The Q-Slope Method for Rock Slope Engineering in Faulted Rocks and Fault Zones

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ABSTRACT: The Q-slope method for rock slope engineering was developed to allow engineering geologists and rock 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 apparent during the construction of road cuts or benches. An empirical relationship between Q-slope and long-term stable slope angles is now supported through over 500 case studies from Asia, Australia, the Americas and Europe. This paper focuses on case studies to help illustrate the ease and logic of applying Q-slope to rock slope engineering problems in the field, as geological and geotechnical conditions become apparent with the progression of excavations. The ability to rapidly assess and act on deviations from expected ground conditions makes Q-slope a particularly powerful tool when dealing with slope excavation in faulted rocks and fault zones.

1 INTRODUCTION

In both civil and mining engineering projects, it is practically impossible to assess the stability of rock slope cuttings and benches in real time, using approaches such as kinematics, limit equilibrium or numerical modelling. Excavation is usually too fast for this. The same limitation usually applies to tunneling; however, rock caverns of larger span are sufficiently 'stationary' for thorough and more necessary analysis, and the same applies to higher rock slopes.

The Q-slope method for rock slope engineering (Barton & Bar, 2015; Bar & Barton, 2017) is based on the Q-system for characterizing rock exposures, drill core and tunnels under construction. This was developed from rock tunneling and rock cavern related case records that has been used by engineers across the world for almost 45 years (Barton et al. 1974; Grimstad & Barton, 1993; Barton & Grimstad, 2014).

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 projects, tunnel, bridge and dam sites, often through strongly varying structural geologies. In rock masses where very few joints and no faults or fault zones exist, very steep slopes including cliffs can form (Barton & Shen, 2018; Barton et al. 2018). On the other side of the spectrum, in faulted rocks and fault zones, slope angles are significantly shallower and more variable.

2 THE Q-SLOPE METHOD

Q-slope utilizes the same six parameters as the Q-system: RQD, J_n, J_r, J_a, J_w and SRF. However, the frictional resistance pair J_r and J_a can apply, when needed, to the individual sides of potentially unstable wedges. Simply applied orientation factors, like $(J_r/J_a)_1$ x 0.75 for set J1 and

$(J_r/J_a)_2$ x 0.9 for set J2, provide estimates of overall whole-wedge frictional resistance reduction, if appropriate. The term J_w, which is now termed J_{wice}, takes into account an appropriately wider range of environmental conditions for rock slopes, which obviously stand in the open for a very long time. These conditions include the extremes of intense erosive rainfall and ice wedging, as may seasonally occur at opposite ends of the rock-type and regional spectrum. There are also slope-relevant SRF categories. The formula for estimating Q-slope is:

$$Q_{slope} = \frac{RQD}{J_n} x \left(\frac{J_r}{J_a} \right)_0 x \frac{J_{wice}}{SRF_{slope}} \tag{1}$$

Tables 1 to 9 present the Q-slope ratings used in Equation 1. The strength reduction factor SRF_{slope} is obtained by using the most adverse, or maximum, of SRF_a, SRF_b and SRF_c. Bar & Barton (2017; 2018a) provide further insight and guidance on the Q-slope method and ratings.

Table 1. Rock quality designation (Deere, 1963)

RQD (%)	Description*	RQD
A	Very poor	0-25
B	Poor	25-50
C	Fair	50-75
D	Good	75-90
E	Excellent	90-100

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

Table 2. Joint set number

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

Table 3. Joint roughness number

Joint Roughness Number	Description	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 joints 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 favorable for stability both from the point of view of orientation and shear resistance: $\tau \approx \sigma_n \tan^{-1} (J_r/J_a)$.

Table 4. Joint alteration number

Joint Alteration Number Description		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 disintegrated rock, etc.	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 & clay (see G, H, J for descriptions)	6, 8, 8-12
N	Zones of 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 descriptions)	10, 13, 13-20

Table 5. Discontinuity orientation (O-) factor

O-factor Description	Set A	Set B
Very favorably oriented	2.0	1.5
Quite favorable	1.0	1.0
Unfavorable	0.75	0.9
Very unfavorable	0.50	0.8
Causing failure if unsupported	0.25	0.5

Table 6. Environmental and geological condition number

J_{wice}*	Desert Environ.	Wet Environ.	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	0.5	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} x1.5.*
When slope reinforcement measures are installed, apply J_{wice} x1.3.
When drainage and reinforcement are installed, apply both factors J_{wice} x1.5 x 1.3.

