INTRODUCING THE Q-SLOPE METHOD AND ITS INTENDED USE IN CIVIL AND MINING ENGINEERING PROJECTS

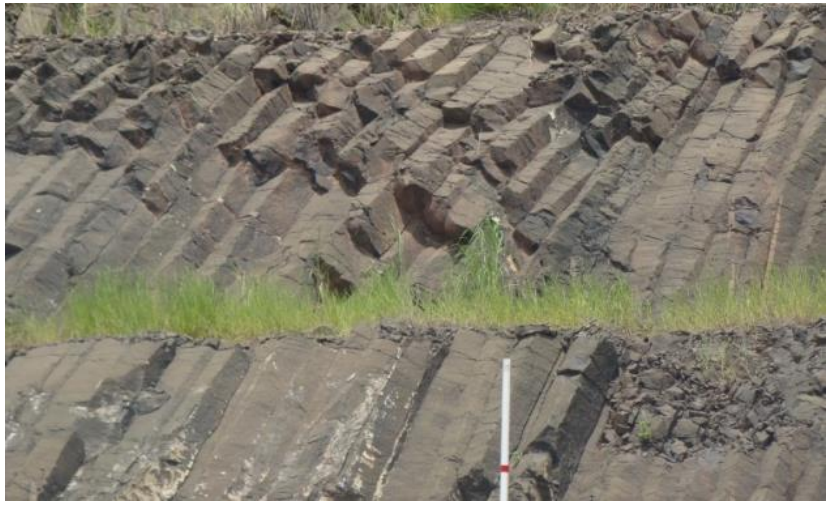
Nick Barton

Nick Barton & Associates, Oslo, Norway

Neil Bar

Gecko Geotechnics, Cairns, Australia

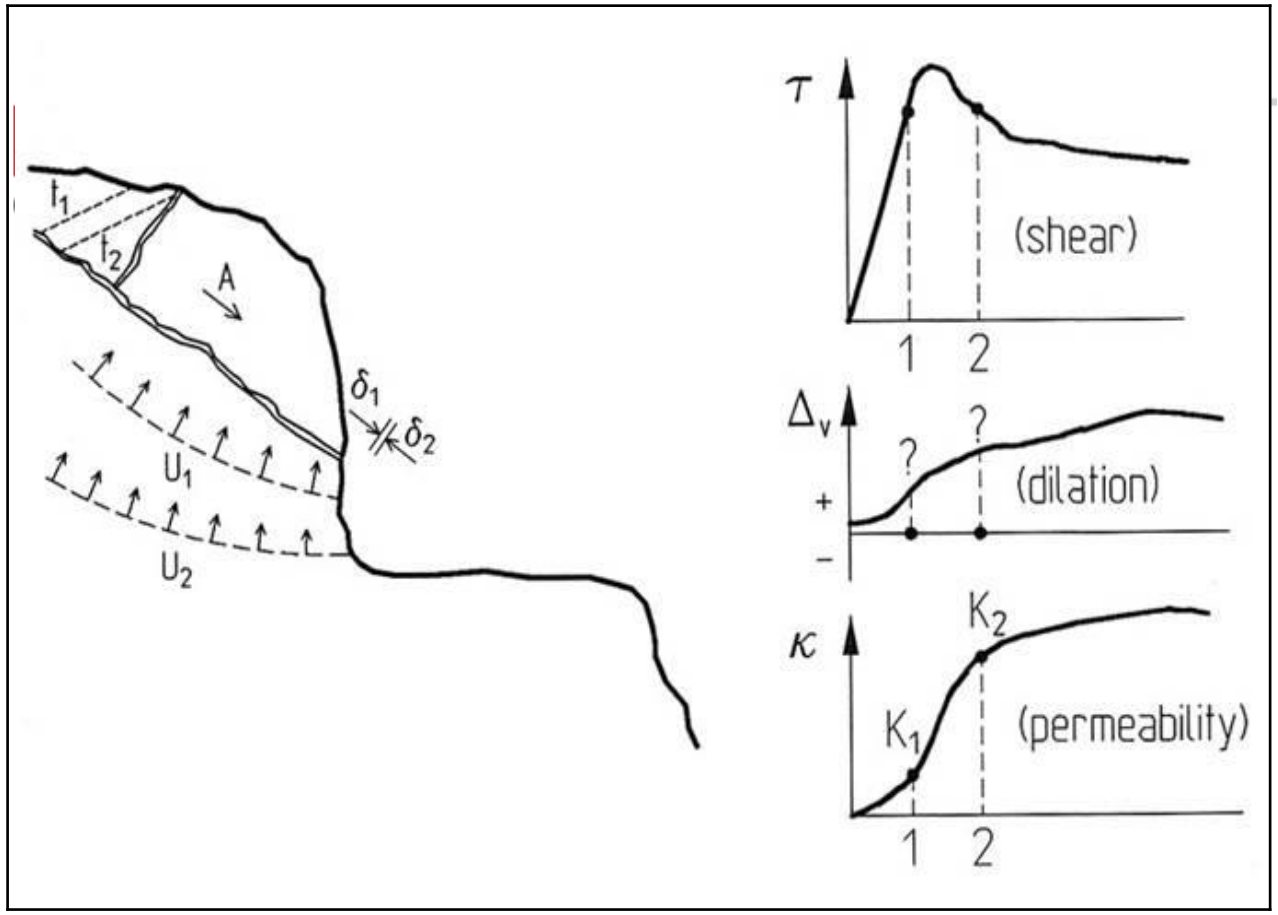
Barton and Bar, 2015. Q-slope.

