Application of the Q-slope method to highly weathered and saprolitic rocks in Far North Queensland

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ABSTRACT: The Q-slope method was developed to allow engineering geologists and geotechnical 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. Q-slope was developed over the last decade by modifying the Q-system for characterizing rock exposures and drill-core, and estimating single-shell support and reinforcement needs in tunnels, caverns and mining roadways. Q-slope features a new method of Jr/Ja ratios for both sides of potential wedges, using relative orientation weightings and also considers long-term exposure to various climatic and environmental conditions (e.g. tropical storms, ice-wedging effects). Q-slope is intended for reinforcement-free road or rail cuttings or individual benches in open cast mines.

Assessing slope stability in highly weathered rocks and saprolites (in-situ, soft, friable, weathered rock that retains the original rock's structure and fabric but with a lower bulk density) is considered complex since failure mechanisms often involve a combination of shearing and rotational sliding through a weak rock mass as well as sliding on relic geologic structures. The Q-slope method was applied to several highly weathered and saprolitic slopes in Far North Queensland and has shown that a simple correlation exists between Q-slope values and long-term stable and unsupported slope angles.

1 INTRODUCTION

1.1 *Original Q-system*

The original Q-system for characterizing rock exposures, drill core and tunnels under construction was developed from rock tunneling related and rock cavern related case records and has been used by engineers across the world for over 40 years (Barton et al. 1974 and Barton & Grimstad, 2014). Single-shell B+S(fr) tunnel support and reinforcement design assistance, and open stope design, utilizing Q' (the first four parameters) have also been the principal focus of application in civil and mining engineering.

1.2 *Q-slope overview*

The Q-slope method (Barton & Bar, 2015) 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.

Q-slope was developed from case records in six countries, spanning 17 rock types (igneous, sedimentary and metamorphic) and some saprolites for slope heights ranging from 5m to 30m.

Shear strength input is similar to the original Q-system, but more critical, as wedges are unconfined, and dilation is less important than around tunnels as there is usually no increase in normal stress or stiffness when shearing initiates. Filled discontinuities follow the same 'contact' scheme as before: a) rock-to-rock contact, b) rock-to-rock contact after shear displacement, c) no rock-to-rock contact due to thick clay fillings. 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 using simple orientation factors. The term Jw, which is now termed Jwice, takes into account an appropriately wider range of environmental conditions pertinent to rock slopes, which are exposed to the elements indefinitely. 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 slope-relevant SRF categories. For Q-system users, the formula for estimating Q-slope is two-thirds familiar (Barton & Bar, 2015):

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

1.2.1 *The first four parameters (RQD, Jn, Jr & Ja)*

The Q-slope ratings for rock quality designation (RQD), joint set number (Jn), joint roughness number (Jr) and joint alteration number (Ja) remain unchanged from the original Q-system (Barton et al. 1974 and Barton & Bar, 2015). Tables 1-4 describe the ratings for RQD, J_n, J_r and J_a, respectively.

Table 1. Rock Quality Designation

Rock Quality Designation 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 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

Table 3. Joint Roughness Number

Joint Set 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, planar	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 τ, where $\tau \approx \sigma_n \tan^{-1}(J_r/J_a)$.

Table 4. Joint Alteration Number

Joint Set 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 and clay (see G, H, J for description of clay condition).	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 description of clay condition).	10, 13, 13-20

1.2.2 *Discontinuity orientation factor: O-factor*

The discontinuity orientation factor (O-factor) described in Table 5 provides orientation adjustments for discontinuities in rock slopes (Barton & Bar, 2015).

The Set A orientation-factor is applied to the most unfavorable discontinuity set. If required, the Set B orientation-factor is applied to the secondary discontinuity set (i.e. in case of potentially unstable wedge formations).