Table 7. SRF_a: Physical condition

Description	SRF_a
Slight loosening due to surface location, disturbance from blasting or excavation.	2.5
Loose blocks, signs of tension cracks and joint shearing, susceptibility to weathering.	5
As above, but strong susceptibility to weathering.	10
Slope in advanced stage of erosion & loosening due to periodic water erosion/ice-wedging effects.	15
Residual slope with significant transport of material down-slope.	20

Table 8. SRF_b: Stress and strength

Description	σ_c/σ_1*	SRF_b
Moderate stress-strength range.	50-200	2.5-1
High stress-strength range.	10-50	5-2.5
Localized intact rock failure.	5-10	10-5
Crushing or plastic yield.	2.5-5	15-10
Plastic flow of strain softened material.	1-2.5	20-15

* *Note:* σ_c *= unconfined compressive strength (MPa);* σ_1 *= maximum principal stress (MPa).*

Table 9. SRF_c: Major discontinuity

Description*	SRF_c
Major discontinuity with little or no clay, and orientation is:	
favorable	1
unfavorable	2
very unfavorable	4
causing failure if unsupported	8
Major discontinuity with RQD_{100}=0 due to clay and crushed rock, and orientation is:	
favorable	2
unfavorable	4
very unfavorable	8
causing failure if unsupported	16
Major discontinuity with RQD_{300}=0 due to clay and crushed rock, and orientation is:	
favorable	4
unfavorable	8
very unfavorable	12
causing failure if unsupported	24

* *Note: RQD_{100}=1m & RQD_{300}=3m perpendicular sample of discontinuity, respectively.*

Barton & Bar (2015) derived a simple formula for the steepest slope angle (β) not requiring reinforcement or support for slope heights less than 30m. This formula was extended to greater slope heights in 2017:

$$\beta = 20\log_{10} Q_{slope} + 65° \tag{2}$$

Equation 2 matches the central data for stable slope angles greater than 35° and less than 85° as shown in Figure 1. Equation 2 does not represent a specific factor of safety as would perhaps be obtained by undertaking numerical analyses. Rather it represents the boundary of long-term stable slopes based on observed performance, normally between six months and over 50 years. When considering only, failed and quasi-stable slopes, Bar & Barton (2017) used iso-potential lines to estimate that application of Equation 2 as a limit gives a probability of failure of 1%.

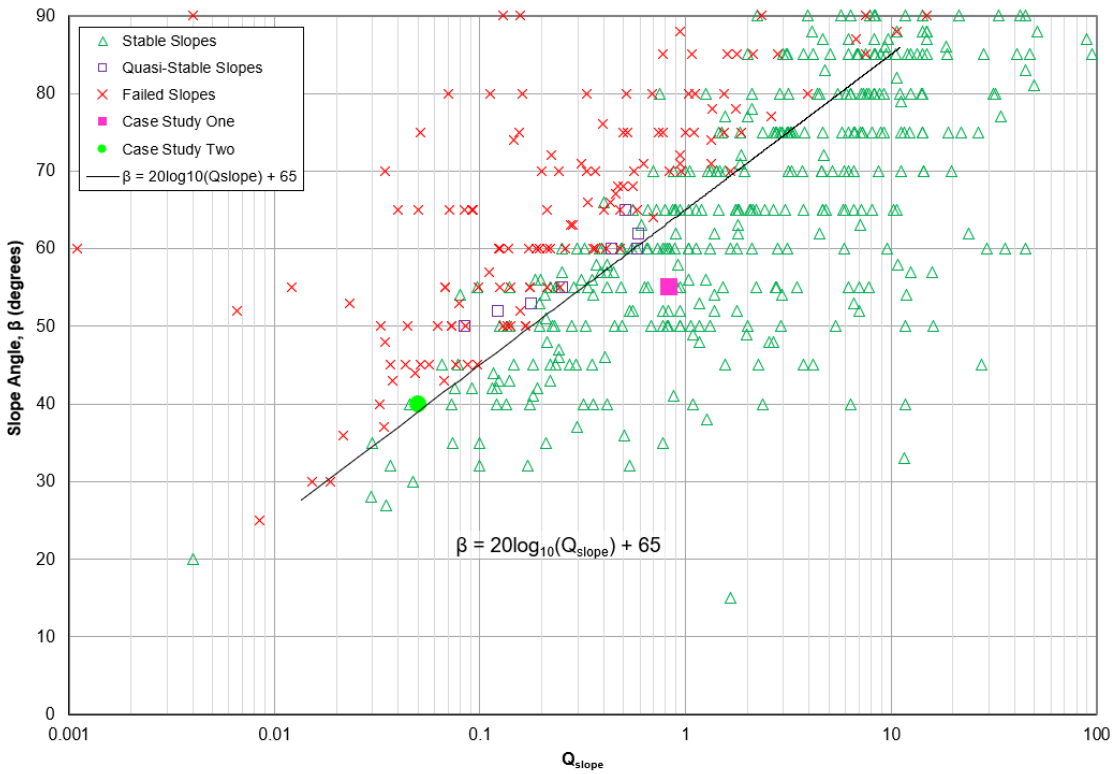

Figure 1. Q-slope data – 503 case studies.