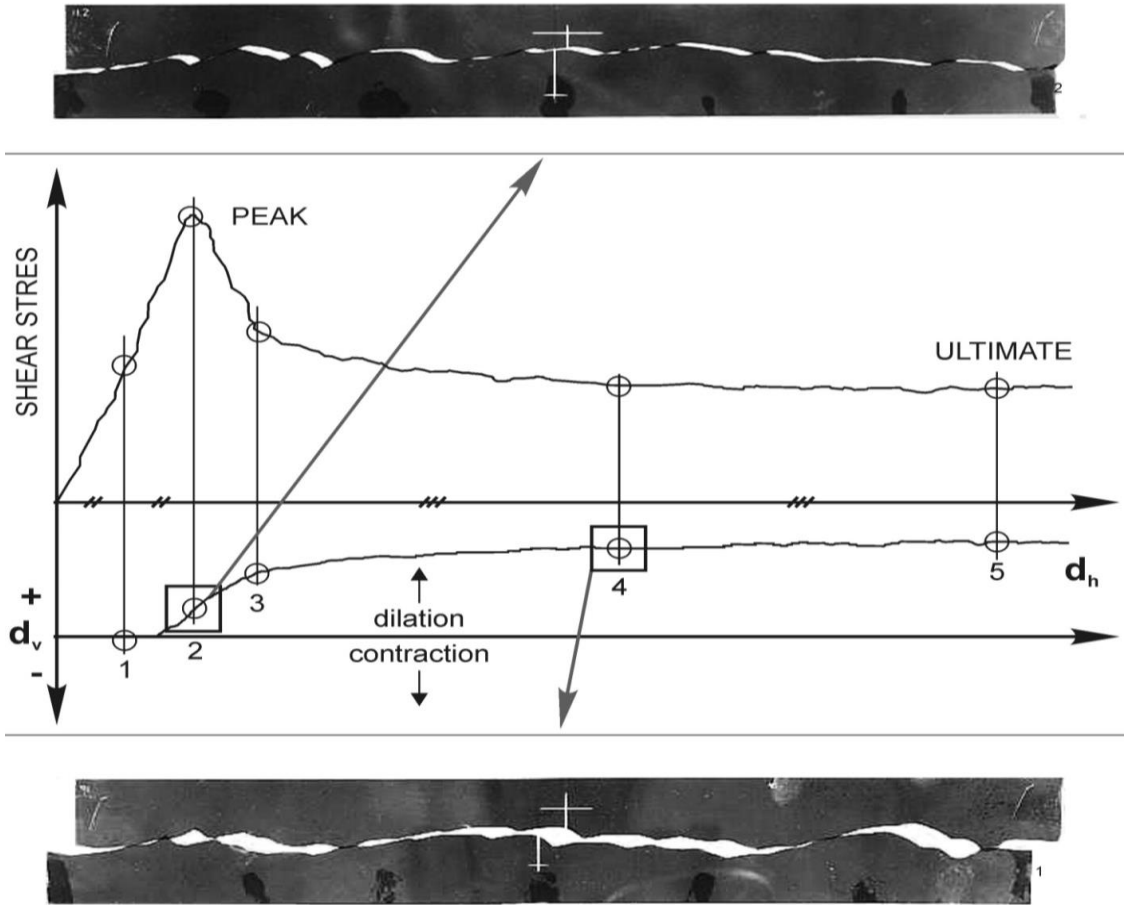


Simple cases, dangerous cases, convenient cases. Billions of rock slopes!

SKILL, TRUST, RECKLESS?

(NON-LINEAR SHEAR STRENGTH?)





IN ADDITION TO SHEAR STRENGTH NEEDS, ROCK SLOPE STABILITY may be a coupled problem: joint shear-deformation can improve drainage due to dilation……..***but only temporarily***, until clogged with run-off fines in future storms. (Sheared, dilated tension fractures: Barton, 1971)

Barton and Bar, 2015. Q-slope.

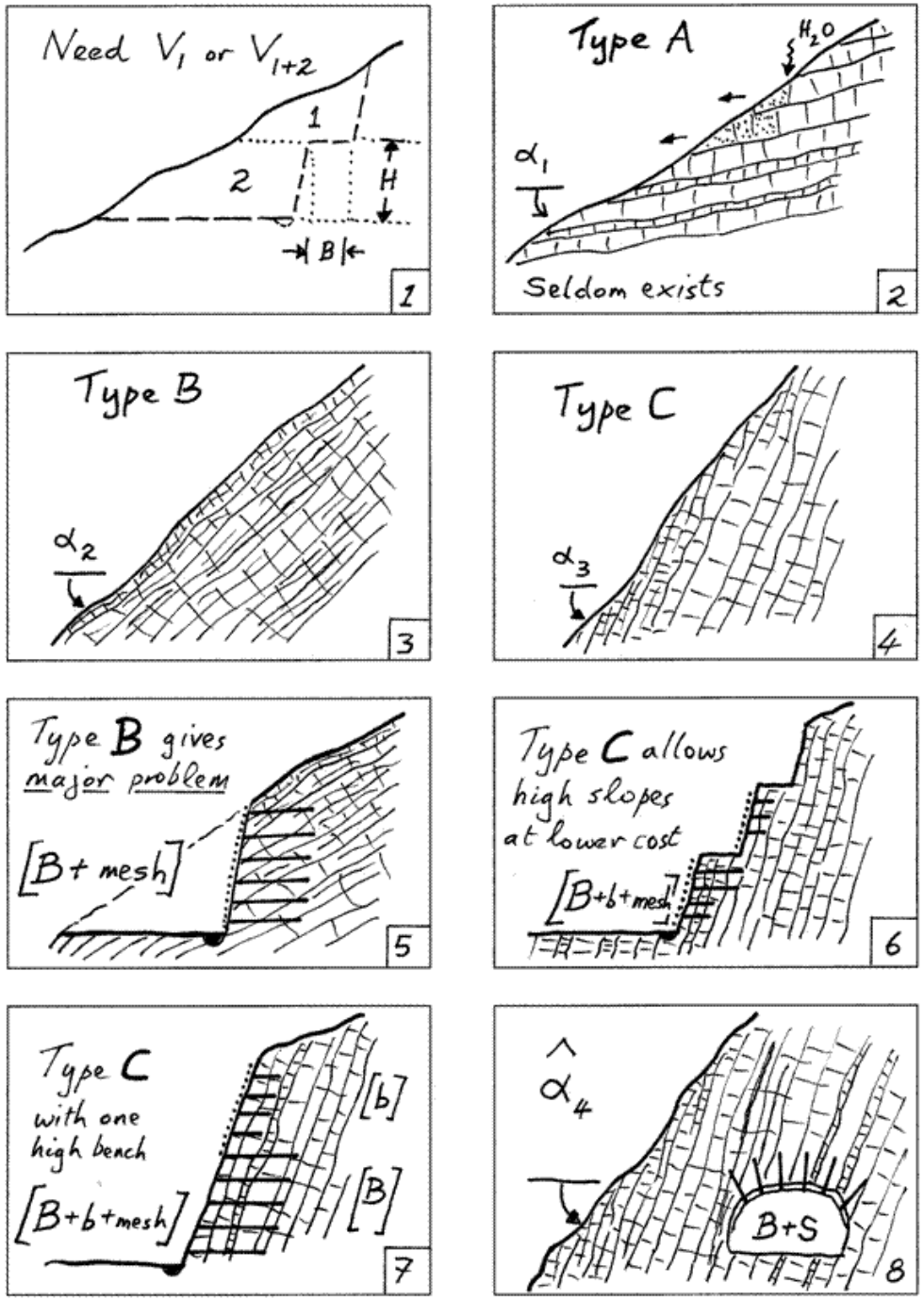
So how can we choose optimal rock slope angle(s)?

- For dam-site, tunnel-site, bridge-site……. access roads
- For a new road, for a widened road, each in hilly terrain
- For a new motorway, in hilly terrain (no tunnels)
- For a new open-pit (applying to bench faces only)
- Where there is not the culture *or need* for 10,000 anchors

Barton and Bar, 2015. Q-slope.

Project #1

How to cut slopes for a 20 km long dam-access road – up this steep valley?



