Introducing the Q-slope method and its intended use within civil and mining engineering projects

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ABSTRACT: The Q-system for characterizing rock exposures and drill-core, and for estimating single-shell support and reinforcement needs in tunnels, caverns and mine roadways has been widely used by engineering geologists and mining engineers. In the last ten years, a slightly modified Q-system called Q-slope was tested by the authors, for application in road cuttings, motorway cuttings, and benches in opencast mines. The purpose of Q-slope is to allow engineering geologists, rock engineers and mining engineers to rapidly assess the stability of excavated rock slopes in the field, and make optimal adjustments to slope angles as rock mass conditions become visible during construction of the road cuts or benches. Trials at several civil engineering and mining projects in Asia, Australia and Central America have shown that a simple correlation exists between Q-slope values and the long-term stable and unsupported slope angles. The new method includes Jr/Ja ratios for both sides of potential wedges, using relative orientation weightings.

1 INTRODUCTION

The Q-system (Barton et al. 1974 and Barton & Grimstad, 2014) for characterizing rock exposures, drill-core, and tunnels under construction, was developed from rock tunneling-related and rock cavern-related case records. Single-shell B+S(fr) tunnel support and reinforcement design assistance, and open stope design, utilizing Q' (the first four parameters) have been the principal focus of applications in civil and mining engineering. Correlations of Qc (Q normalized with UCS/100) with stress-dependent P-wave velocities and depth-dependent deformation moduli have also proved useful in site characterization and as input to numerical modelling. These approximate correlations remain with the new Q-slope value, which may also vary over six orders of magnitude, from approx. 0.001 to 1000. This large numerical range is an important reflection of the large variation of parameters such as deformation moduli and shear strength.

Q-slope utilizes the same six parameters RQD, Jn, Jr, Ja, Jw and SRF. However, the frictional resistance pair Jr and Ja can apply, when needed, to the individual sides of potentially unstable wedges. Simply applied orientation factors, like (Jr/Ja)1 x 0.7 for set J1 and (Jr/Ja)2 x 0.9 for set J2, provide estimates of overall whole-wedge frictional resistance reduction, if appropriate. The term Jw, which is now termed Jwice (one of two symbol-modifications), takes into account an appro-