The Q-system (Barton, 2006) and Q-slope (Bar & Barton, 2018b) have been correlated with P-wave velocity using Equations 3-6, where unconfined compressive strength (UCS or σ_c) is in megapascals (MPa), Q_c is the normalized Q-value, and P-wave velocity (V_p) is in kilometers per second (km/s).

$$Q_c = \frac{\sigma_c}{100} xQ \tag{3}$$

$$V_p \approx 3.5 + \log Q_c \tag{4}$$

$$Q_c \approx 10^{(V_p - 3.5)} \tag{5}$$

The Q-value, and therefore, the normalized Q-value (Q_c) does not *fully* consider the orientation of geological structures relative to the proposed rock slope design and the environmental conditions in which the slope will be constructed, but selection of the least favorable J_r/J_a condition still applies as for tunnels (see Note iv, Table 3). However, the discontinuity orientation factor (O-factor) and environmental and geological conditions number (J_{wice}) have not yet been considered (Bar & Barton, 2018b).

SRF_{slope} in most cases should be equal to one as stress reduction factors were already considered in the Q-value relationship with V_p. However, users need to take special care to ensure that appropriate SRF_{slope} values are used to effectively represent expected ground conditions with respect to the excavation.

Geophysical surveys and borehole geophysics used in conjunction with outcrop mapping and drill core logging provide very useful data for identifying local faults, fault zones and rock mass changes across a larger spatial area. Bar & Barton (2018b) discuss opportunities of using these as a predictive tool, prior to slope excavation.

3 Q-SLOPE APPLICATION IN FAULTED ROCKS AND FAULT ZONES

Empirical methods such as the Q-system and Q-slope have the benefit of being easy to use and can be rapidly applied to assess ground conditions and subsequent support or slope angle requirements, respectively. This aspect makes them a particularly powerful tool for assessing faulted rocks and fault zones. Case studies are presented to assist users who encounter such ground conditions. Of course, where appropriate, more rigorous methods might be warranted and advised.

3.1 *Case Study One: Fault Zone encountered in Slope Excavation*

A 500-1000mm wide fault zone was encountered striking into a mine pit slope where stable bench face angles were excavated at 55±5°. The rock mass comprises a hard quartzite with unfavorable bedding, daylighting and undercut by the benches, as shown in Figure 2.

The fault zone shows signs of shearing, has some slickensides (sub-vertical), and has siliceous fault breccia within the ‘semi-ductile’ shear zone (Hudson et al. 2011). It is generally undulating with smooth surfaces and no rock-to-rock contact. Some clay is present in a matrix of angular rock fragments less than 20mm in diameter. Visible displacement is difficult to measure although it has been estimated to be in the order of 30-50cm. The fault zone was estimated to be at least 1,000m in length and was also identified in the underground mine below the pit.

Given the fault’s significance to both the slope and the underground excavations, it was assessed using both the Q-system and Q-slope in Table 10. The assessments were carried out for each individual scanline region in Figure 2 as well as an overall assessment for a 15m wide area.

Region ‘B’, representing solely the fault zone attained the ‘extremely poor’ rock class for Q, and a very low Q-slope value corresponding to a long-term stable slope angle of less than 30°. Regions, ‘A’, ‘C’ and ‘D’ attained ‘poor’ rock classes and long-term stable slope angles in excess of 65°.

The overall area was assessed as being stable for long-term stable slope angles of up to 63°, which is slightly steeper than the excavated bench face angle.