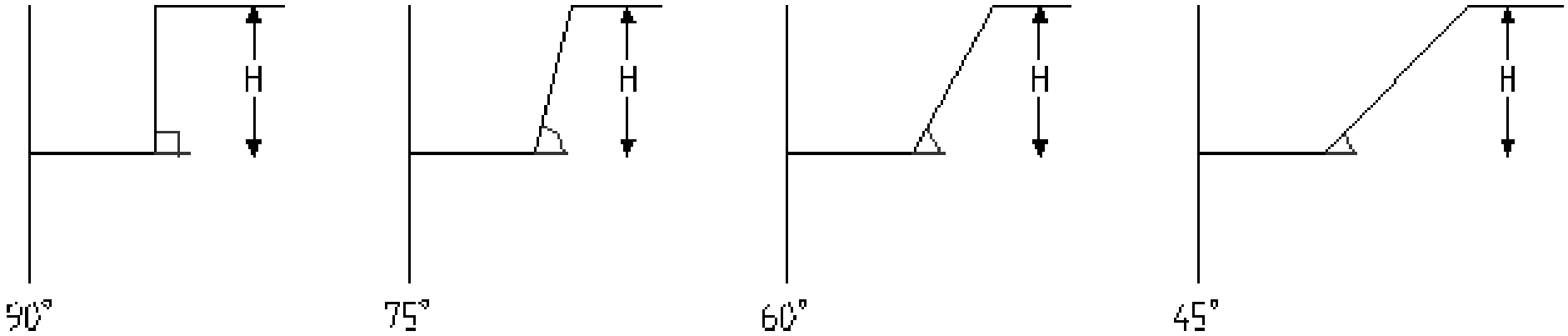
Sketches made at dam site after 6 hours on a ‘mula’

But the client actually wanted to minimise rock-slope reinforcement, and avoid tunnels.

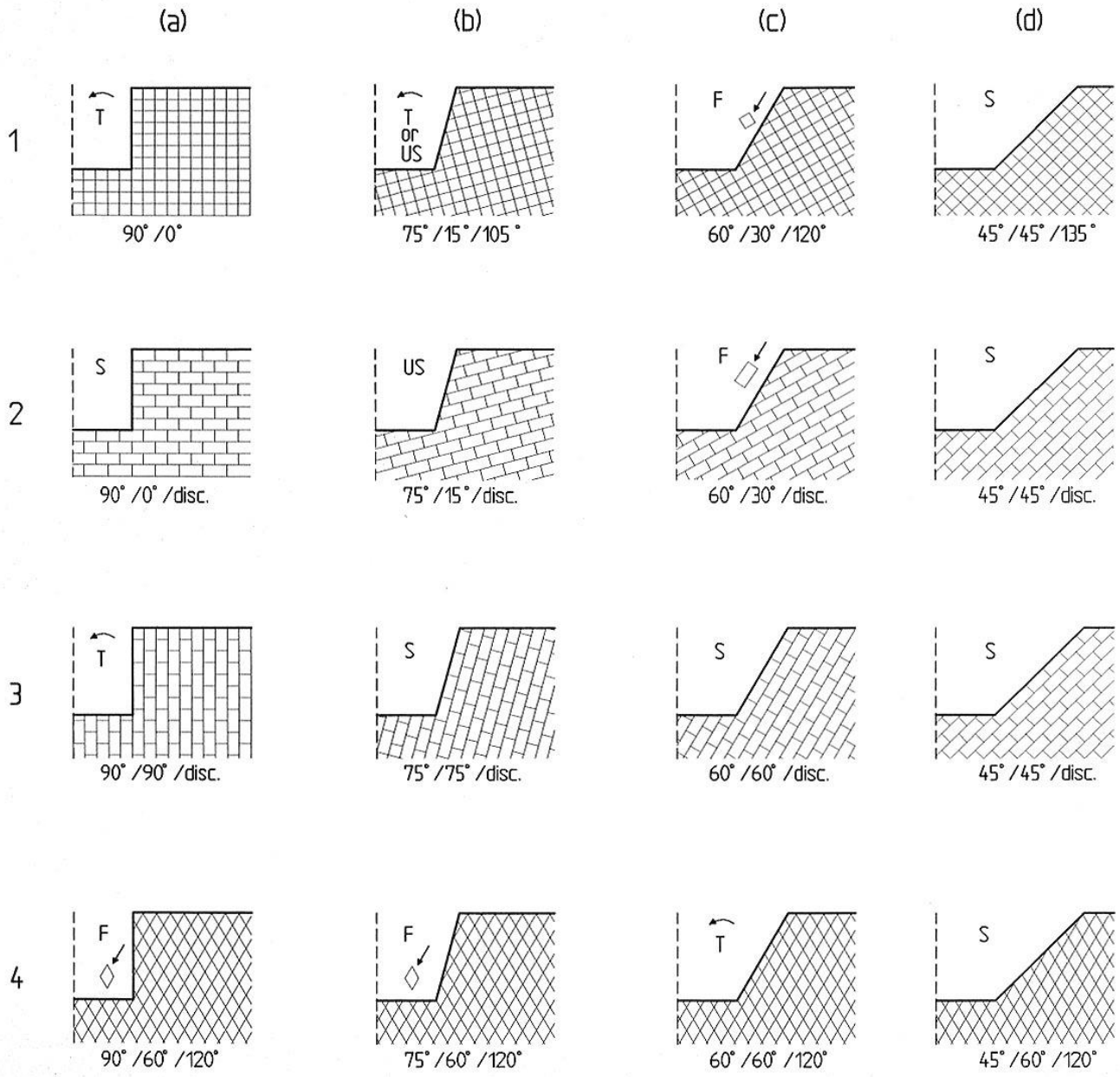
My suggested reinforcement principles ……

were not wanted!

Need very basic decisions! 45° to 90°…..or < 45°



Barton and Bar, 2015. Q-slope.



Obviously we select **'common sense' solutions** in relation to dominant joint orientations.
(at least 5 x 'S')

The project during which Q-slope was tested and adjusted, with the help of seismic refraction and core logging, is briefly shown in the next few screens.

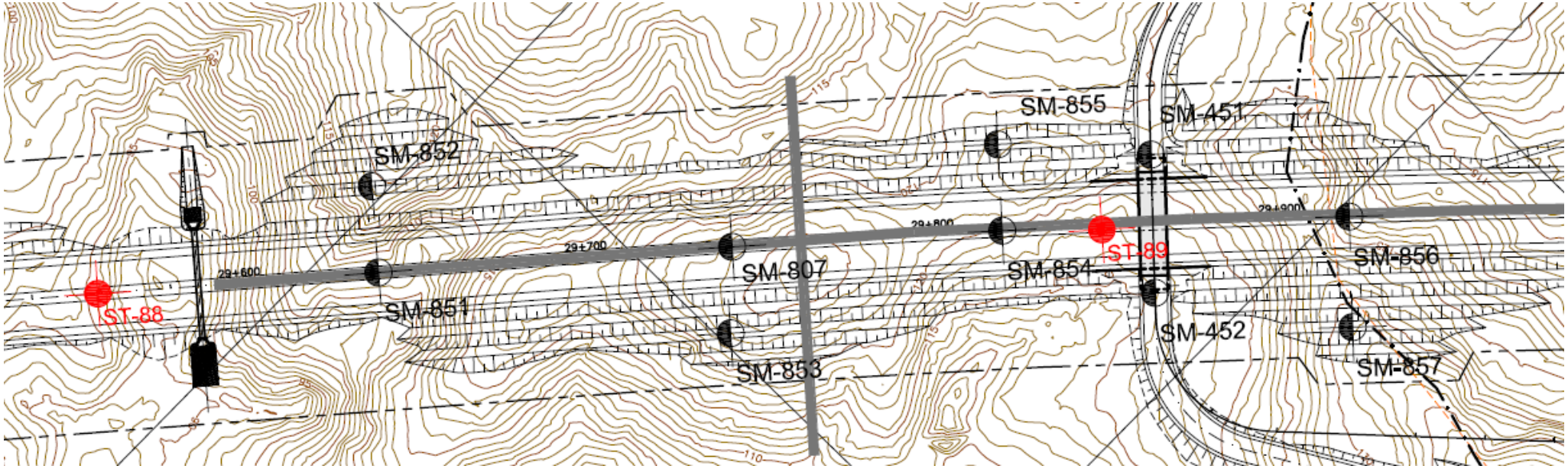
Barton and Bar, 2015. Q-slope.