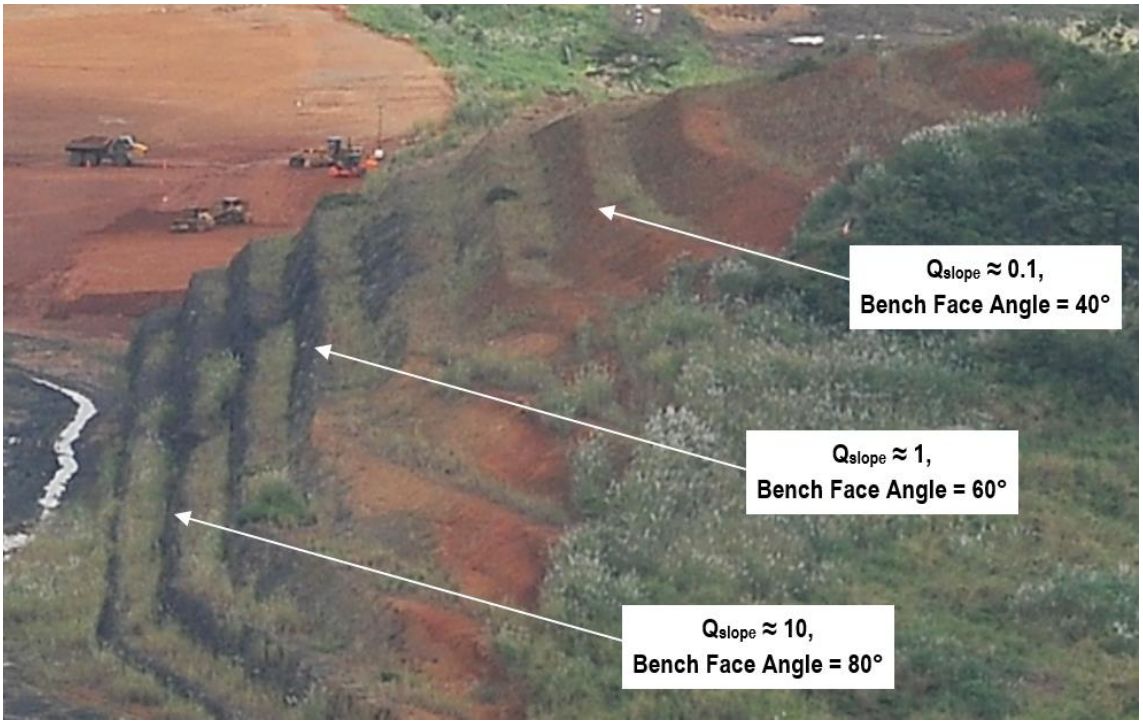

Figure 1. A convenient example of differentiated saprolite, weathered rock and fresher rock mass qualities, help to explain the appropriately steepened, unreinforced permanent slopes. (Panama Canal Authority office photograph. By permission).

priately wider range of environmental conditions appropriate to rock slopes, which obviously stand in the open *for ever*. These conditions include the extremes of erosive intense rainfall, ice wedging, as may seasonally occur at opposite ends of the rock-type and regional spectrum. There are also (shallow) slope-relevant SRF categories.

Q-slope was conceived a decade ago, firstly at a hydropower dam-access road in the Dominican Republic, requiring a precipitous day's journey on a mule, adjacent to very steep planned slopes to reach a dam-site 20 kilometers distant. Q-slope in a more developed form, was subsequently applied at a new motorway to be excavated through hilly, forested tropical terrain in Panama. How wide the contractor should clear the forest to make way for appropriately shallow-angle cuttings in relic-jointed saprolite, and successively steeper-angle cuttings in weathered, then fresher jointed rock masses, was answered using a combination of seismic refraction and about 1 km of core logging. Planned slope angles were subsequently confirmed with Q-slope logging during their construction.

A visual demonstration of the ultra-simple initial objective of Q-slope, is shown in Figure 1. The differently inclined slopes of a high cutting for the new Panama canal extension were geotechnically designed by the PCA. Q-slope is designed such that it suggests similar safe, maintenance-free, reinforcement-free bench-face slope angles of for instance 40-45º, 60-65º and 80-85º for respective Q-slope values of approximately 0.1, 1.0 and 10. Subsequent figures provide our case records.

In both civil engineering and mining projects, it is practically impossible to assess the stability of rock cuttings and benches in real-time, using analytical approaches such as kinematics, limit equilibrium or finite element methods. Excavation is usually too fast for this. The same limitation usually applies to tunneling, despite numerical modeler's wishes to the contrary. However caverns are sufficiently 'stationary' for thorough and more necessary analysis. The purpose of Q-slope is to allow engineering geologists and rock engineers to assess the stability of excavated rock slopes in the field, and make potential adjustments to slope angles as rock mass conditions become visible during construction. Prime areas of application are 'from-surface-and-downwards' bench angle decisions in open pits, and for the numerous slope cuttings needed to reach remote hydropower project tunnel and dam sites, often through strongly varying structural geologies. Application of Q-slope can help to reduce maintenance (and bench-width needs) due to local failures. Such are frequently seen when constant slope angles are cut through varied structural domains. A series of

‘interesting’ but troublesome local failures is often the result. Quite often these have been the result of adverse plane failures, wedge failures, or more rarely local toppling.

2 Q-SLOPE DATA AND Q-SLOPE EQUATION

Figure 2 presents the slope-angle and rock mass quality data collected from several open cast mine bench slopes and road cuts in Australia, Papua New Guinea and Laos, and from motorway and road cuts in Panama. Each have been back-analyzed using Q-slope:

- Green triangles – stable slopes
- Squares – quasi-stable slopes (more than likely to fail with prolonged heavy rainfall)
- Red crosses – failed / collapsed slopes which have been back-analyzed

