineering soil and rock mass classification systems and may provide insight for geotechnical design in very weak rock masses.

Keywords Rock Mass Rating (RMR) · Unified Soil Classification System (USCS) · Weak rock mass · Geo-Pick Strike Index · Mining · Underground · Nevada

1 Introduction

Underground gold mines in Nevada are exploiting increasingly deeper ore bodies comprised of weak to very weak rock. Production zones within the ore body are typically composed of intensely fractured and highly altered rock with Rock Mass Ratings (RMR) less than 45 (Sandbak and Rai 2013; Sun and Chen 2013). Access drifts and infrastructure often intersect faults and altered material of varying thickness and geotechnical quality ranging from blocky competent rock to soil-like material. These weak and variable ground conditions pose challenges to support design and implementation. As a result, underground mining in Nevada is often difficult and hazardous (Brady et al. 2005).

The geotechnical mining engineering research group at the University of Nevada, Reno (UNR) has been conducting research on empirical support design methods for use in underground gold mines in Nevada. Recognizing the

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highly variable ground conditions in Nevada, the authors anticipated that traditional rock mass classification systems alone would not predict material behavior or characterize ground conditions adequately for support design. Hence, the need for a more flexible and comprehensive geotechnical classification system was recognized as an important first step in developing support guidelines for weak rock in Nevada and is the focus of this paper.

The Rock Mass Rating System (RMR) is commonly used at underground gold mines in Nevada, and several empirical support design tools have been developed based on this system including: Bieniawski (1976, 1989), (Kondorski et al. 1983), Laubscher (1990), Mathis and Page (1995), Ouchi et al. (2008), and Lowson and Bieniawski (2013). However, it is widely recognized that the RMR system as described by Bieniawski (1976, 1989) lacks sensitivity and is difficult to apply to very weak rock (Hoek et al. 1995; Hoek and Marinos 2007; Mathis and Page 1995). This reduces the reliability of empirical design methods in weak rock resulting in uncertainty in excavation stability or expensive and over-supported ground control procedures. In addition, lack of RMR sensitivity in weak and highly fractured ground hinders the development of new empirical support recommendations based on RMR in weak rock masses. To increase the applicability of the RMR system and associated empirical systems in weak rock, this paper presents RMR rating calculation formulas tailored to weak rock which are back-compatible with traditional RMR calculation methods in moderate to good-quality rock.

Although the calculation of RMR ratings can be adjusted to increase the sensitivity of RMR in weak ground, there comes a point when soil classification would better predict material properties and behavior; however, the boundary or transition between soil and rock mechanics is not well defined or understood. Based on the author's experience, there are conditions encountered at underground gold mines in Nevada where engineering soil classification would be more appropriate, including highly altered material such as advanced argillic alteration, and faulted, folded and highly fractured rock masses. The Unified Soil Classification System (USCS) [ASTM (2011, 2009) D2487 and D2488], commonly applied in tunnel engineering projects (Hung et al. 2009; Parker 1996), is capable of describing these very weak ground to soil-like conditions. However, unlike the RMR rating system, the USCS is descriptive and uses letter-groups to classify material. Consequently, numeric spreadsheet calculations and geostatistical analyses are difficult to perform on material classified using the USCS. The authors propose the use of the USCS as a vehicle to characterize and predict the behavior of very weak rock to soil-like masses and present a numeric correlation between the RMR and USCS

classification systems for comparative purposes and to better define the boundary or transition between engineering rock and soil classification.

The USCS provides good insight into how a material may behave especially in the presence of water; however, it gives no indication of the relative strength of the material. In addition to USCS soil classification, civil-geotechnical engineering investigations usually include relative density or consistency estimates which are considered in the design process. Relative density or consistency estimates are typically made through a down borehole standard penetration test (SPT) (ASTM D1586-11) blow count or through field observations such as the ground reaction to hand pressure (cohesive soils), or reaction to a 1/2-in.-diameter rebar rod pounded with a 5-pound hammer (granular soils) (Parker 1996). To provide a strength index comparison for weak rock, the authors propose the Geo-Pick Strike Index (GPSI), defined as the number of blows with the pick end of a standard 22 ounce, 12–13 in. handle rock pick (geologic hammer) required to excavate or to penetrate the rock mass 1 in.

The USCS–RMR correlation, RMR rating equations, and the Geo-Pick Strike Index are collectively introduced as the Weak Rock Mass Rating System (W-RMR) and are capable of characterizing material from a wide range of geotechnical conditions. The W-RMR system is also the primary geotechnical input for empirical support recommendations for use at underground gold mines in Nevada presented by Warren (2016), and by Warren and Kallu (2016).

1.1 Methods

Many of the RMR-based empirical support design methods are based on experience in moderate- to good-quality rock or on civil engineering projects having little in common with underground mining conditions in Nevada. To add to the empirical database of support design in the weak rock mining environment and to develop additional empirical support design recommendations, the authors developed a database of 413 hand-on underground support case studies from several underground gold mines in Nevada. Parameters documented by the authors are listed below, and the field logging sheet is presented in Fig. 1.

- Excavation properties including: dimensions, depth, use, and location.
- Geotechnical parameters including: rock type, RMR (Bieniawski 1976, 1989, 2011), Geological Strength Index (GSI) (Marinos et al. 2005), Tunnel Quality Index (Q) (Grimstad and Barton (1993), USCS (ASTM D2488-09a), hand penetrometer test, and Geo-Pick Strike Index.