PROJECT # 2

HOW WIDE TO CLEAR THE FOREST, *WITH SPACE FOR* ***DIFFERENTLY INCLINED*** *MOTORWAY SLOPES?*

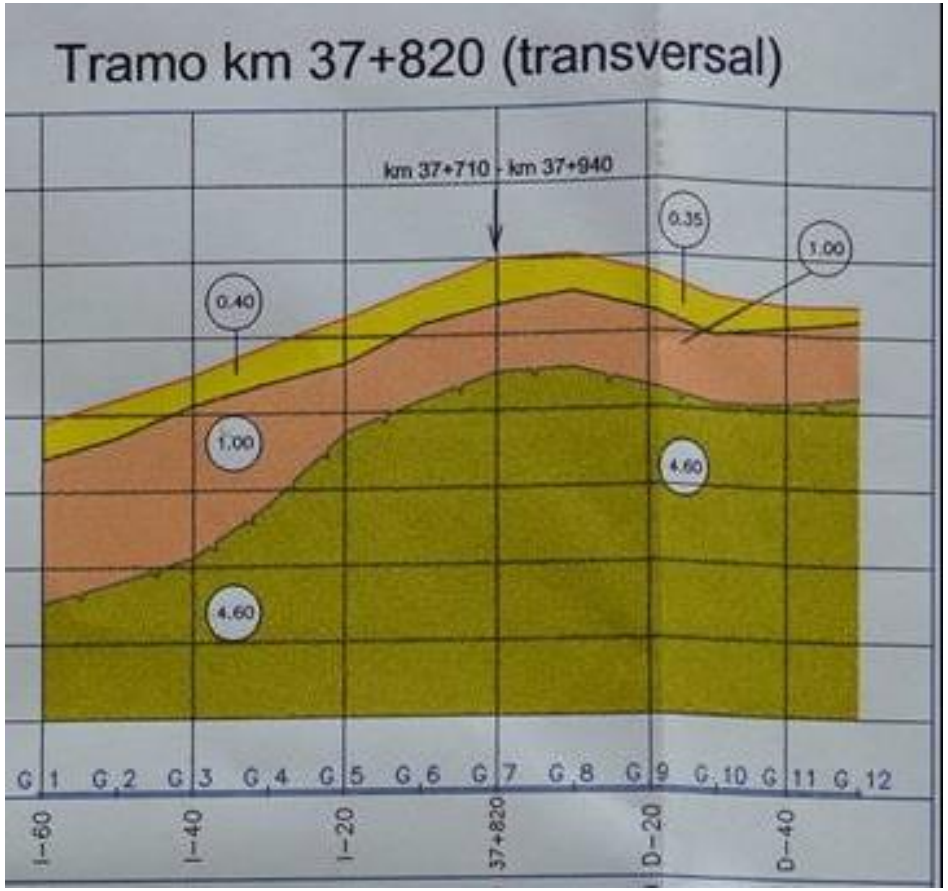
(i.e. saprolite, weathered rock, fresh rock)…..25°, 45°, 85°…each with no support, but catch benches, and low maintenance)

Barton and Bar, 2015. Q-slope



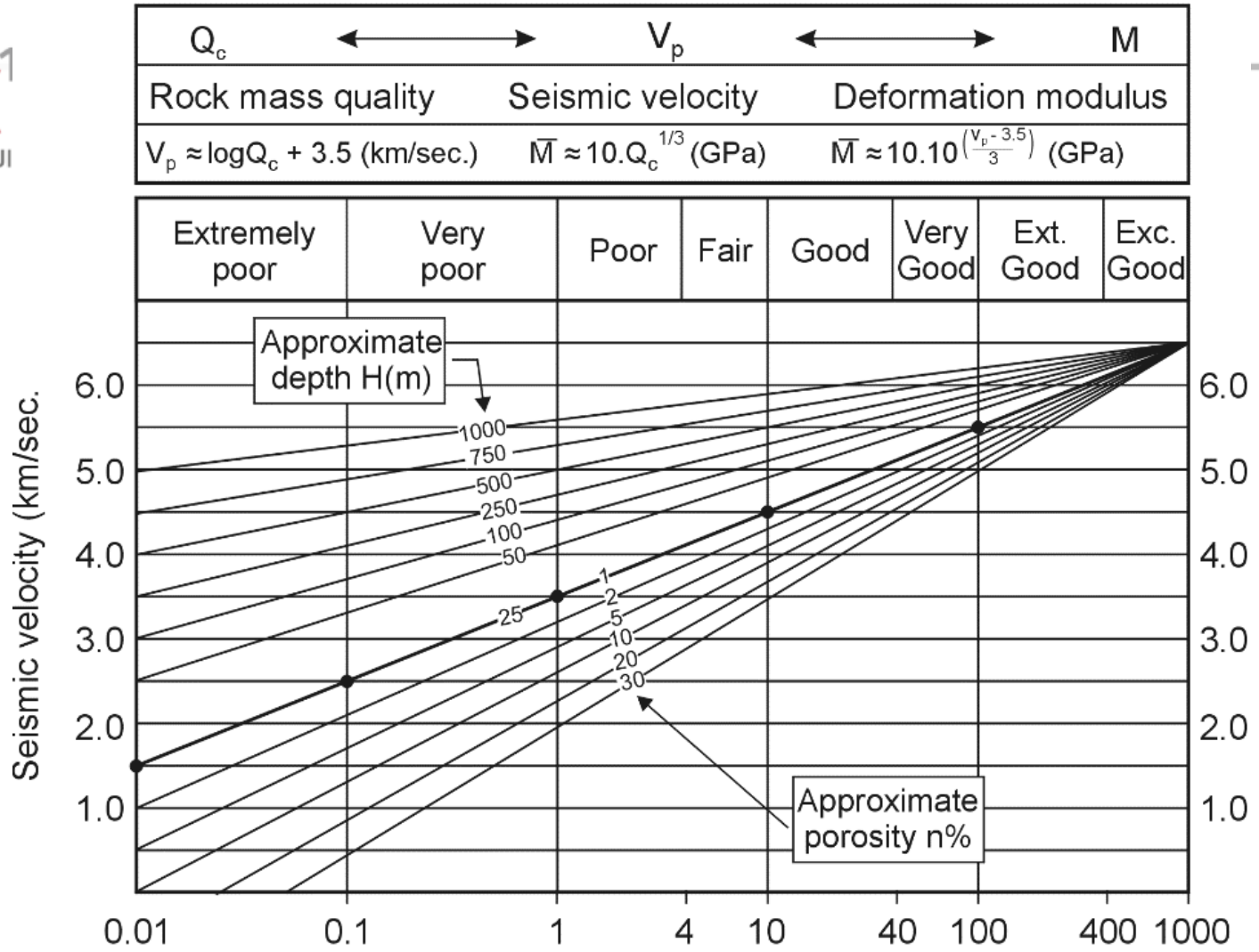
Core-logging and seismic refraction……..Q-V_P ……..slope angle estimates