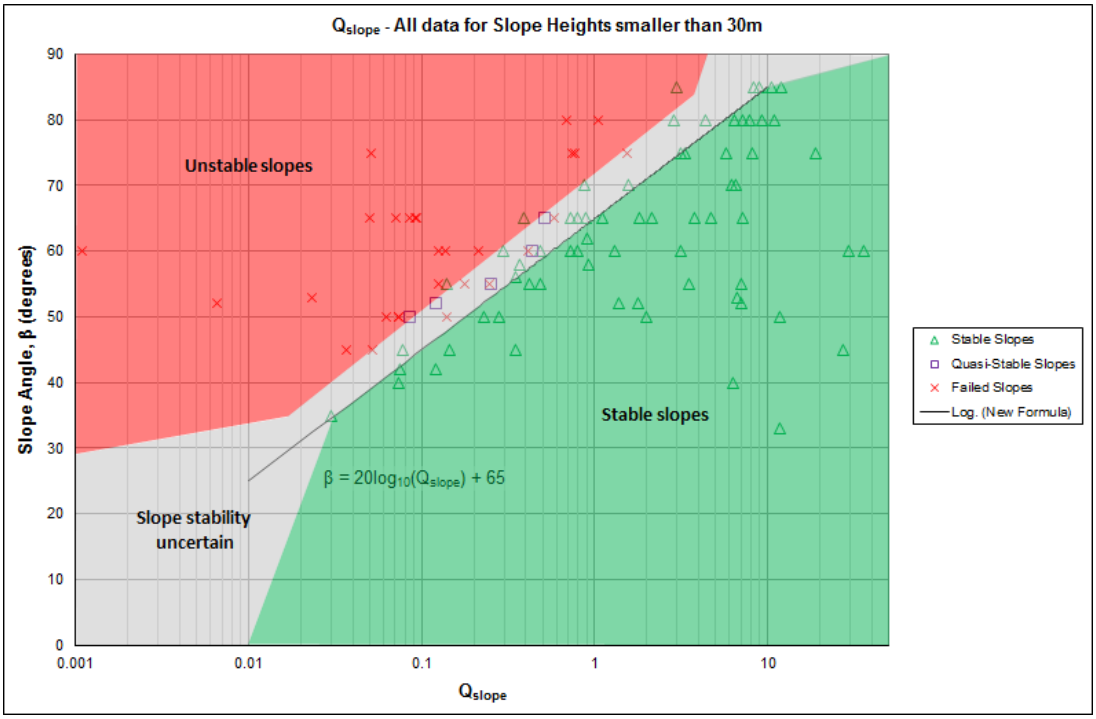

Figure 2. All Q-slope data for slope heights smaller than 30m. Conservative, easy to remember lower-bound.

- Q-slope = 0.01 – slope angle 25° (extrapolated from nearest 35°data)
- Q-slope = 0.1 – slope angle 45°
- Q-slope = 1.0 – slope angle 65°
- Q-slope = 10 – slope angle 85°

The simple formula for the steepest slope angle (β) not requiring reinforcement or support is therefore:

$$\beta = 20 \log_{10} Q_{slope} + 65° \qquad (1)$$

This matches central data for stable slope angles >35° and < 85°. Q-slope is intended for use in reinforcement-free site access road cuts, road or rail cuttings or individual benches in open cast mines. It is not intended for assessing the stability of large slopes developed by several excavation stages over significant periods of time, such as inter-ramp or overall slopes in open cast mines.

3 SOME OF THE RATIONALE AND RATINGS BEHIND Q-SLOPE

Shear strength input is similar to the Q-system, but more critical, as wedges will be unconfined, and dilation is less important than around tunnels as there is usually no increase in normal stress or stiffness when shearing is initiated. Filled discontinuities follow the same 'contact' scheme as before: a) rock-to-rock contact, b) rock-to-rock contact after some shear displacement, c) no rock-to-rock contact due to thick clay-fillings. The formula for estimating Q-slope is two-thirds familiar (input parameters are described in Table 1 on the subsequent pages):

$$Q_{slope} = \frac{RQD}{J_n} x \left(\frac{J_r}{J_a}\right)_0 x \frac{J_{wice}}{SRF_{slope}} \qquad (2)$$

