Peck W, 2000. ***Australian Geomechanics, Journal and News of the Australian Geomechanics Society, 35(2)***

Determining The Stress Reduction Factor In Highly Stressed Jointed Rock

By W Peck [1]

Introduction

A number of Australian underground mines are using empirical rating systems to characterize the ground conditions in developmental headings for geotechnical design. The two best-known rating systems are Barton's Rock Tunnelling Quality Index (Q-System, also known as the NGI System) and Bieniawski's Rock Mass Rating (RMR, also known as the Geomechanics Classification). As the RMR makes no allowance for high ground stresses at depth, Barton's Q-System is more likely to be used in deep Australian underground mines. The Q-value is determined from equation 1 using the six parameters listed in table 1. The numerical value of Q ranges from 0.001 (exceptionally poor) to 1000 (exceptionally good) quality rock.

Table 1 - ***Parameters used to determine the value of Q in Barton's Q-System.***

$$Q = (RQD / Jn) \times (Jr / Ja) \times (Jw / SRF) \qquad (1)$$

Parameter	Symbol	Quantifies	Min.Value	Max.Value
Rock Quality Designation	RQD	Rock mass quality	10	100
Joint Set Number	Jn	Joint pattern	0.5	20
Joint Roughness Number	Jr	Frictional characteristics of joint walls	0.5	4
Joint Alteration Number	Ja	Properties of joint infillings	0.75	20
Joint Water Reduction Factor	Jw	Water effects	0.05	1.0
Stress Reduction Factor	SRF	Stress effects, loosening & swelling loads	0.5	400

Quantification of the Stress Reduction Factor

The Stress Reduction Factor (SRF) assesses loosening loads in weakness zones, rock stress concerns in competent rock and squeezing loads in plastic incompetent rocks. One difficulty in using the Q-System is quantification of the SRF for those sections of highly stressed rock masses that are not located in weakness zones such as shears and faults. In the deeper levels of Australian mines and where problems with rock stress are experienced, the SRF for areas not located in weakness zones is likely to be assessed as

> *"b) Competent rock, rock stress problems (σ_c = unconfined compressive strength; σ_1 = major principal virgin stress)*
>
> L. Moderate slabbing after > 1 hour in *massive* rock; $\sigma_c / \sigma_1 = 5 - 3$; SRF = 5 – 50*"*

using the most recently published Q tables (Barton and Grimstad, 1994). The Q-System tables seem to include in the competent category both massive rock and jointed rock that is not in a weakness zone.

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No criteria are given for making a choice within the range of 5 to 50 but, as can be seen from equation 1, whether the SRF rating is 5 or 50 affects the overall Q-value by an order of magnitude! Some guidance is clearly needed as to the interpolation of SRF-values within these wide limits. The tables state that this rating applies to massive rock and hence one can assume it is most unlikely to also apply to jointed rock, yet the SRF rating tables do not give ratings for jointed rock with a strength/stress ratio (σ_c / σ_1) less than 5.

When the Q-System was updated (Grimstad and Barton, 1993), the greatest changes were made to SRF values in highly stressed rock. Case studies were reported to have *"shown that in the most extreme cases of high stress and hard massive (unjointed) rock, the maximum SRF-value has to be increased from 20 to 400 in order to give a Q-value which correlates with the modern rock support"*. Table 2 indicates the magnitude of the changes for highly stressed rock. Typical of the changes is an old SRF of 9 becomes a new SRF of 50.

The absence of SRF ratings for highly stressed jointed rock masses is unfortunate. In the author's experience the old SRF values given in table 2 produced good results for jointed rock masses even though the 1974 rating table specified they applied to massive rock. When the new SRF values were published, the doubt was then created as to whether they applied to jointed rock as well as to massive rock. Are SRF values in excess of 20 realistic? As originally published in 1974, the upper limit was 10, except for heavy swelling rock pressure (10-15) or heavy squeezing rock pressure and heavy rock burst which both rated 10-20. A number of practitioners have not accepted the new ratings, particularly SRF-values >20, and adhere to the original 1974 rating tables. An example is the SRF graph presented as figure 2.14.7 in the book ***"Cablebolting in Underground Mines"*** (Hutchinson and Diederichs, 1996) which has a maximum SRF of 20. The author is not aware of any documented Australian case where an SRF >20 was appropriate for jointed or massive rock. More local case histories need to be published.