Table 5. Discontinuity orientation factor - O-factor

O-factor Description	Set A	Set B
Very favorable 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

Equation 2 provides an example of O-factor application where a single discontinuity (Set A) influences stability:

- Set A: Jr=1.5, Ja=2 is dominant & unfavorable, O-factor=0.75.

$$\left(\frac{J_r}{J_a}\right)_0 = \left(\frac{1.5}{2} x0.75\right) = 0.5625 \quad (2)$$

Equation 3 provides an example of O-factor application to wedges formed by two discontinuity sets (Set A & Set B) which influence stability:

- Set A: Jr=1.5, Ja=2 is dominant & very unfavorable, O-factor=0.5.
- Set B: Jr=1.3, Ja=1 is slightly less dominant & is unfavorable, O-factor=0.9.

$$\left(\frac{J_r}{J_a}\right)_0 = \left[\left(\frac{1.5}{2} x0.5\right) x \left(\frac{3}{1} x0.9\right)\right] = 1.0125 \quad (3)$$

1.2.3 *Environmental & geological condition: J_{wice}*

The environmental and geological condition number, Jwice, is more sophisticated than Jw of the original Q-system since slopes are outside and exposed to the elements for a very long time (Barton & Bar, 2015).

Described in Table 6, Jwice has a new structure for slopes, including tropical rainfall erosion-effects and ice-wedging effects. Adjustment factors for slope reinforcement and drainage measures are also included.

Table 6. Environmental and geological condition number - Jwice

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

1.2.4 *Strength reduction factor: SRF_{slope}*

The strength reduction factor SRF_{slope} is obtained by using the maximum of SRF_a, SRF_b and SRF_c described in the subsequent tables.

Table 7 describes strength reduction factors (SRFa) for the physical condition of the slope surface (now or expected) due to susceptibility to weathering and erosion.

Table 7. SRF_a : Physical condition

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

Table 8 describes strength reduction factors (SRF_b) for adverse stress-strength ranges in the slope.

Table 8. SRF_b: Stress and strength

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

* *Note: σ_c =unconfined compressive strength (UCS)*
σ_1=maximum principal stress

Table 9 describes strength reduction factors (SRFc) for major discontinuities such as faults, weakness zones and joint swarms which may also contain clay filling that adversely affects slope stability.

Table 9. SRF_c: Major discontinuity

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

* *Note: RQD_{100} = 1 meter perpendicular sample of discontinuity.*
RQD_{300} = 3 meter perpendicular sample of discontinuity.

1.3 *Q-slope equation and stability chart*

Barton & Bar (2015) derived a simple formula for the steepest slope angle (β) not requiring reinforcement or support for slope heights less than 30m:

$$\beta = 20 \log_{10} Q_{slope} + 65° \quad (4)$$

Figure 1 presents the Q-slope stability chart with an uncertain slope stability 'corridor' in grey. The unstable area is shown in red, and the conservative stable slope area is shown in green (Barton & Bar, 2015).

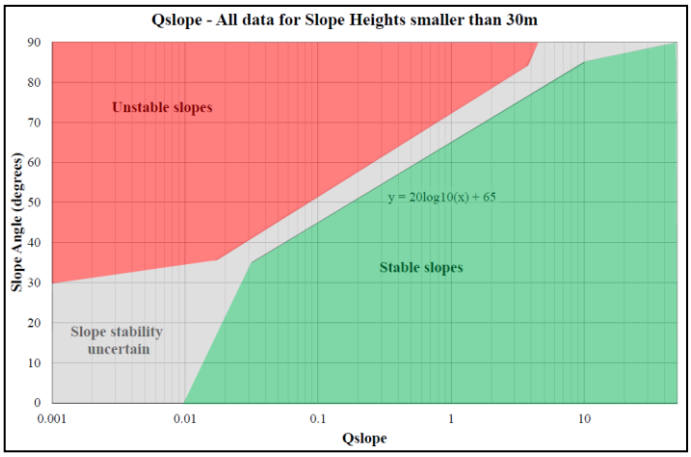

Figure 1. Q-slope stability chart for slope heights less than 30m (adapted from Barton & Bar, 2015)

2 SAPROLITES AND HIGHLY WEATHERED ROCKS IN FAR NORTH QUEENSLAND

2.1 *Context*

Near surface and shallow excavations in Far North Queensland often encounter saprolites and highly weathered rocks in the lower zones of soil profiles.