Location ID	Date		Location					
Mapper	Time							
Span/ Design Span	Depth	Drift Purpose		Description				
Height/Design Height	GSI behind zone							
Geotech Zone Length	GSI forward zone							
Rock Mass	Left Rib		Back		Right Rib		Notes/Comments	
Rock Type								
RMR	Value	Rating	Value	Rating	Value	Rating		
Weath/Alt								
Intact ISRM "R"								
RQD								
F/foot								
JCR avg								
G water								
Structure note								
Q Barton								
JN								
JR								
JA								
JW								
SRF								
Geotech cont.								
GSI								
Hand pen								
Pick strike/in								
USCS 2 letter								
Stiff/density								
Eng Soil/ rock								
Description								
Initial Support								
Support Ribs	Type	Length'	Pattern (RxL)	Capacity	Screen Type		Shotcrete type	
Bolt					height sill		thickness"	
					tight? 0-3		height sill	
					bagging ? 0-3		notes	
lowest bolt								
Support Back	Type	Length'	Pattern (RxL)	Capacity	Screen Type		Shotcrete type	
Bolt					overlap?		thickness"	
					tight? 0-3		notes	
					bagging? 0-3			
General Support Notes								
Excavation age			Drilled/ installed by			Arch Back 0-3		
Stability 0-3			Round Length			Other notes		
Support adequacy 0-3			Exposure dimensions					
Stress level note 0-3			support description conf 0-3					
Support sequence								
Describe instability/ sketch								

Fig. 1 Case study field logging sheet

- Installed support/reinforcement including:
 - Rock bolt type, length, spacing, and capacity.
 - Screen type, gauge, and height above sill.
 - Shotcrete type, thickness, and height above sill.
 - Excavation performance including: age, stability, and required rehabilitation.
 - Notes on stress, instability, support sequence, confidence parameters, sketches, etc.
 - Photographs and bulk samples when appropriate or possible.
- Acquired data were used to develop a geotechnical classification system presented in this paper and were used

to derive empirical support guidelines for use at underground gold mines in Nevada in the future presented by Warren (2016) and Warren and Kallu (2016).

2 Rock Mass Rating (RMR)

The Rock Mass Rating system (RMR) is the most commonly used engineering rock mass classification in Nevada for both underground and surface mining applications. RMR has stood the test of time and benefited from extensions and applications by many authors around the world (Bieniawski 1993). RMR has many advantages, including its relative ease of application, ability to directly compare rock quality across both surface and underground operations throughout a site, and its use in empirical relationships, including the Hoek–Brown failure criterion (Hoek and Marinos 2007). In addition, RMR is widely used as a geotechnical communication tool for both technical and non-technical staff and is reliable in fair- to good-quality rock masses.

2.1 Application of RMR in Weak and Highly Fractured Rock

It is widely recognized that the RMR system is difficult to apply to very weak rock masses (Hoek et al. 1995; Hoek and Marinos 2007; Mathis and Page 1995). Experience by the authors indicates that the most common method to calculate RMR in Nevada is using the tables presented in Bieniawski (1976, 1989), referred to subsequently as Bin-RMR₇₆ and Bin-RMR₈₉. Bin-RMR is convenient and works well for rocks of fair to good quality, but this method exacerbates the poor applicability of RMR in weak to very weak rock masses. The main problem with using Bin-RMR for weak rock mass classification is that ratings are not sensitive to changes in rock quality designation (RQD) when RQD < 25 % and fracture spacing is < 2.4 in. (60 mm) (RMR₈₉). For example, the RQD and fracture frequency ratings for sound rock with 24 % RQD and fracture spacing of 2.3 in. (59 mm) would receive the same Bin-RMR₈₉ ratings as clay, 3 and 5, respectively. The other problem with using the classification table is that RMR cannot be zero because of the implied minimum ratings of 3 and 5 for RQD and fracture spacing, respectively. Figure 2 shows that the minimum combined fracture spacing and RQD rating of eight accounts for 43 % of locations mapped for this study using the RMR₈₉ system. Clearly, the Bin-RMR method for calculating RQD and fracture spacing is not sensitive to the highly fractured and weak rocks found in Nevada underground gold mines.

Bieniawski (2011) addressed concerns and “misconceptions” related to the application of RMR in weak rock

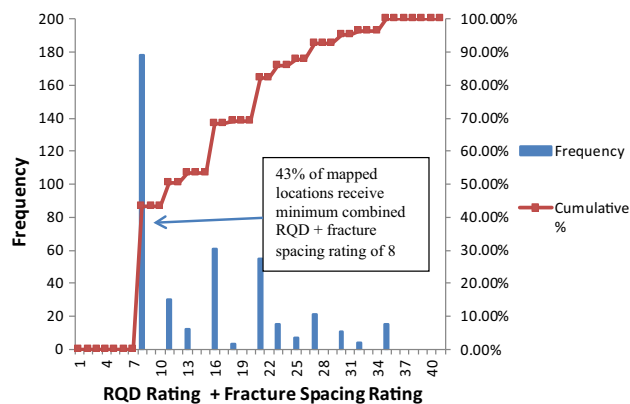


Fig. 2 Histogram of RQD plus fracture spacing ratings for the Nevada underground geotechnical data set

clarifying that the table ratings in Bieniawski (1989) are the “average rating for each range of parameters,” and he presented fracture frequency and RQD rating graphs bottoming out at zero. Note that Bieniawski (2011) was a clarification of the RQD and fracture spacing ratings of 1989 system and is referred to subsequently as RMR₈₉₋₁₁.

Bieniawski’s (2011) philosophy was applied to the RMR₇₆ system, and graphs were produced (Figs. 3 through 8) comparing RMR₈₉₋₁₁ to RMR₇₆. The rating systems were converted to units familiar to geotechnical engineers in Nevada, and best fit lines were applied to generate numerical equations to increase RMR sensitivity in weak rock and facilitate spread sheet calculations.