Barton and Bar, 2015. Q-slope



0.6-1.0	1.1-1.5	1.6-2.0	2.1-2.5	2.6-3.0	3.1-3.5	3.6-4.0	4.1-4.5	4.6-5.0
IIIIIIIII	IIIIIII	IIIIIIIIII I IIII	II	IIIIIIIIII II	IIIIIIIIII IIII	IIIIIIIIII IIIIIIIIII IIIIIIIIII IIIIIIII	IIIIIIIIII IIIIIIIIII IIII	IIIIIIIIII IIIIIIIIII I
9	7	14	2	12	14	39	24	21
n=30-20%	n=20-15%	n=15-5%	n= 5-2%	n=2-1%	n=1%	n=1%	n=1%	n<1%
UCS=5	UCS =10	UCS =10	UCS =25	UCS =25	UCS =50	UCS =75	UCS =100	UCS =150
Q≈ 0.001-0.01	Q≈ 0.01-0.1	Q≈ 0.1-0.2	Q≈ 0.2-0.5	Q≈ 0.5-1	Q≈ 1-2	Q≈ 2-4	Q≈ 4-10	Q≈ 10-20

Barton and Bar, 2015. Q-slope



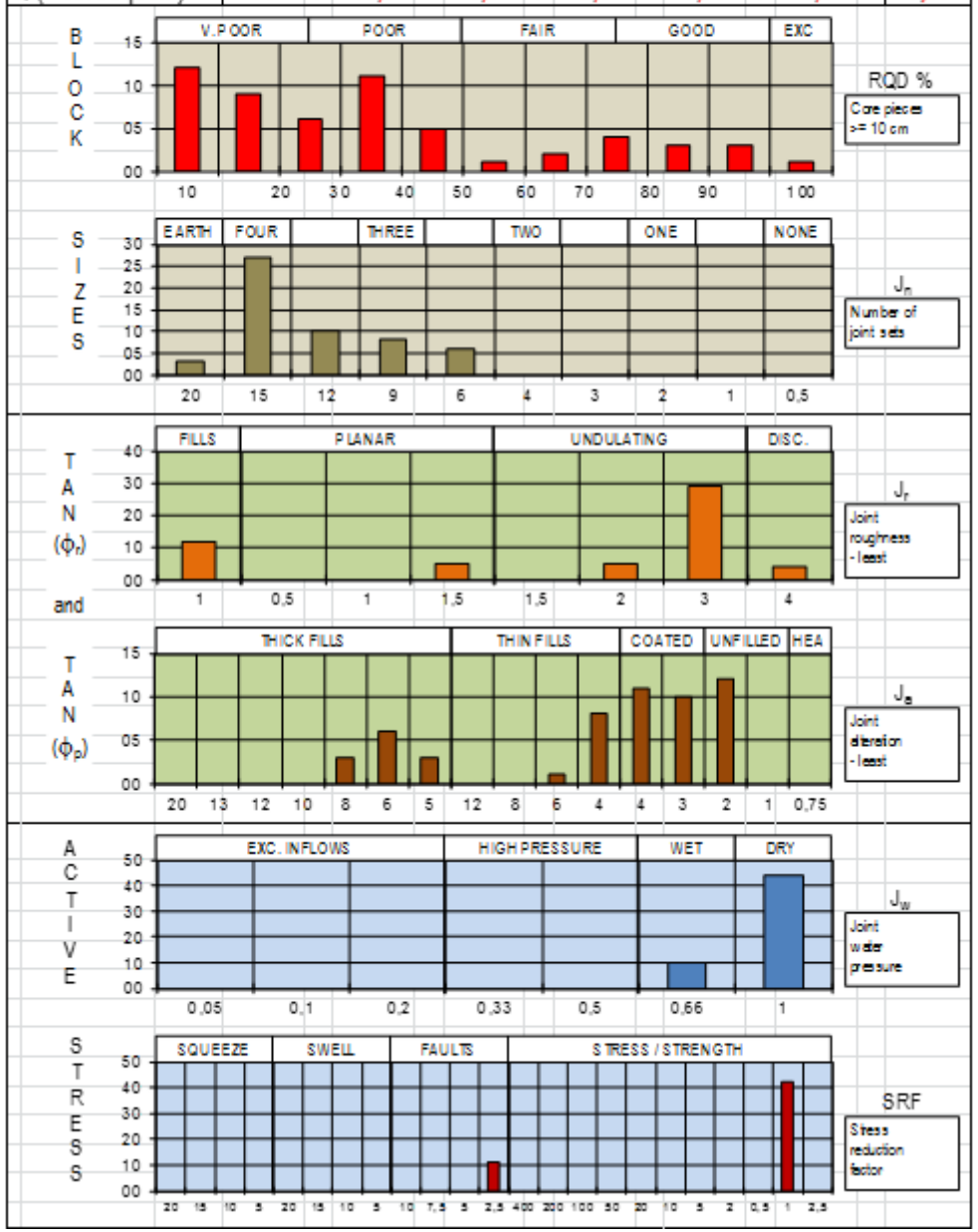
$$Q_c = \left[\frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \right] \frac{\sigma_c}{100}$$

When seismic results are available: use link to Q-value

(Barton, 1995, 2006-book)

Q-histogram method – originally developed for rapid (NB in moving car) logging of 10's of kilometers of *rock slopes* near a long head-race tunnel in Turkey.