Saprolites represent deep weathering of the bedrock surface and most commonly form on continental landmasses between latitudes 35°N and 35°S. Conditions for the formation of saprolites include a topographically moderate relief flat enough to prevent erosion and to allow leaching of the products of chemical weathering, long periods of tectonic stability and a humid tropical to temperate climate (Butt et al. 2000).

Far North Queensland in Australia is host to saprolites and highly weathered rocks from the bauxite deposits near Weipa to road cuttings and residential properties located on the hillsides in the greater Cairns region (i.e. Cairns, Babinda, the Atherton tablelands and the Daintree rainforest).

In the greater Cairns region, saprolites of, and highly weathered rocks, include granites, basalts, greywacke and low grade metamorphic rocks, such as shales and phyllite, are frequently encountered near the surface. According to Murtha et al. (1995), the thickness of deeply weathered saprolite is usually in the order of 5m in the region. However, the saprolite generally overlies highly weathered rocks with only marginally improved geomechanical properties for tens of meters thereafter.

2.2 *Engineering challenges*

Designing slopes in saprolites and highly weathered rock present engineering challenges since:

- Shearing and rotational sliding can occur through low strength, weathered rock masses.
- Sliding (planar and wedge) can occur along relic geologic structures, which may be very inconspicuous, within the saprolites or highly weathered rock masses.

Modes of instability in saprolitic or highly weathered rock slopes often occur as a combination of shearing and rotational sliding in weak material with sliding along relic geologic structures.

The aforementioned modes of instability, whether simple or complex, are frequently exacerbated by environmental effects such as rainfall.

3 Q-SLOPE APPLICATION

The Q-slope method was applied to several road cuttings, mine access roads and subdivisional earthworks cuttings in hilly terrain throughout Far North Queensland. These ranged from 5m to 30m in height.

Various rock types were encountered and included low-grade metamorphics, intrusive igneous and sedimentary rocks (greywacke, phyllite, shale, granite, conglomerates, sandstones, and siltstones). These were typically of low strength (intact material strength less than about 25MPa) as a result of near-surface weathering effects. Saprolites of the aforementioned rock types were also commonly encountered (very low strength <5MPa).

Figure 2 presents the slope-angle and rock mass quality data from several saprolitic and highly weathered slopes in Far North Queensland. Each have been back-analyzed using Q-slope:

- Green triangles – stable slopes
- Squares – quasi-stable slopes (note: the two quasi-stable slopes in Figure 2 were rehabilitated by flattening the slope angle prior to their collapse)
- Red crosses – failed / collapsed slopes which have been back analyzed.

It was found that Equation 4 (Barton & Bar, 2015) remains applicable for saprolitic and highly weathered slopes not requiring reinforcement or support, and when less than 30m high.

3.1 *Example of Saprolitic Phyllite Slope in a Residential Subdivision*

Residential subdivision earthworks cuttings in Far North Queensland often comprise saprolites since excavations are usually relatively shallow. Figure 3