2.1.1 Fracture Frequency (FF) Rating

The fracture spacing or fracture frequency parameter of the RMR system is fundamentally a simple parameter to quantify; however, in practice, blast damage, healed joints, weakness planes, and foliation can complicate matters. For

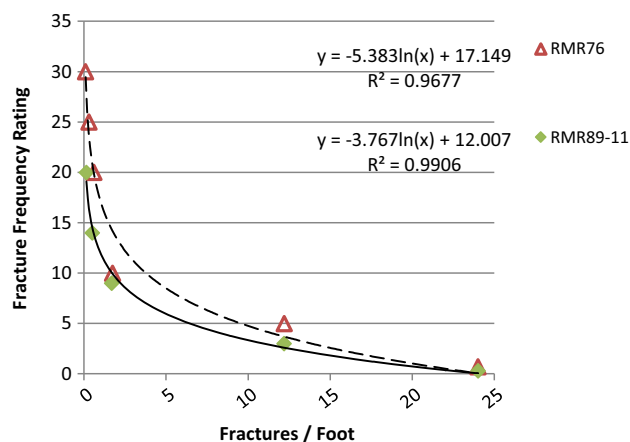


Fig. 3 Fracture frequency (frac/ft) ratings after Bieniawski (1976, 2011)

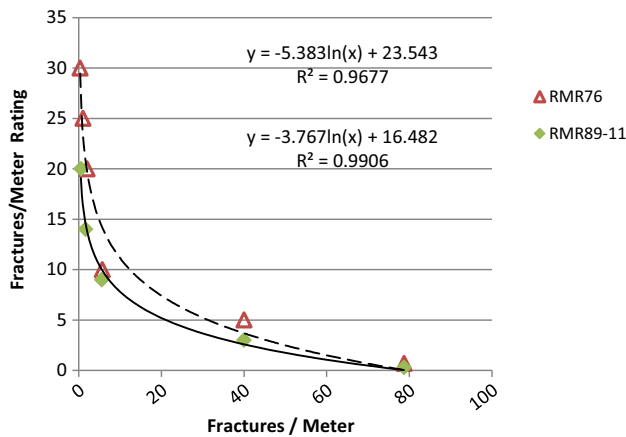


Fig. 4 Fracture frequency (frac/m) ratings after Bieniawski (1976, 2011)

core logging purposes, the authors recommend defining a discontinuity as unable to resist a tensile load by gentle hand pressure alone. For underground face mapping and stability considerations, blast damage can cause local fractures requiring bolting to prevent local wedge failures near the excavation, but often these discontinuities do not extend deep into the excavation. The intended application of the RMR rating, and thus, the fracture spacing, should be considered when determining the fracture spacing parameter. Fracture frequency (FF) ratings for the RMR₇₆ and RMR₈₉₋₁₁ rating systems are presented in the US customary and SI units as shown in Figs. 3 and 4, respectively. An upper bound for FF rating = 0 is not recommended or

made clear in Bieniawski (1976, 1989, 2011). Best fit lines through FF bin points generally point at FF rating = 0 for Fractures per Foot = 24/ft (78/m); therefore, this is taken as an upper bound for FF rating and is a convenient clast size of approximately one-half-inch (12.7 mm).

2.1.2 Rock Quality Designation (RQD) Rating

The rock quality designation (RQD) parameter was introduced by Deere et al. (1967) and is defined as a modified core recovery percentage in which all the pieces of *sound* core over 100 mm (4 in.) are summed and divided by the length of the core run. RQD is an index of rock quality in that problematic rock, that is, highly weathered/altered, soft, fractured, sheared, and jointed, is counted against the rock mass and thus is simply a measurement of the percentage of good rock recovered from an interval of a corehole (Deere and Deer 1988). The definition of *sound* core is somewhat ambiguous and can have different meanings for different practitioners depending on project needs; however, for general purposes, the authors consider any rock that can be peeled by a knife (ISRM R2 “weak rock”) (Table 1) as not sound rock. RQD ratings for RMR₇₆ and RMR₈₉₋₁₁ are presented in Fig. 5. Note that RMR₇₆ reaches a maximum rating of 20 at RQD = 95 %, while RMR₈₉₋₁₁ reach maximum rating at RQD = 100 %. This is mainly because of RMR₇₆, RQD rating of 20 is for RQD = 90–100 or an average of 95. Because of negligible difference and for simplicity, the RMR₈₉₋₁₁ RQD ratings are recommended for the RMR₇₆ system as well.

Table 1 ISRM strength modified from Brown (1981) and Hoek (2007)

ISRM R strength	Description	Field identification	Uniaxial compressive strength (MPa)	Uniaxial compressive strength (psi)	Examples
R0	Extremely weak rock	Indented by thumbnail	0.25–1	36–145	Stiff fault gouge
R1	Very weak rock	Crumbles under firm blows with a geological hammer	1–5	145–725	Highly weathered or altered rock
R2	Weak rock	Can be peeled with a pocket knife, shallow indentations made by firm blow of a geological hammer	5–25	725–3625	Chalk, rocksalt, potash
R3	Medium strong rock	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single firm blow of a geological hammer	25–50	3625–7250	Concrete, limestone shale, siltstone, coal, schist
R4	Strong rock	Specimen requires more than one blow of a geological hammer to fracture	50–100	7250–14,500	Limestone, marble, phyllite, sandstone, shale, dolomite
R5	Very strong rock	Specimen requires several blows of a geological hammer to fracture	100–250	14,500–36,250	Basalt, gneiss, granite, dolomite
R6	Extremely strong rock	Specimen can only be chipped with geological hammer	>250	>36,250	Quartzite, chert, granite, gneiss