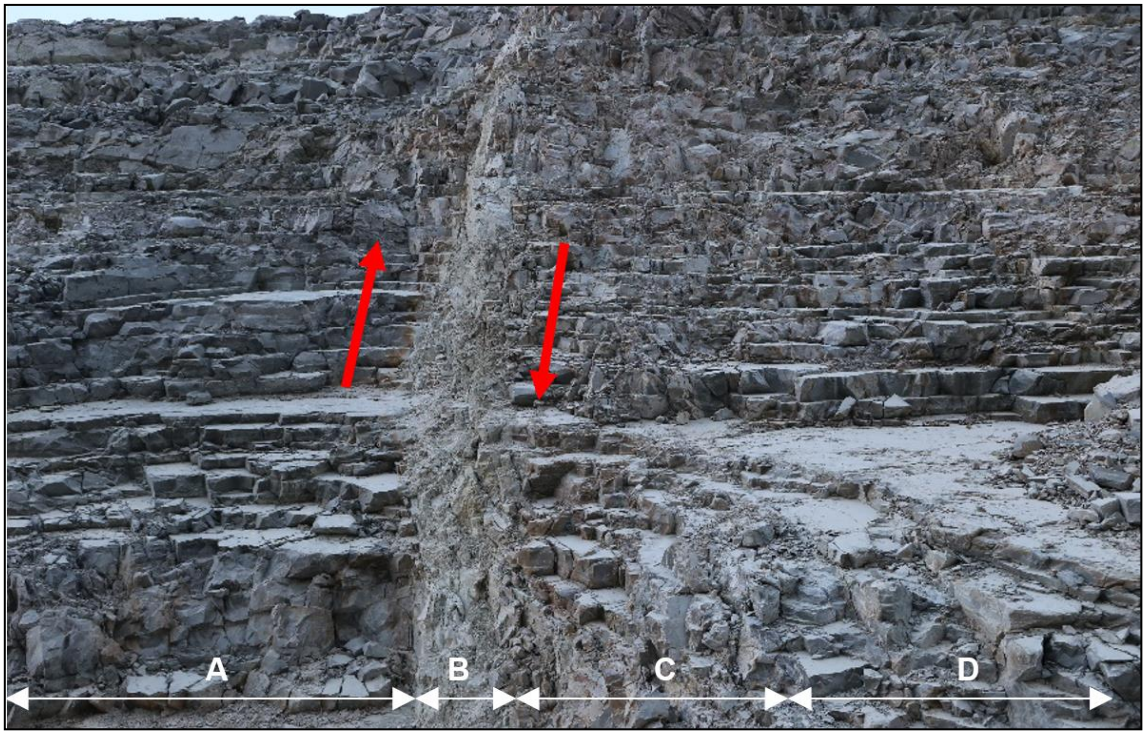

Figure 2. Quartzite rock mass with 500-1000mm wide fault and daylighting bedding and ground condition scanline regions A to D.

Table 10. Case Study 1: Q-system and Q-slope assessment of ground conditions involving fault zone.

Case Study 1 Scanline Region	A	B	C	D	Overall
Zone Width (m)	5	0.8	4	5	15
RQD (%)	60-70	0 (10)	30-40	50-60	40-60
J_n	12	20	15	15	15
J_r	2	2	2	2	2
J_a	3	8	3	3	3
J_w	1	1	1	1	1
Q’	3.611	0.125	1.556	2.444	2.222
Q	0.722	0.025	0.311	0.489	0.444
Rock Class	E	F	E	E	E
O-factor (Set A)	0.75	1.0	0.75	0.75	0.75
J_{wice}	1	0.7	1	1	1
σ_c (MPa)	150	5	150	150	150
SRF_a	1	1	1	1	1
SRF_b	1	6	1	1	1
SRF_c	1	2	1	1	2
SRF_{slope}	1	6	1	1	2
Q_{slope}	2.701	0.015	1.167	1.833	0.833
β (degrees)	73	28	66	70	63

This case study illustrates the importance of assessing Q-slope with respect to the intended excavation, not just as a calculation based on rock mass intervals in a scanline or similarly from a borehole (i.e. if the slope was excavated based on the Q-slope value for region ‘B’ alone, and in the case of a much greater zone thickness, the volumes of additional material excavation would be very high, and the slope quite possibly not economical).

However, in the case of tunnels or mine development drives, ground support classes may change frequently based on the ground conditions. As such, the presence of region ‘B’ and especially its width, is critical for avoiding unwanted overbreak, potential collapses or excessive deformation.

3.2 *Case Study Two: Slope Excavation in Weak Faulted Rock*

A discrete, local, favorably oriented fault was identified within a weak, faulted rock mass illustrated in Figure 3A. This 12m high slope was excavated at an angle of approximately 40±3° and remained quite stable. However, the rock mass is highly susceptible to weathering, is friable and erodes easily. Erosion-created gullies form preferentially on otherwise quite favorable, relic joint sets.

Table 11. Q-slope application in weak faulted rock.