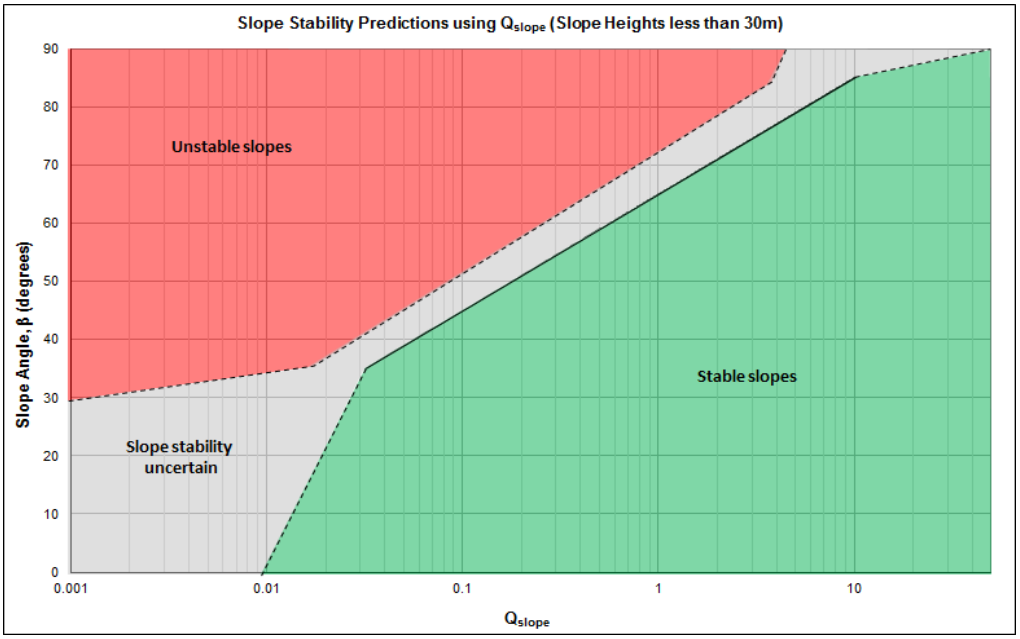

Figure 3. The uncertain slope stability 'corridor' is shown in grey. The unstable area is shown in red, and the conservative stable slope area is shown in green.

It should be noted that RQD/J_n and $(J_r/J_a)_o$ have unchanged ratings. However, there is the possibility now to have an orientation and 'wedge' adjustment factor, as shown in the second part of Table 1 on the subsequent pages. J_{wice} has a new structure for slopes, including ice-wedging effects and tropical rainfall erosion-effects. SRF_{slope} has new (shallower) categories tailored for slopes.

REFERENCES

Barton, N.R., Lien, R. & Lunde, J. (1974). Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics.* Volume 6, pp. 189-236. Springer-Verlag.

Barton, N.R., & Grimstad, E. (2014). *An illustrated guide to the Q-system following 40 years use in tunnelling*. In-house publisher: Oslo. Retrieved March 12, 2015 from www.nickbarton.com.

Table 1a. The descriptions and ratings for the Q-slope parameters (numbered 1 to 7 across two pages).

1. Rock Quality Designation		**RQD**
A	Very poor	0-25
B	Poor	25-50
C	Fair	50-75
D	Good	75-90
E	Excellent	90-100

i) Where RQD is reported or measured as ≤ 10 (including zero), a nominal value of 10 is used to evaluate Q-slope.
ii) RQD intervals of 5, i.e., 100, 95, 90, etc., are sufficiently accurate.

2. Joint set number		**J_n**
A	Massive, no or few joints	0.5-1
B	One joint set	2
C	One joint set plus random joints	3
D	Two joint sets	4
E	Two joint sets plus random joints	6
F	Three joint sets	9
G	Three joint sets plus random joints	12
H	Four or more joint sets, random, heavily jointed	15
J	Crushed rock, earthlike	20

3. Joint roughness number		**J_r**
a) Rock wall contact, b) contact after shearing		
A	Discontinuous joints	4
B	Rough or irregular, undulating	3
C	Smooth, undulating	2
D	Slickensided, undulating	1.5
E	Rough or irregular, planar	1.5
F	Smooth, planar	1.0
G	Slickensided, planar	0.5
c) No rock-wall contact when sheared		
H	Zone containing clay minerals thick enough to prevent rock-wall contact.	1.0
J	Sandy, gravely or crushed zone thick enough to prevent rock-wall contact	1.0

i) Descriptions refer to small-scale features and intermediate scale features, in that order.
ii) Add 1.0 if mean spacing of the relevant joint set is greater than 3m.
iii) J_r = 0.5 can be used for planar, slickensided joint having lineations, provided the lineations are oriented for minimum strength.
iv) J_r and J_a classification is applied to the joint set or discontinuity that is least favourable for stability both from the point of view of orientation and shear resistance τ (where $\tau \approx \sigma_n \tan^{-1} (J_r / J_a)$).