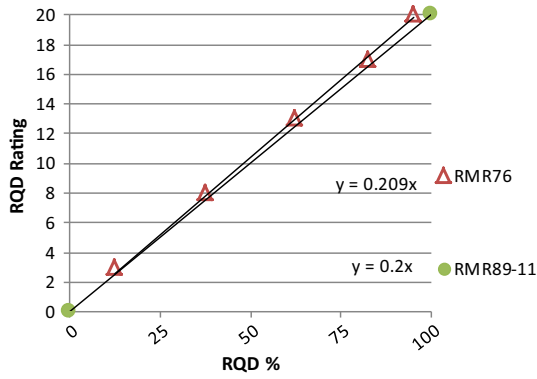


Fig. 5 RQD ratings after Bieniawski (1976, 2011)

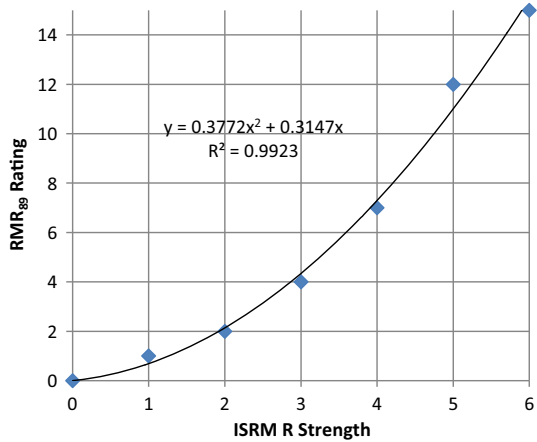


Fig. 6 Intact rock strength ratings after Bieniawski (1989). ISRM R strength from Brown (1981)

2.1.3 Intact Rock Strength Rating

The intact rock strength parameter is straightforward for rocks masses that are relatively homogenous; however, this parameter gets complicated in altered and weathered material of varying intact rock strength. The authors recommend documenting the range of intact rock strength; however, for rating simplicity, the average intact rock strength should be used. Intact rock strength ratings for RMR₈₉ are presented in Fig. 6 which reflects the ISRM recommended “grade” or R strengths (Brown 1981) presented in Table 1. It is the author’s experience that consultants for underground mine operations in Nevada using RMR₇₆, often assign intact rock strength ratings based on the RMR₈₉ system. Because the allocated intact rock strength points for RMR₈₉ and RMR₇₆ are equal (15), and the ratings for the RMR₈₉ system are more sensitive to weak rock strength, the authors also agree with the application of RMR₈₉ intact rock strength ratings to the RMR₇₆ system.

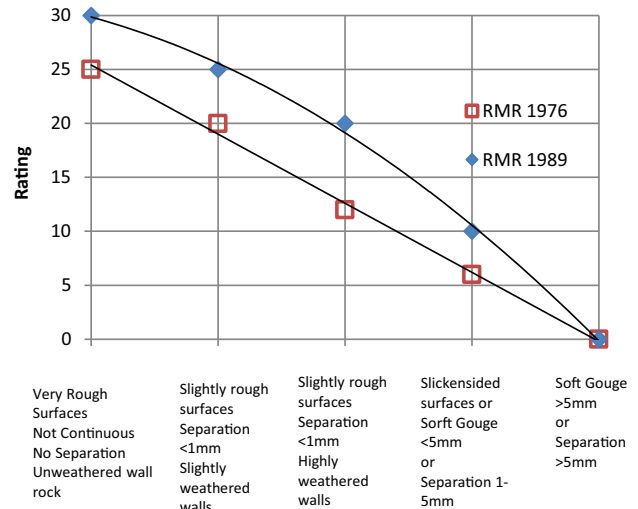


Fig. 7 Condition of joint ratings after (Bieniawski 1976, 1989)

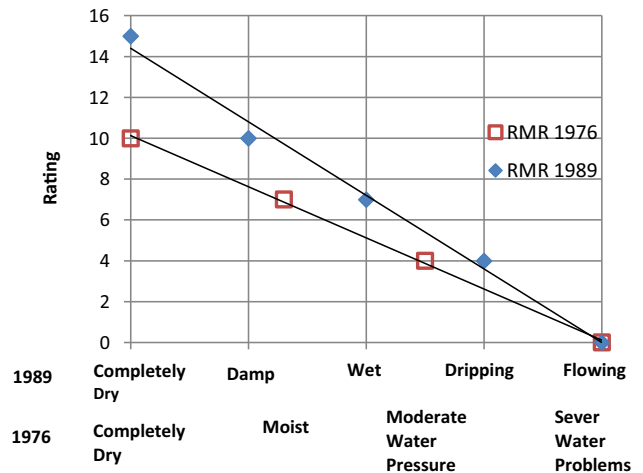


Fig. 8 Groundwater ratings after Bieniawski (1976, 1989)

2.1.4 Condition of Joints and Groundwater Rating

For RMR completeness and comparative purposes, the condition of joints and groundwater rating values are presented in Figs. 7 and 8. The authors recommend interpolating between rating categories as necessary.

2.2 Suggested RMR Numerical Formulas for Use in Weak Rock

Based on Figs. 3 through 5, the following equations are recommended to be used for calculation of RMR in weak rock masses. Use of Eqs. 1 through 6 for fracture frequency, RQD, intact rock strength, plus joint condition and ground water ratings from Bieniawski (1976, 1989) are

subsequently referred to as Equation-RMR (abbreviated as *Eq-RMR*).