Case Study 2		
RQD (%)	0 (10)	
J_n	3	
Set	A	B
J_r	2	2
J_a	4	4
O-factor (planar)	1.0	1.0
J_{wice}	0.3	
σ_c (MPa)	3	
SRF_a	5	
SRF_b	5	
SRF_c	1	
SRF_{slope}	5	
Q_{slope}	0.05	
β (degrees)	39	

From hand-specimen scale to meter scale, the rock mass is considered to be a BIM (block-in-matrix) rock (Medley, 2004; Kalender et al. 2014). In most exposures, the BIM rock strength is controlled by the weaker, rapidly weathering matrix (Figure 3B). However, from a slope stability perspective, relic joints that are even weaker than the matrix, more often than not, dictate stability on a bench scale as illustrated in Figure 3C.

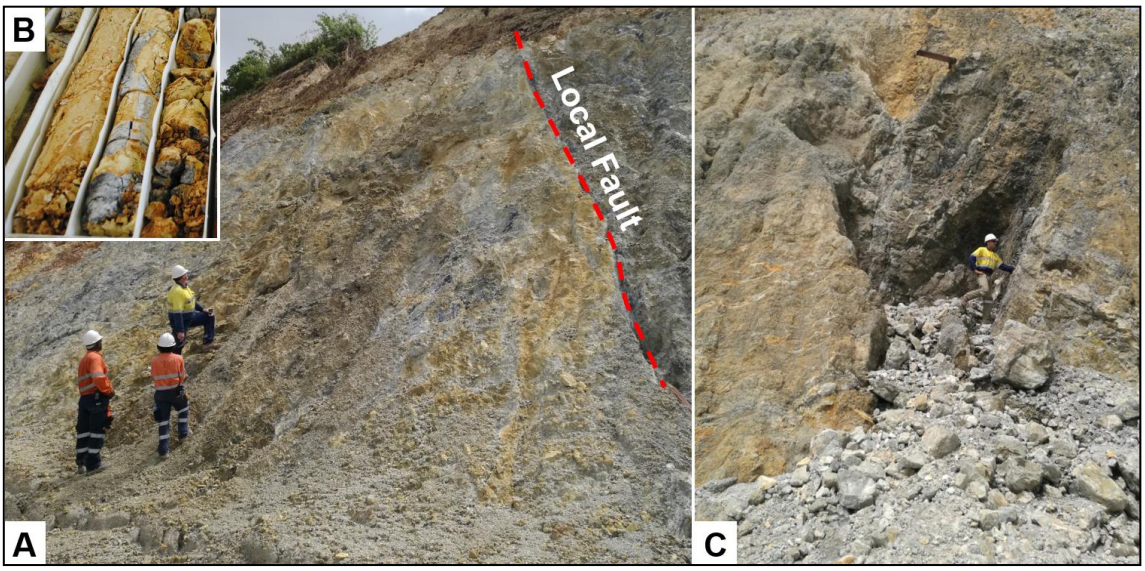

Figure 3. Faulted rock mass – typically matrix-controlled BIM rock; A: Q-slope assessed in Table 11; B: example of nearby drill core (one month after exposure) illustrating both the matrix-control within the BIM rock and its susceptibility to weathering; C: nearby exposure where preferential erosion occurred on otherwise quite favorably oriented relic joints.

This case study provides an example where the engineering geological logic inherent within the Q-slope method can be used to assess stability conditions of a slope excavated in a highly complex, faulted rock mass. These principles can also be applied in BIM rocks.

Again, the advantage of using Q-slope is the ability to rapidly adjust slope angles if or when unexpected ground conditions are encountered.

4 DISCUSSION

Q-slope can be applied to rock slope engineering problems irrespective of rock strength, degree of fracturing, degree of weathering, etc. It also remains unchanged whether it is being used as a predictive or retrospective analysis tool. However, Q-slope cannot be applied to soil masses, rock fill, or landslide debris. Our experiences continue to show that Q-slope enables geotechnical engineers and engineering geologists to rapidly and effectively assess the stability of rock slopes in the field, both during, and after excavation. This remains true in highly complex, faulted rocks and fault zones in which, locally, ground conditions can change very rapidly with respect to slope excavation.

It is not the intention to promote Q-slope as a substitute for more rigorous analyses of slope stability. Where such is warranted, and where time permits, more rigorous analyses would always be preferred. For example, when dealing with larger slopes (heights in excess of 50m, or when several stages of excavation are required), the increased excavation time should permit more rigorous analyses to be made. However, engineers may sometimes need to respond at slope-construction rates of many tens of meters per day, stretching to hundreds of meters in the case of some large open cut mines or multiple-pit operations. In such cases, some quantifiable estimates, with significant *a posteriori* case record supporting evidence, may prove valuable because Q-slope is applicable at low cost and is rather fast.

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