4. Joint alteration number		**J_a**
a) Rock-wall contact (no clay fillings, only coatings)		
A	Tightly healed, hard, non-softening, impermeable filling, i.e., quartz or epidote.	0.75
B	Unaltered joint walls, surface staining only.	1.0
C	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	2.0
D	Silty- or sandy-clay coatings, small clay fraction (non-softening).	3.0
E	Softening or low friction clay mineral coatings, i.e., kaolinite or mica. Also chlorite, talc, gypsum, graphite, etc., and small quantities of swelling clays.	4.0
b) Rock-wall contact after some shearing (thin clay fillings, probable thickness ≈ 1-5mm)		
F	Sandy particles, clay-free disintegrated rock, etc.	4.0
G	Strongly over-consolidated non-softening clay mineral fillings.	6.0
H	Medium or low over-consolidation, softening, clay mineral fillings.	8.0
J	Swelling-clay fillings, i.e., montmorillonite. Value of J_a depends on per cent of swelling clay-size particles, and access to water.	8-12
c) No rock-wall contact when sheared (thick clay/crushed rock fillings)		
M	Zones or bands of disintegrated or crushed rock and clay (see G, H, J for description of clay condition).	6, 8, or 8-12
N	Zones or bands of silty- or sandy-clay, small clay fraction (non-softening).	5.0
OPR	Thick, continuous zones or bands of clay (see G, H, J for description of clay condition).	10, 13, or 13-20

Table 1b. The descriptions and ratings for the Q-slope parameters (numbered 1 to 7).

5. Discontinuity Orientation Factor – O-factor

Set A	Set B	Description
2.0	1.5	Very favourably oriented
1.0	1.0	Quite favourable
0.75	0.9	Unfavourable
0.50	0.8	Very unfavourable
0.25	0.7	Causing failure if unsupported

Note: Orientation adjustment for joints in rock slopes. Apply Set A orientation-factor to most unfavourable joint set. If required, apply Set B orientation-factor to secondary joint set in case of potentially unstable wedge formation.

Example of 0-factor application: *Set A is dominant and least favourable: Jr = 1.5, Ja = 2; Set B is less dominant: Jr = 2, Ja = 1. Wedges assumed formed by these two sets due to dip: A) Jr/Ja=1.5/2; 0-factor = 0.5 (very unfavourable).* ***B)*** *Jr/Ja = 2/1; 0-factor = 0.9 (unfavourable).* ***Total wedge assumption:*** *$(Jr/Ja)_0$ in Q-slope = (1.5/2)x0.5x(2/1)x0.9 = 0.68 (φ= 34°- 35°)*

6. Envrionmental & Geological Condition Number – J_{wice}

J_{wice}	*Desert Environment*	*Wet Environment*	*Tropical Storms*	*Ice Wedging*
Stable structure, competent rock	1.0	0.7	0.5	0.9
Stable structure, incompetent rock	0.7	0.6	0.3	0.5
Unstable structure, competent rock	0.8	0.6	0.1	0.3
Unstable structure, incompetent rock	0.5	0.3	0.05	0.2

Note: When drainage measures are installed apply J_{wice} x 1.5
When slope reinforcement measures are installed apply J_{wice} x 1.3
When drainage and reinforcement is installed apply both factors: J_{wice} x 1.5 x 1.3

7. Strength Reduction Factor – SRF_{slope} (use maximum of SRF_a, SRF_b & SRF_c)

SRF_a - Physical Condition

A	2.5	Slight loosening due to surface location
B	5	Loose blocks, signs of tension cracks & joint shearing, susceptibility to weathering
C	10	As B but strong susceptibility to weathering effects
D	15	Slope is in advanced stage of erosion and loosening due to periodic water erosion and/or ice-wedging effects
E	20	Residual slope with significant transport of material down-slope

SRF_b - Stress

F	2.5-1	Moderate stress-strength range (σ_c/σ_1: 50-200)
G	5-2.5	High stress-strength range (σ_c/σ_1: 10-50)
H	10-5	Localised intact rock failure (σ_c/σ_1: 5-10)
J	15-10	Crushing or plastic yield (σ_c/σ_1: 2.5-5)
K	20-15	Plastic flow of strain softened material (σ_c/σ_1: 1-2.5)

SRF_c - Major Discontinuity		***Discontinuity Orientation***			
		Favo-urable	***Unfavourable***	***Very Unfavourable***	***Causing Failure if Unsupported***
L	Major disc. with little or no clay	1	2	4	8
M	Major discontinuity with RQD_{100} due to clay and crushed rock	2	4	8	16
N	Major discontinuity with RQD_{300} due to clay and crushed rock	4	8	12	24

Note: RQD_{100} = 1 metre perpendicular sample of discontinuity
RQD_{300} = 3 metre perpendicular sample of discontinuity