*Eq-RMR*₇₆:

$$\text{Fracture frequency rating} = -5.383 \ln \frac{\text{Discontinuities}}{\text{Foot}} + 17.149 \quad (1)$$

(for $0.1 < \text{FF} < 25$)

$$\text{Fracture frequency rating} = -5.383 \ln \frac{\text{Discontinuities}}{\text{Meter}} + 23.543 \quad (2)$$

(for $0.3 < \text{FF} < 83$)

*Eq-RMR*₈₉₋₁₁:

$$\text{Fracture frequency rating} = -3.767 \ln \frac{\text{Discontinuities}}{\text{Foot}} + 12.007 \quad (3)$$

(for $0.15 < \text{FF} < 25$)

$$\text{Fracture frequency rating} = -3.767 \ln \frac{\text{Discontinuities}}{\text{Meter}} + 16.482 \quad (4)$$

(for $0.5 < \text{FF} < 83$)

*Eq-RMR*₇₆ and *Eq-RMR*₈₉₋₁₁:

$$\text{RQD rating} = 0.2 (\text{RQD}\%) \quad (5)$$

(for $\text{RQD} = 0\text{--}100$)

$$\text{Intact rock strength rating} = 3.772 (\text{ISRM R})^2 + 0.3147 (\text{ISRM R}) \quad (6)$$

(For ISRM R 0–6)

Eq-RMR and traditional Bin-RMR calculations were applied to a data set obtained from underground geotechnical mapping by the authors at 413 underground locations in Nevada. Figures 9 and 10 show that *Eq-RMR*₇₆ and *Eq-RMR*₈₉₋₁₁ result in lower RMR values and a smoother transition of RMR values from $\text{RMR} < 35$ and provides more sensitivity in this range. Above $\text{RMR} = 35$, the bin and equation rating systems are approximately in agreement, making *Eq-RMR*₇₆ and *Eq-RMR*₈₉₋₁₁ equations compatible with Bin-RMR₇₆ and Bin-RMR₈₉₋₁₁, respectively.

The authors recommend the use of the *Eq-RMR*₇₆ and *Eq-RMR*₈₉₋₁₁ at locations with weak rock masses below $\text{RMR} \sim 35$ to increase the sensitivity of RMR, making comparisons between weak rock more apparent. The use of this *Eq-RMR* should also improve the use of current and future empirical design tools by picking up small changes in rock quality that the traditional Bin-RMR rating system would lump together.

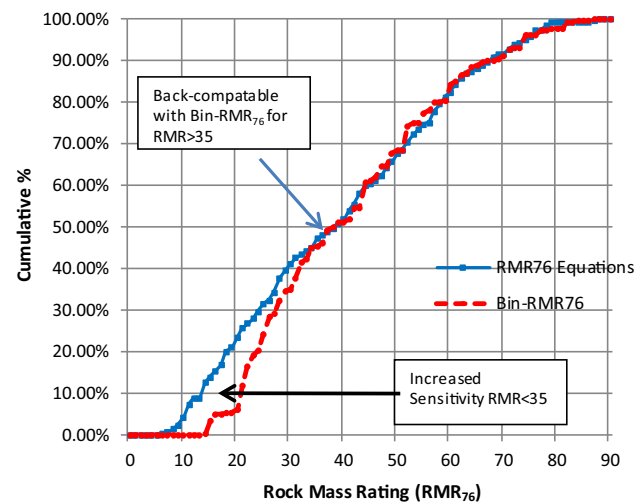


Fig. 9 Histogram of case study RMR values. *Eq-RMR*₇₆ is more sensitive for $\text{RMR} < 35$. *Eq-RMR*₇₆ and Bin-RMR₇₆ are approximately back-compatible for $\text{RMR} > 35$

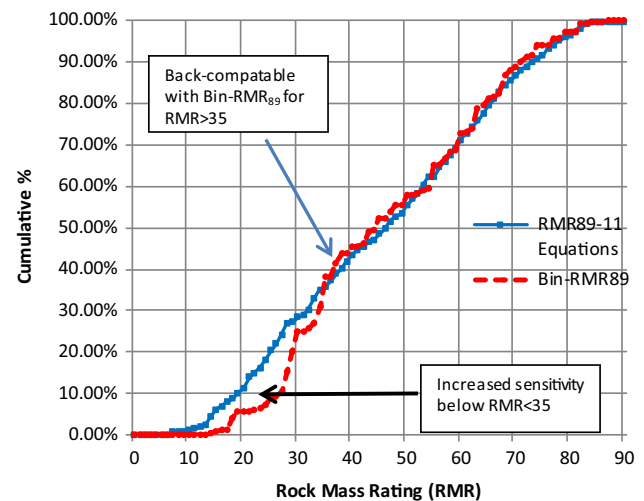


Fig. 10 Histogram of case study RMR values. *Eq-RMR*₈₉₋₁₁ is more sensitive for $\text{RMR} < 35$. *Eq-RMR*₈₉₋₁₁ and Bin-RMR₈₉₋₁₁ are approximately back-compatible for $\text{RMR} > 35$

3 Soil Classification for Classification of Very Weak Rock

Because weak rock represents the transition between rock and soil, engineering soil classification systems are likely to be useful to classify this type of material. Terzaghi (1950) recognized the need to describe or anticipate the behavior of weak ground/soil in a tunneling environment when he introduced the *Tunnelman's Ground Classification for Soils*, describing soil as: firm, raveling, squeezing, running, flowing, and swelling. Excavation design and construction strategy are influenced by ground behavior; therefore, a formal classification system capable of predicting ground behavior is useful.