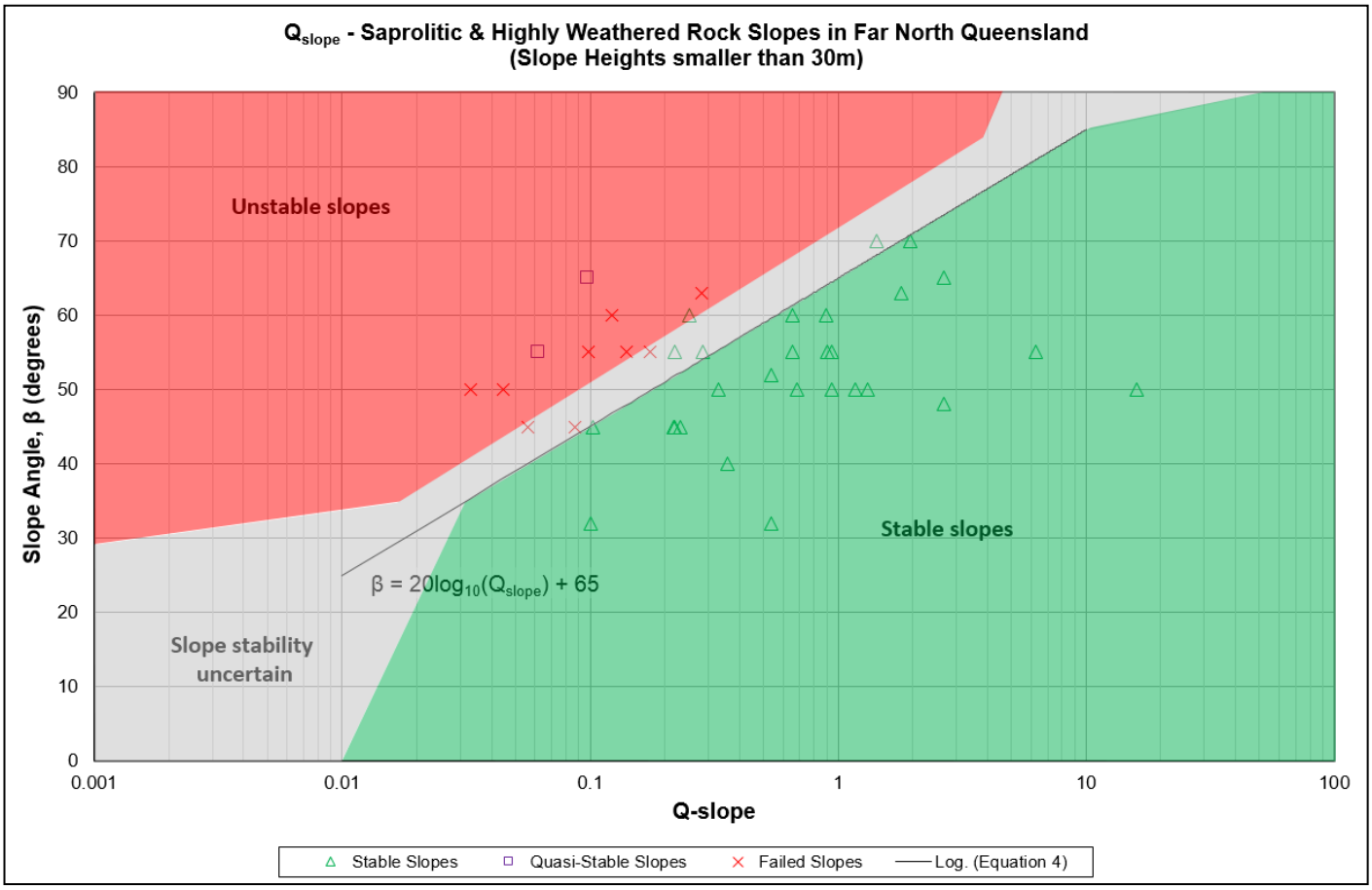

Figure 2. Q-slope data for highly weathered and saprolitic slopes in Far North Queensland (slope heights less than 30m)

is an example of such a slope excavated 5m high at an angle of 40° without any form of geotechnical investigation or design.

The slope comprised 0.3m topsoil at the surface with the remainder being very low strength saprolitic phyllite.