Table 2. ***Comparison of old and new SRF values in relation to stress-strength ratios (after Grimstad and Barton, 1993).***

σ_C / σ_1	OLD SRF	NEW SRF
5	**5**	**5**
3	**9**	**50**
2	**15**	**200**

SRF-Values Above 20 Apply Only To Massive Rock

Evidence to support the proposition that the new SRF ratings above 20 do not apply to jointed rock, can be found in the Q-System database for sites with high SRF values. This data is presented as a plot of SRF versus the ratio RDQ/Jn in Figure 3 of Grimstad and Barton (1993). The ratio RQD/Jn is roughly proportional to the block size of rock masses. Of the data plotted with SRF > 20, the vast majority (83%) of the points had a RQD/Jn ratio of 50 or over, and 94% of the points had a RQD/Jn ratio above 30. The lowest RQD/Jn ratio plotted on the graph is 13. RQD/Jn ratios above 30 equate to relatively large block sizes, with excellent RQD ratings combined with either few joints (Jn = 0.5 - 1), or one joint set (Jn = 2), or one joint set plus random joints (Jn = 3). They do not represent blocky rock.

A typical Australian underground mining situation was presented in Table 1 of Technical Update No. 1 (1999) of the Western Australian Department of Minerals and Energy (WADME). That example has an RQD of 70% and three joint sets (Jn = 9). These values give a RQD/Jn value of 7.8, which is about half that of the lowest data point plotted on Figure 3 of Grimstad and Barton (1993). Only one conclusion can be drawn from this data; the WADME example is jointed rock with an RQD/Jn ratio that is far too low to be eligible for Grimstad and Barton's SRF ratings of 20 - 400. This was confirmed by Dr. Barton. *"The RQD/Jn "relative block size" (or degree of freedom) concept does indeed mean that RQD/Jn of approx 70/9 would be unlikely to have (need) a high SRF as the greater deformation/deformability of such rock would leave the highest tangential stresses well away from the mining/tunnelling perimeter. It would certainly not be classified as massive rock either"* (Barton, 2000).

SRF Varies Exponentially

Table 2 does not give SRF-values for $\sigma_c / \sigma_1 = 4$. The interpolation of an SRF-value for massive hard rock with a strength/stress ratio of 4 ($\sigma_c / \sigma_1 = 4$) requires a knowledge of whether the variation is linear or exponential in the range 5 to 50. If an exponential variation of SRF with σ_c / σ_1 is assumed, the answer is SRF = 15. But if a linear variation is assumed, one would get SRF = 27.5. When the SRF values for σ_c / σ_1 = 2, 3 and 5 (given in Table 2) are plotted on linear and logarithmic graph paper, the SRF/(σ_c/σ_1) relationship seems exponential. This was confirmed by Dr. Barton who wrote *" I think you are correct to assume an exponential SRF - σ_c / σ_1 relation, rather than linear; this fits the concept of a "logarithmic" scale of Q–value somewhat better"*(Barton, 2000).

The exponential relationship that applies to the old SRF values given in Table 2 is

$$\mathbf{SRF} = 34(\sigma_C / \sigma_1)^{-1.2} \qquad (2)$$

For strongly anisotropic virgin stress fields (if measured) Barton et al (1974) provided a correction to the SRF-value by downrating σ_c. The following relationship provides the best fit through the data. $\boldsymbol{\sigma_3}$ is the minor principal virgin stress.

$$\mathbf{SRF} = 31(\sigma_1 / \sigma_3)^{0.3}(\sigma_C / \sigma_1)^{-1.2} \qquad (3)$$

The above relationships are for the calculation of SRF in those sections of highly stressed jointed rock masses not located in weakness zones. They are based on the author's observations at Broken Hill in jointed rock and on Barton's data, prior to the inclusion of the eight tunnels with strong massive rock and high stresses (Grimstad, 1984). They can be used to determine SRF for highly stressed jointed rock, until such time as they are updated following publication of further Australian case studies.

Kirsten's SRF Equations

Another means of quantifying SRF was provided when Kirsten (1988) published the following relationship to determine $\mathbf{SRF_h}$ applicable to high stress environments. Since the maximum principal stress is essentially vertical in Southern Africa, the input parameters he used are **H** ("the head of rock corresponding to the maximum principal field stress") $\boldsymbol{\sigma_c}$ (UCS) and **K** ("maximum-to-minimum principal field stress ratio").

$$\mathbf{SRF_h} = 0.244K^{0.346}(H / \sigma_c)^{1.322} + 0.176(\sigma_c / H)^{1.413} \qquad (4)$$

Equation 4 requires σ_1 to be expressed as the “head of rock” which is quite sensible for South Africa’s gold fields, where σ_1 is generally vertical, but is not appropriate for Australia where σ_1 is more likely to be horizontal. Assuming an overburden weight of 25kN/m^3 the equation to suit Australian conditions becomes: -

$$\mathbf{SRF_h = 32K^{0.346}(\sigma_c/\sigma_1)^{-1.322} + 0.00096(\sigma_c/\sigma_1)^{1.413}} \qquad \mathbf{(5)}$$