Table 2 Unified soil classification system (USCS) modified from ASTM D2487-11

Major division	USCS group symbol	Typical description	Possible ground behavior ^a
Fine grained soils clays and silts >50 % (by weight) passing the 75 µm (#200) sieve	CH	High-plasticity clay	Squeezing
	CL	Low-plasticity clay	Squeezing
	MH	High-plasticity silt	Squeezing
	ML	Low-plasticity silt	Squeezing
Coarse grained soils sands and gravels may contain up to 49 % silt and clay >50 % (by weight) coarser than 75 µm (#200) sieve	SC	Clayey sands	Squeezing, raveling
	SM	Silty sands	Squeezing, raveling
	SW	Clean sand—well graded	Raveling
	SP	Clean sand—poorly graded	Raveling
	GC	Clayey gravel, sand-clay-gravel	Squeezing, raveling
	GM	Silty gravel, gravel-sand-silt	Squeezing, raveling
	GW	Clean gravel—well graded	Raveling, possible squeezing
	GP	Clean gravel—poorly graded	Raveling, possible squeezing

^a Possible ground behavior based on authors' experience in Nevada

3.1 Unified Soil Classification System (USCS)

Based on work by Casagrande (1948), the USCS (ASTM D2487 and D2488) has become the standard geotechnical engineering soil classification for civil engineering applications system in the USA (ASTM D2487-11, and Das 2011), including tunnel engineering applications (Hung et al. 2009 and Parker 1996). Correlations intended to predict raveling and running conditions roughly based on the USCS have been proposed by Deere et al. (1969) and Heuer and Virgens (1987). Advantages of the USCS include: (1) Standardized ASTM classification procedures; (2) Empirical correlations to engineering properties, including friction angle, cohesion, permeability, and elastic moduli; (3) Ease of use for field classification (ASTM D2488); and (4) Commercial availability of laboratory testing equipment. Major divisions and group symbols of the USCS including possible ground behavior are presented in Table 2.

Unified Soil Classification System group symbol classification can provide insight into ground behavior which can assist engineers with excavation strategy, sequencing, and support design. For example, clean sands and gravels often require a flash coat of shotcrete (prior to bolting) from roof to floor to prevent raveling in the back or hollowing behind shotcrete-covered ribs. Long-term development in squeezing ground may require heavy support and/or high-strain capacity ground support, while production openings may require faster advance rates and continuous mining so areas can be mined out and backfilled before squeezing becomes a serious problem. Whether the classification is completed on drill core as part of a geotechnical investigation or at the face of an active underground mine, the USCS can provide insight into material behavior and excavation strategy.

3.2 Correlations Between RMR and USCS Classification Systems

To better define the boundary between engineering soil and rock classification, bulk samples (Fig. 11) were taken from 70 underground RMR classification sites in Nevada and were tested in a laboratory to determine a correlation between the USCS and RMR systems. Samples were tested in accordance with:

- Sieve analysis of fine and coarse aggregates [ASTM (2004) D6913-04].
- Liquid limit, plastic limit, and plasticity index of soils [ASTM (2010a) D4318-10].
- Laboratory determination of water (moisture) content of soil and rock by mass [ASTM (2010b) D2216-10].



Fig. 11 Bulk samples of very weak rock taken from RMR mapped locations underground

Classification of the samples was determined in accordance with ASTM D2487-11, classification of soils for engineering purposes (Unified Soil Classification System), except when a dual classification was required. For ease of numerical classification, a single USCS classification was determined by evaluating which group the material most closely resembled. For example, if a sample was classified as a GP-GC, the percent fines measurement was used to determine a single-group classification.

Figures 12 and 13 show a reasonable correlation between Eq-RMR₇₆/Eq-RMR₈₉ and the USCS based on mapping and sampling at sites with zero RQD. To cover the transition between the USCS and RMR systems, sites with up to 25 % RQD (very poor quality) were plotted. Note that material not passing a 3-in. sieve is not included in the USCS classification.

Based on Figs. 12 and 13, Figs. 14 and 15 are created to be used as a correlation between the USCS and RMR system for use in poor-quality rock masses at underground gold mines in Nevada.

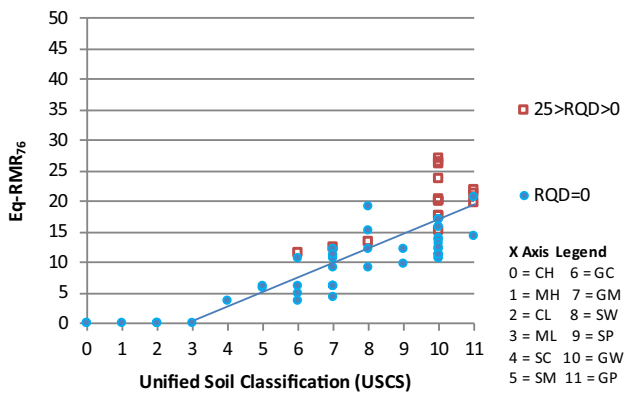


Fig. 12 Laboratory determination of USCS vs. Eq-RMR₇₆. Zero points for groundwater