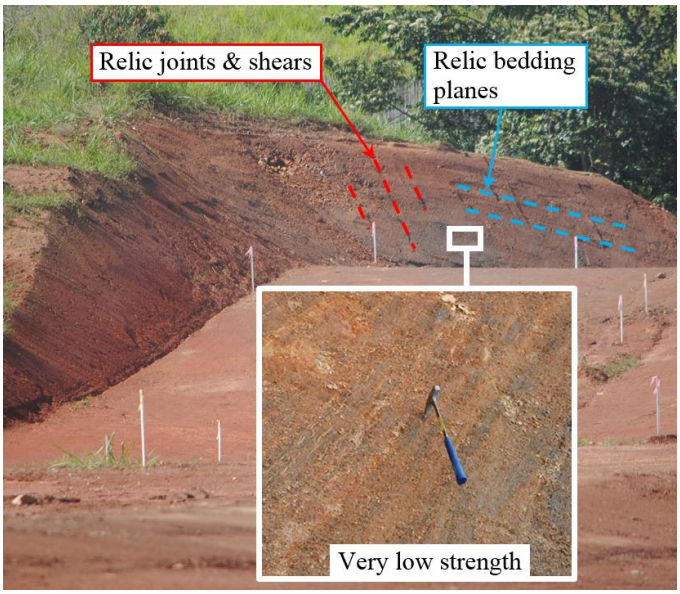

Figure 3. Saprolitic phyllite slope (5m high)

Relic geologic structure was clearly visible, even after excavation, and was quite favorably oriented.

Applying Q-slope, the steepest slope angle not requiring reinforcement was derived as 56°.

By steepening the slope to 50° while retaining the crest position, an additional 70 square meters of salable land area (1.75m per meter length of slope) are realized.

3.2 *Example of Highly to Completely Weathered Conglomerate and Sandstone Slope on a Mine Access Road Cutting*

A 22m high slope at angles ranging between 60° and 70° provides access for light vehicle traffic and a conveyor belt system to a mine site in remote Far North Queensland (Figure 4).

The existing slope is in highly to completely weathered conglomerate and sandstone. Intact material strength was low to very low for both rock types. It has sub-horizontal bedding and unfavorably oriented sub-vertical joint sets.

The slope has been the source of several rock falls (block toppling) and minor debris-slides. Tension cracks were prevalent behind the slope crest. It is understood that the deterioration progressively worsened after each wet season over a ten-year period.

Upon preliminary investigation in the field using Q-slope, the steepest slope angle not requiring reinforcement was derived as 41°.

Subsequent geotechnical investigations using 2D limit equilibrium analysis and physical observations determined that the existing slope was quasi-stable with a factor of safety near equilibrium. Remedial work was required and limit equilibrium analysis