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	15,0	*	1,0	/	6,0	*	0,66	/	2,5	=	0,029
Q (typical max)=	75	/	6,0	*	4,0	/	2,0	*	1,00	/	1,0	=	25,0
Q (mean value)=	38	/	12,8	*	2,4	/	3,9	*	0,94	/	1,3	=	1,29
Q (most frequent)=	10	/	15,0	*	3,0	/	2,0	*	1,00	/	1,0	=	1,00



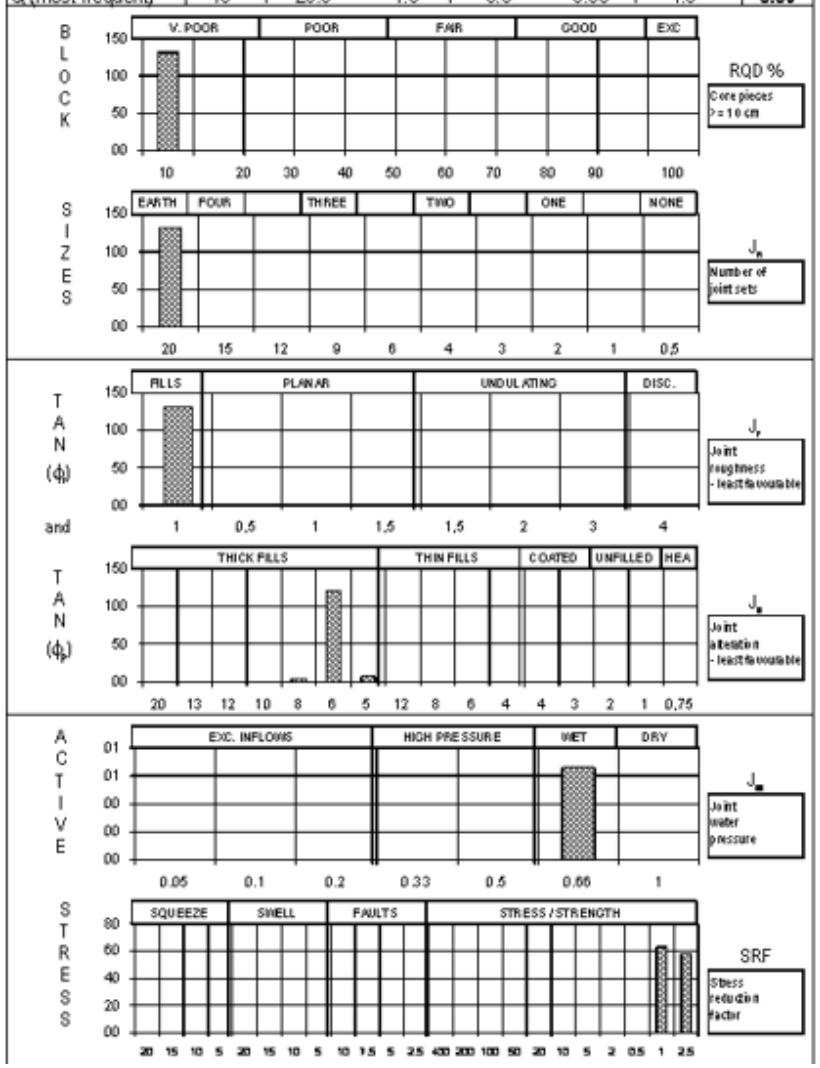
I	ROCK MASS STRUCTURE			
1	RQD	Deere et al., 1967)	block size	Q Q
2	J_n	= joint set number		
3	F	= joint frequency (per metre)		
4	J_v	= volumetric joint count (Palmström, 1982)		
5	S	= joint spacing (in metres)		
6	L	= joint length (in metres)		
7	w	= weathering grade (ISRM, 1978)		
8	α/ß	= dip/dip direction of joints (Schmidt diagram)		
II	JOINT CHARACTER			
9	J_r	= joint roughness number	shear strength	Q Q
10	J_a	= joint alteration number		
11	JRC	= joint roughness coefficient		
12	a/L	= roughness amplitude of asperities per unit length (mm/m)		
13	JCS	= joint wall compressive strength		
14	ϕ_r	= residual friction angle		
15	r,R	= Schmidt rebound values for joint and rock surfaces		
III	WATER, STRESS, STRENGTH			
16	J_w	= joint water reduction factor	active stress	Q Q
17	SRF	= stress reduction factor		
18	K	= rock mass permeability (m/s)		
19	σ_c	= compressive strength		
20	σ_1	= major principal stress		

Q IS ONLY PART OF A ROCK MASS DESC-RIPTION EXERCISE

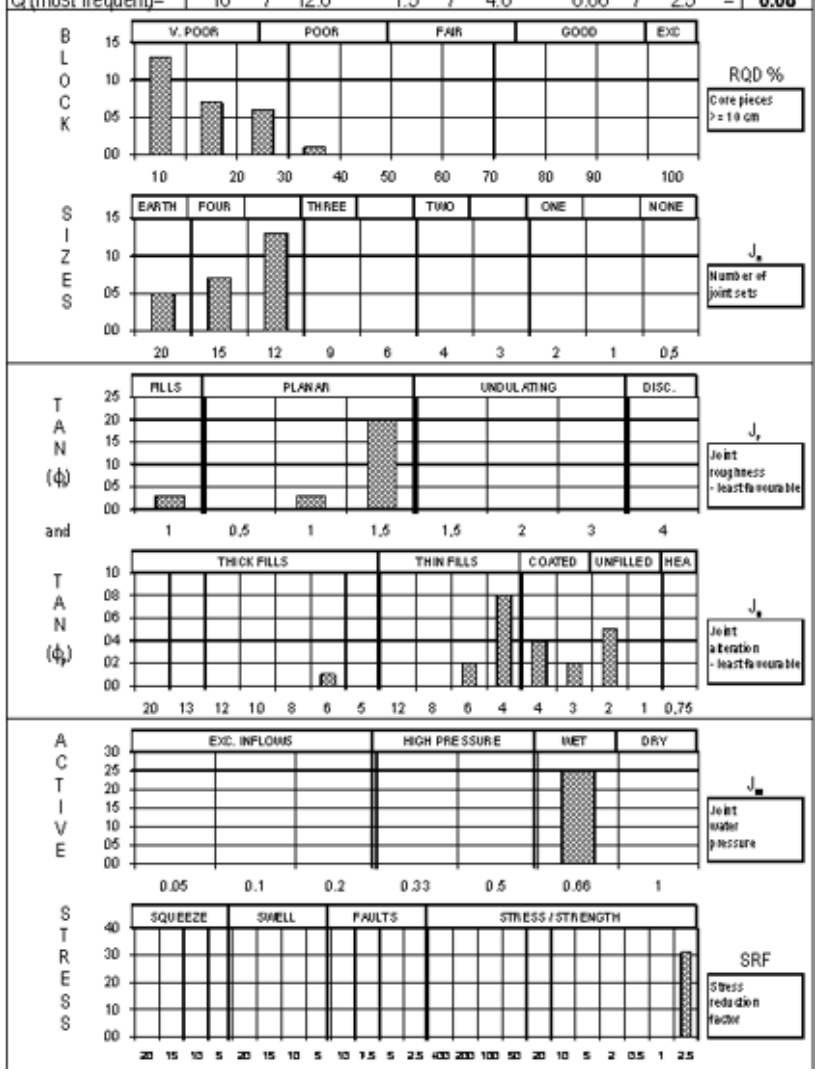
On the next screen:

saprolite, weathered rock, fresh rock

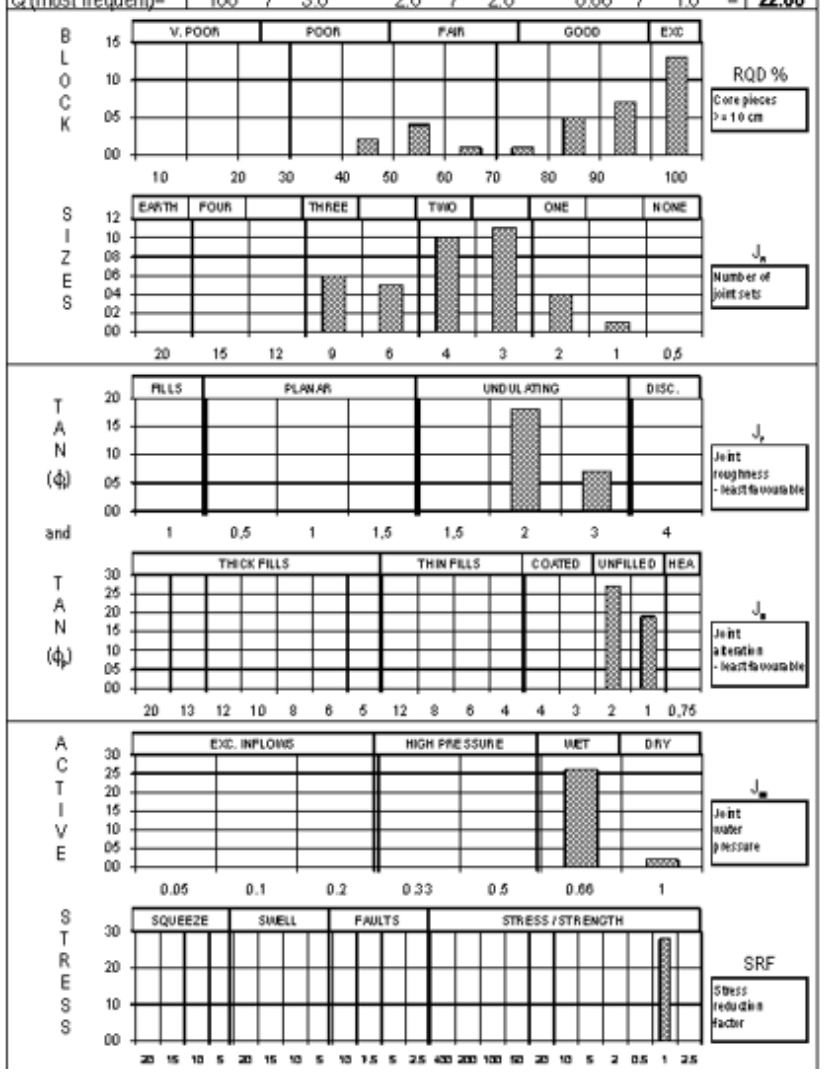
Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	20.0	*	1.0	/	8.0	*	0.66	/	2.5	=	**0.017**
Q (typical max)=	10	/	20.0	*	1.0	/	5.0	*	0.66	/	1.0	=	**0.1**
Q (mean value)=	10	/	20.0	*	1.0	/	6.0	*	0.66	/	1.7	=	**0.03**
Q (most frequent)=	10	/	20.0	*	1.0	/	6.0	*	0.66	/	1.0	=	**0.06**



Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	20.0	*	1.0	/	4.0	*	0.66	/	2.5	=	**0.033**
Q (typical max)=	25	/	12.0	*	1.5	/	2.0	*	0.66	/	2.5	=	**0.4**
Q (mean value)=	16	/	14.4	*	1.4	/	3.7	*	0.66	/	2.5	=	**0.11**
Q (most frequent)=	10	/	12.0	*	1.5	/	4.0	*	0.66	/	2.5	=	**0.08**



Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	55	/	9.0	*	2.0	/	2.0	*	0.66	/	1.0	=	**4.033**
Q (typical max)=	100	/	2.0	*	3.0	/	1.0	*	0.66	/	1.0	=	**99.0**
Q (mean value)=	86	/	4.5	*	2.3	/	1.6	*	0.68	/	1.0	=	**18.86**
Q (most frequent)=	100	/	3.0	*	2.0	/	2.0	*	0.66	/	1.0	=	**22.00**



So what is Q-slope?

(it is a simple synthesis of experience: a model with an empirical data base)

Barton and Bar, 2015. Q-slope

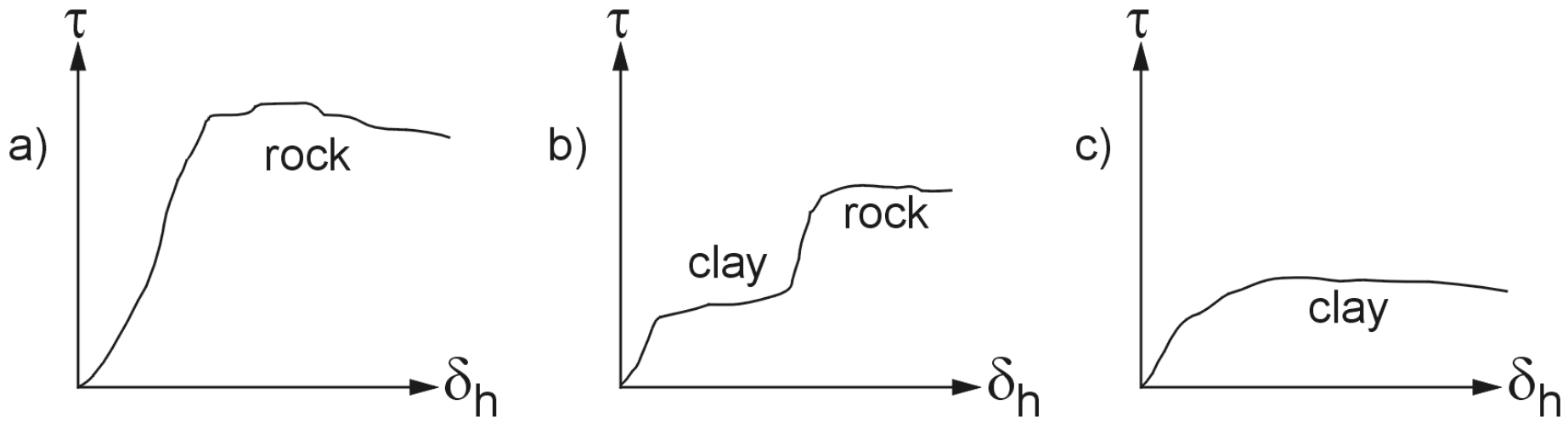
$$Q\ slope = \frac{RQD}{J_n} \ x \left(\frac{J_r}{J_a}\right)_o \ x \ \frac{J_{wice}}{SRF_{slope}}$$

RQD/J_n are unchanged

$(J_r/J_n)_o$ are unchanged, BUT have an orientation, and 'wedge' adjustment

J_w (now J_{wice}) has a new structure for slopes, including ice-effects and *tropical rainfall-effects*

SRF_{slope} has new categories tailored for slopes



(a) Rock wall contact

		(thin coatings)				
	Ja/Jr =	0.75	1.0	2	3	4
		$\tan^{-1}(Jr/Ja)$°				
A. Discontinuous joints	4	79°	76°	63°	53°	45°
B. Rough, undulating	3	76°	72°	56°	45°	37°
C. Smooth, undulating	2	69°	63°	45°	34°	27°
D. Slickensided, undulating	1.5	63°	56°	37°	27°	21°
E. Rough, planar	1.5	63°	56°	37°	27°	21°
F. Smooth, planar	1.0	53°	45°	27°	18°	14°
G. Slickensided, planar	0.5	34°	27°	14°	9.5°	7.1°