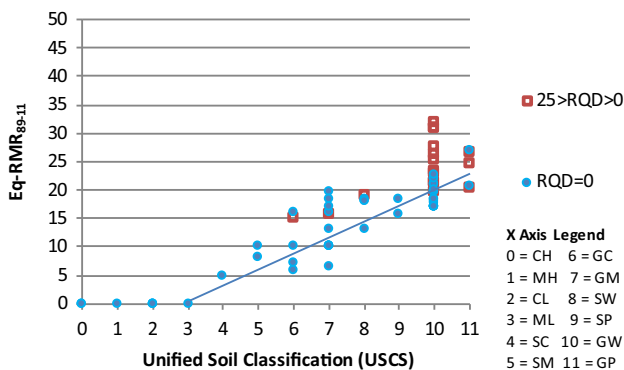


Fig. 13 Laboratory determination of USCS versus Eq-RMR₈₉₋₁₁

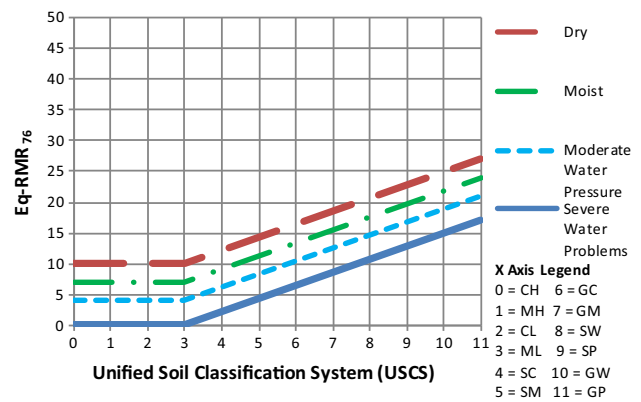


Fig. 14 Suggested correlation of USCS with Eq-RMR₇₆

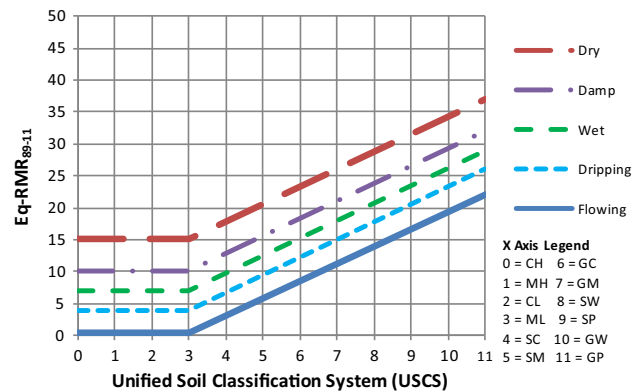


Fig. 15 Suggested correlation of USCS with Eq-RMR₈₉₋₁₁

3.2.1 Derivation of the RMR–USCS Correlation

The creation of a rock–soil classification correlation required some consideration outside of geotechnical mapping, sampling, and testing. As noted before, the application of the RMR system in very weak rock to soil-like conditions is difficult, and for practical purposes, a bottom or zero RMR had to be established. The entire fine grained soils group with >50 % passing #200 sieve (CH, MH, CL, ML) under flowing groundwater conditions is assumed to exhibit zero to few rock-like properties; consequently, this group was defined as 0 RMR. The rating of these materials is entirely dependent on the RMR ground water condition rating for both RMR 1976 and RMR 1989.

Coarse grained soils are defined as >50 % retained on the #200 sieve. Sands and particularly gravels, with clast size up to 3 in., are considered rock–soil transition-type materials that can be classified using the RMR system. These coarse materials were classified and ordered as shown in Figs. 12 and 13 based on their respective RMR ratings.

3.2.2 Use of the RMR-USCS correlation

Instead of attempting the difficult task of applying the RMR system to a soil-like material, a numeric RMR value can be assigned to the material by first determining the “group” USCS classification using ASTM D2487-11 or D2488. This material type is plotted on the x axis in Figs. 14 or 15 (depending on RMR system used) and combined with the observed or anticipated groundwater condition to estimate an equivalent RMR rating.

This USCS–RMR correlation was developed to assign a numeric RMR value to USCS classified material for geo-statistical calculation of RMR data on weak soil-like material. The correlation also provides a link between the systems for comparative purposes and better defines the boundary between engineering rock and soil classification. The applicability of this correlation as it relates to established empirical relationships including the Hoek–Brown failure criterion and elastic moduli correlations has not been investigated. Use of the RMR–USCS correlation in these empirical relationships should be approached with caution.

4 Geo-Pick Strike Index (GPSI)

The USCS provides good insight into how a material will behave, particularly in the presence of water, but gives no indication of the relative strength of the material. Civil engineering geotechnical investigations typically acquire samples for USCS using a downhole standard penetration test (SPT) (ASTM D1586-11) which uses a standardized hammer to drive a standardized hollow tube into the ground for sampling. The number of blows (commonly referred to as blow count) required to drive the sample tube 1 foot is recorded as the “ N ” value and is used in engineering applications including foundation design (Das 2011). When SPT tests are not available, the N -value or relative density can be estimated through field tests such as ground reaction to hand pressure (cohesive soils), or reaction to a 1/2-in.-diameter rebar rod pounded with a 5-pound hammer (granular soils) (Parker 1996). SPT tests are typically not available or applicable in underground mines, and experience by the authors has shown that weak rocks at underground mines in Nevada are generally too strong for the field test described previously. A strength index that can put a “number” on the reaction of the rock mass to kinetic energy would be useful for a strength index comparison.

To satisfy the need for a strength index, the Geo-Pick Strike Index (GPSI) was defined by our research group as the number of blows with the pick end of a standard 22 ounce, 12- to 13-in. handle, rock pick (geologic



Fig. 16 Photograph of a weak rock mass with a Geo-Pick Strike Index (GPSI) of approximately one

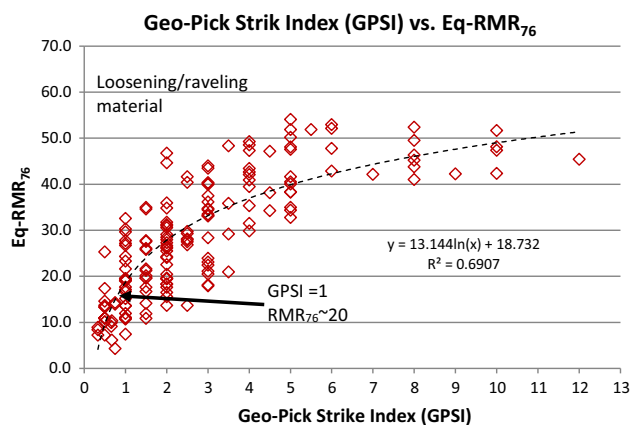


Fig. 17 Correlation of the Geo-Pick Strike Index with Eq-RMR₇₆

hammer) required to excavate or to penetrate the rock mass 1 in. Figure 16 shows a rock mass with a GPSI of approximately one. GPSI was selected as a weak rock mass parameter because: (1) A geologic hammer or pick is a common tool carried by geo-type personnel; (2) geo-type personnel often strikes the rock mass for a variety of reasons (including ore control sampling), and this parameter makes use of this action; (3) GPSI is a simple, intuitive index that gives a good “real world” relative comparison of weak rock mass strength and gives the “upstairs engineer” a feel for the rock mass. Correlations of Eq-RMR₇₆ and Eq-RMR_{89–11} to the GPSI which are derived from support case studies are presented in Figs. 17 and 18, respectively.