The second term has negligible impact if σ_c/σ_1 is < 15. When σ_c/σ_1 is greater than 15, SRF values are low (around 1 or less). Hence, for practical purposes in high stress environments, the second term can be omitted and the SRF equation simplifies to:-

$$\mathbf{SRF_h = 32K^{0.346}(\sigma_c/\sigma_1)^{-1.322}} \qquad \mathbf{(6)}$$

Mining geotechnical engineers often think in terms of σ_1/σ_3 rather than **K.** If equation 6 is rewritten in terms of σ_1/σ_3 it becomes:-

$$\mathbf{SRF_h = 32(\sigma_1/\sigma_3)^{0.346}(\sigma_C/\sigma_1)^{-1.322}} \qquad \mathbf{(7)}$$

Equation 7 is very similar to the author’s equation (3), which is based mainly on Barton’s old SRF data. As the Q-System is empirical, the only way to further develop a better SRF relationship for highly stressed jointed rock masses in Australia, is to back-calculate it from local case histories. This process must assume that the installed rock support is correct and that the other five Q-parameters are accurately known.

Revised SRF Chart For Australian Conditions

Based on the available Australian case histories, a revised SRF Rating Chart is proposed for Australia to replace the current chart for Category (b) Competent rock, rock stress problems. The revised chart recognizes an additional case of jointed, highly stressed rock, frequently encountered in Australian mines. In the absence of Australian case histories for ***massive*** rock where SRF >20 was appropriate, it lists SRF ratings found to be appropriate in Australian mines to date.

It is proposed that the current cases in the other SRF rating categories - (a) Weakness zones, (c) Squeezing rock and (d) Swelling rock - remain unchanged.

Conclusions

While the new Q-System tables provide appropriate SRF-values for weakness zones such as faults and shears, they do not seem to provide appropriate SRF values for the highly stressed jointed rock masses frequently encountered in Australian underground mines. The new SRF-values above 20 given by Grimstad and Barton (1993) only apply to massive rock and not to jointed rock. There are no published Australian case studies to date where an SRF >20 was appropriate for highly stressed massive or jointed rock. A Revised SRF Rating Chart for Australian conditions has been presented.

Should it be necessary to interpolate an SRF value for highly stressed rock, SRF has been shown to vary exponentially with the strength/stress ratio (σ_c/σ_1).

Table 3 - ***Proposed Revised SRF Rating Chart for Australian competent rock masses with rock stress problems.***

(b)	***Rock stress problems, competent rock, Australia***	σ_c/σ_1	σ_θ/σ_c	**SRF**
H*	Low stress, near surface, open joints	**> 200**	**< 0.01**	**2.5**
I*	Medium stress, favourable stress condition	**200 - 10**	**0.01 – 0.3**	**1**
J*	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability.	**10 - 5**	**0.3 – 0.4**	**0.5 – 2**
K	High stress, jointed rock. RQD/Jn < 30. If σ_3 is known then **SRF = 31**$(\sigma_1/\sigma_3)^{0.3}(\sigma_C/\sigma_1)^{-1.2}$ **(3)** **else SRF = 34**$(\sigma_C/\sigma_1)^{-1.2}$ **(2)**	**10 – 1.5**	**0.3 - >1**	**From either equation 3 if** σ_3 **is known, or equation 2**
L*	Moderate slabbing after > 1 hour in ***massive*** rock. RQD/Jn ≥ 30	**5 - 3**	**0.5 – 0.65**	**5 – 9[#]**
M *	Slabbing and rock burst after a few minutes in ***massive*** rock. RQD/Jn ≥ 30	**3 - 2**	**0.65 - 1**	**9[#] – 15[#]**
N*	Heavy rock burst (strain burst) and immediate dynamic deformations in ***massive*** rock. RQD/Jn ≥ 30	**< 2**	**> 1**	**15[#] – 20[#]**

Notes: σ_θ = maximum tangential stress (estimated from elastic theory). # = SRF value subject to future review.
* = **Except for case K**, correction should be made for strongly anisotropic virgin stress field (if measured):
when σ_1/σ_3 = 5 – 10 then reduce σ_c to 0.75 σ_c ; when σ_1/σ_3 >10 then reduce σ_c to 0.5 σ_c .

Although there is a striking similarity between equations 3 and 7, they need further validation for Australian mining conditions. The constant and the two exponents in equation 3 are based mainly on Barton’s pre-1984 case histories, while those in equation 7 are presumed to be based on Kirsten’s data at the time he published his equation in 1988.

It is proposed that equations 2 and 3 be used to estimate SRF-values for highly stressed but jointed rock masses. The equations should be reviewed once further Australian case studies have been published.

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