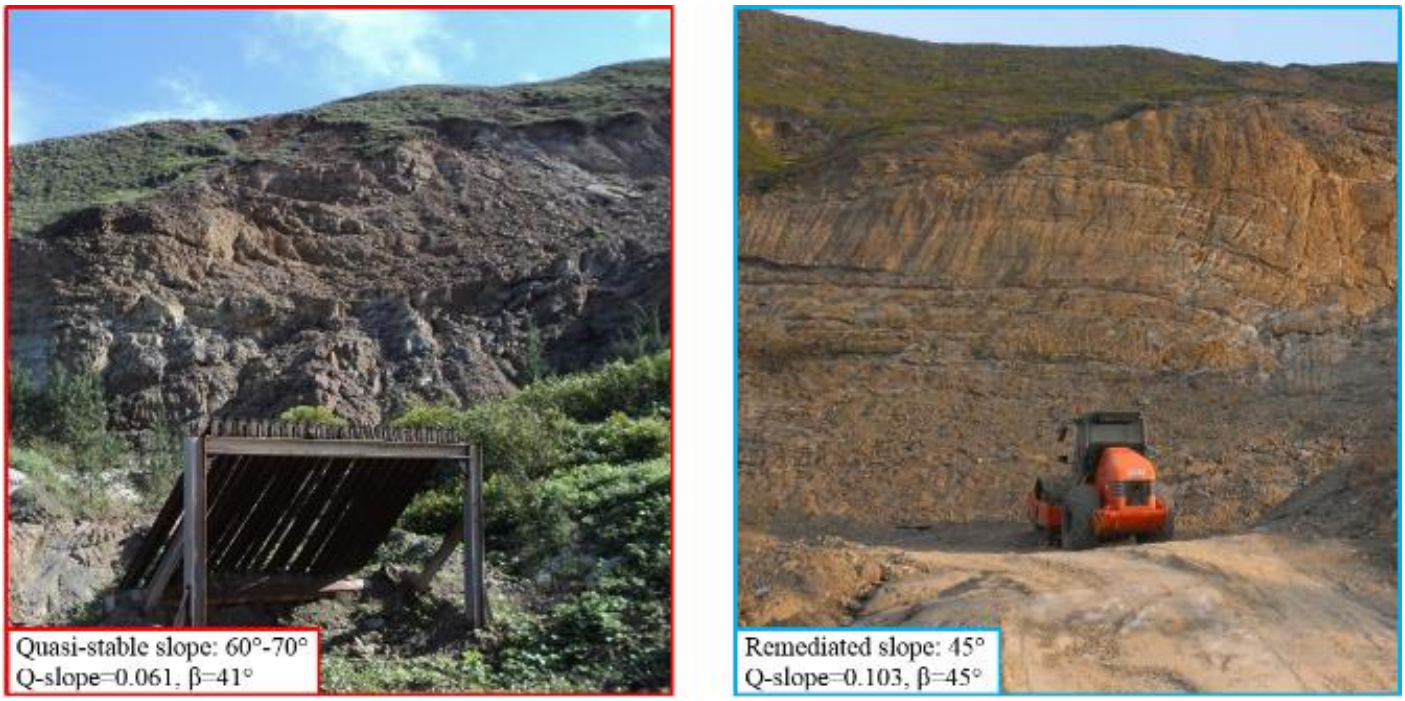

Figure 4. Left: 10 year old quasi-stable slope (22m high); Right: Slope shortly after rehabilitation work, Cape Flattery FNQ.

indicated that the slope could be flattened to 45° and maintain a factor of safety of 1.3 with a periodic perched groundwater table. By removing the quasi-stable portions of the slope and not expecting deterioration from weathering effects (no physical condition strength reduction required), Q-slope was re-evaluated to be 0.103 (β=45°).

4 KEY FINDINGS FOR Q-SLOPE APPLICATION IN SAPROLITIC AND HIGHLY WEATHERED SLOPES

Using Q-slope to assess the stability of saprolitic and highly weathered slopes is in principle no different to assessing fresh rock slopes. However, it has been found that certain aspects of the equation become more prevalent.

In strong or competent rocks, stability is usually dictated by geologic structures. In weak or incompetent rocks, the rock mass, geologic structure or a combination of both, may influence stability. The Jwice description for saprolites in Far North Queensland has solely been 'incompetent rock'. Highly weathered rocks, have been described either as 'incompetent' or 'competent' depending on estimations of the intact material strength.

When dealing with lower strength rocks and saprolites, the appropriate use of strength reduction for adverse stress-strength (SRF_b) becomes ever more vital. By way of example, the saprolitic phyllite slope in the residential subdivision was 5m high, required a SRF_b of 7, and had a Q-slope of 0.36 (β=56°). If the same slope were to be 15m high, it would require a SRF_b of 15, and attain a Q-slope of 0.17 (β=49°). However, if the slope was of strong, fresh rock (intact material strength of 100MPa), a SRF_b of 1 would be required whether the slope was 5m or 15m high. Appropriately estimating in-situ stress are vitally important when using Q-slope in weak materials such as saprolites and highly weathered rocks.

Q-slope enables geotechnical engineers to rapidly assess the stability of excavated slopes in the field, identify potentially unstable areas, and areas which may be steepened if required.

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