The Geo-Pick Strike Index (GPSI) is useful in that it allows comparison of the complex interaction of rock mass properties including intact strength, fracture spacing, condition of joints, and water content. Figure 16 indicates that depending on the RMR system used, the GPSI is useful in comparing weak ground from around GPSI = .33

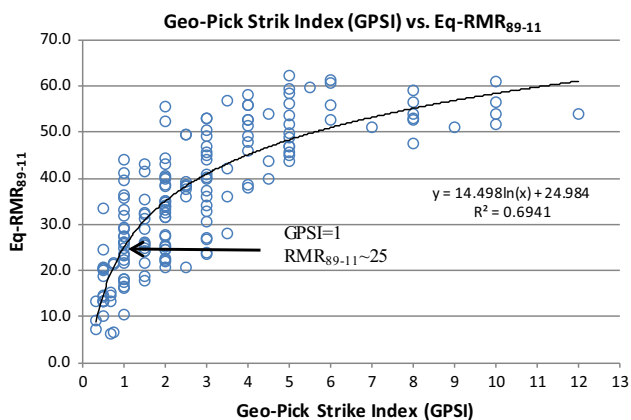


Fig. 18 Correlation of the Geo-Pick Strike Index with Eq-RMR₈₉₋₁₁

(3 in./strike) representing very weak material, to around GPSI = 5 or 6 (5–6 strikes/in.) representing ground with an RMR of 30–50. Experience by the authors indicates that the GPSI can identify squeeze potential ground (GPSI < 1), and raveling ground which might rate as RMR 40–50 but raveling several inches when struck by a geo-pick.

Part of the job of an underground geotechnical engineer is making decisions regarding difficult ground conditions or unusual circumstances. Ideally, the engineer would visit a geotechnical site in question and actually strike the rock mass to get a good idea of its properties before making a decision about how to proceed; however, limited resources and time restraints often prohibit a site visit. The advantage of the GPSI is that it gives the engineer who did not get a chance to see a weak rock mass, an intuitive idea of the how the rock behaves when struck with a hammer as he likely would have done under ideal circumstances. The authors believe that the GPSI is one more way of putting a “number” on the rock mass quality which can be used as a communication and relative comparison tool for use in poor-quality rock masses.

5 Weak Rock Mass Rating System (W-RMR)

The number of RMR-related methods and classification procedures presented in the literature over the years is staggering particularly to the dedicated investigator. The authors have been involved in projects where RMR data were called into question because little was known about the version or classification procedures used. For these reasons, the version and methods used to calculate RMR should always accompany reported RMR data. The authors recommend that the overall geotechnical classification approach described in this paper be referred to as the Weak Rock Mass Rating System or W-RMR₇₆ or W-RMR₈₉₋₁₁ depending on the version used.

6 Summary and Conclusions

Underground gold mines in Nevada encounter ground conditions ranging from highly altered and fractured soil-like material to blocky competent rock. The Rock Mass Rating (RMR) system is a common and entrenched engineering rock mass classification tool used in Nevada, and is likely to remain a staple classification system in the future. It is widely accepted that the RMR system is difficult to apply in weak and highly fractured rock masses, which is at least in part a consequence of common RMR rating practices that exacerbate the inapplicability of RMR in poor-quality rock masses. RMR rating formulas presented in this paper increase the sensitivity of RMR in weak ground and extend its application deeper into the poor-quality rock mass spectrum while ensuring back-compatibility with traditional RMR rating methods in fair- to good-quality ground.

The boundary or transition between engineering rock and soil classifications is not well defined, and some ground conditions encountered at underground mines in Nevada can more easily and reliably be classified using the Unified Soil Classification System (USCS). The USCS is commonly used in the tunneling industry and is introduced as a vehicle to classify and predict properties of weak, highly altered, and fractured materials. To place a numeric value on USCS classification for geostatistical analyses, and to better define the boundary between engineering and rock and soil classification, a correlation between the USCS and RMR classification is presented. Users are cautioned that the use of this correlation in established empirical tools including the Hoek–Brown failure criterion and elastic moduli correlations has not been investigated.

Geotechnical classification is more useful when accompanied by a strength or density description as is often documented for civil-geotechnical engineering investigations. The Geo-Pick Strike Index (GPSI) is introduced as a weak rock strength index defined as the number of blows with the pick end of a standard 22 ounce, 12- to 13-in.-long-handle rock hammer, required to penetrate or excavate the rock mass 1 in. The GPSI is useful in that it compares the complex interaction of rock mass properties including intact rock strength, fracture spacing, and moisture content between locations. The advantage of the GPSI is that it gives an intuitive idea of how the rock mass reacts to a hammer strike when limited resources prohibit the engineer from visiting the site in question.

The USCS–RMR correlation, RMR rating equations, and the Geo-Pick Strike Index are collectively introduced as the Weak Rock Mass Rating System (W-RMR), and is capable of characterizing material from a wide range of geotechnical conditions ranging from competent rock to soil-like material. The W-RMR system was developed for

and is used as input for empirical ground support recommendations for use at underground gold mines in Nevada presented by Warren (2016) and Warren and Kallu (2016). The authors feel that this comprehensive but not overly complicated classification approach will result in more reliable use of existing empirical design tools and facilitate the development of future empirical relations for use in poor-quality rock masses.

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