Jr/Ja is like a 'friction coefficient' (the same as before, since 1974)

Orientation adjustment for joints in rock slopes $(J_r/J_a)_o$

For J_r 'contact' categories a) and b)
J_a 'contact' categories a) and b)

(Note: Use A) and B) when wedges are formed:

For A) the least favourable set or discontinuity:
Multiply J_r/J_a by following:

			0-factor
if	(i)	v. favourably oriented	2
	(ii)	quite favourable	1
	(iii)	unfavourable	0.75
	(iv)	very unfavourable	0.5
	(v)	causing failure if unsupported	0.25

For B) the second least favourable set or discontinuity:
Multiply J_r/J_a by following:

			0-factor
if	(i)	v. favourably oriented	1.5
	(ii)	quite favourable	1.0
	(iii)	unfavourable	0.9
	(iv)	very unfavourable	0.8
	(v)	causing failure if unsupported	0.7

Example: set 1 dominant, least favourable $J_r = 1.5$, $J_a = 2$
set 2 less dominant $J_r = 2$, $J_a = 1$

Wedge structures are formed by these two sets

A) $J_r/J_a = 1.5/2$ 0-factor = 0.5
B) $J_r/J_a = 2/1$ 0-factor = 0.9

The total "J_r/J_a" term used in Q_{slope} is the combined term:
$1.5/2 \times 0.5 \times 2/1 \times 0.9 = 0.68$

The meaning of $(Jr/Ja)_o$

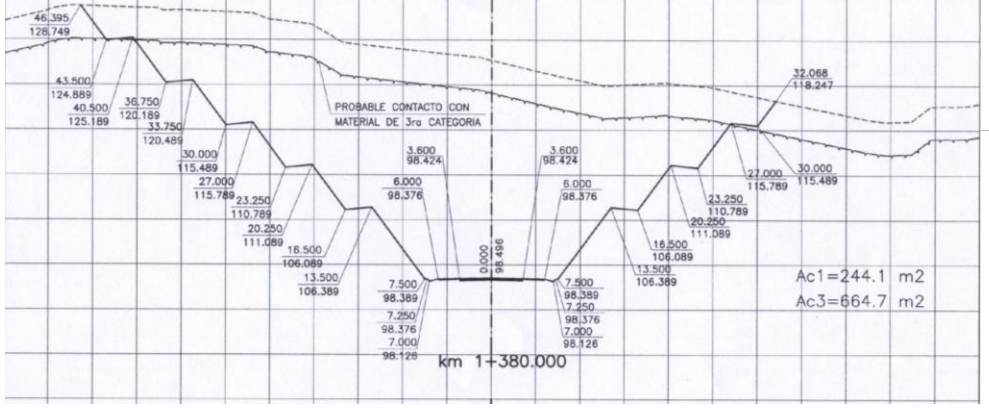
Jr/Ja is for both sides of wedges (if applicable)

Orientation factors for set 1, set 2

Barton and Bar, 2015. Q-slope.

A slope designed with Q-slope, in Panama, viewed after several years (and after several cyclones)

Barton and Bar, 2015. Q-slope



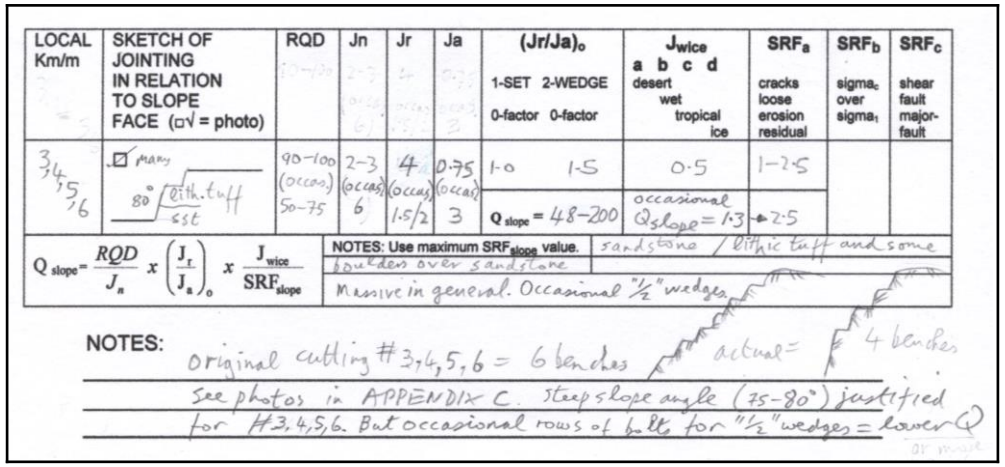
Top: original uniform-slope-angle design in 2006

Middle: actual *multiple-angle* (based on core-logging Q and V_p)

Saprolite over tuff over sandstone

Bottom: Early (2007) Q-slope parameter registration

(a method in development)



LOCAL Km/m	SKETCH OF JOINTING IN RELATION TO SLOPE FACE (☐√ = photo)	RQD	Jn	Jr	Ja	$(Jr/Ja)_o$ 1-SET 2-WEDGE 0-factor 0-factor	J_{wice} a b c d desert wet tropical ice	SRF_a cracks loose erosion residual	SRF_b sigma$_c$ over sigma$_1$	SRF_c shear fault major-fault
3,4,5,6	☑ many 80° lith. tuff est	90–100 (occas) 50–75	2–3 (occas) 6	4 (occas) 1.5/2	0.75 (occas) 3	1.0 1.5	0.5	1–2.5		
						Q_{slope} = 48–200	occasional Q_{slope} = 1.3	→ 2.5		

$$Q_{slope} = \frac{RQD}{J_n} \times \left(\frac{J_r}{J_a}\right)_o \times \frac{J_{wice}}{SRF_{slope}}$$

NOTES: Use maximum SRF_{slope} value.
sandstone / lithic tuff and some boulders over sandstone
Massive in general. Occasional "½" wedges

NOTES: original cutting #3,4,5,6 = 6 benches actual = 4 benches
See photos in APPENDIX C. Steep slope angle (75–80°) justified for #3,4,5,6. But occasional rows of bolts for "½" wedges = lower Q

AUSTRIAN SOCIETY FOR GEOMECHANICS

INTERNATIONAL SOCIETY FOR ROCK MECHANICS

Barton and Bar, 2015. Q-slope

Shallower-angle slopes seen in the overlying weathered-saprolitic materials

.....

and finally the edge of the forest.

Barton and Bar, 2015. Q-slope

ALLOW FOR SUSCEPTIBILITY TO WEATHERING !!

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 $\tau \approx \sigma_n \tan^{-1} (J_r / J_a)$.

Familiar unchanged Q-parameter ratings –

so far.

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

Familiar unchanged Q-parameter ratings – so far.

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

Orientation weightings for Jr/Ja (includes wedges)

More sophisticated Jw (now ***Jwice***) since slopes are ***outside forever.***

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

Familiar ratings, but new slope-related categories

Now over 100 case studies for Q_{slope}

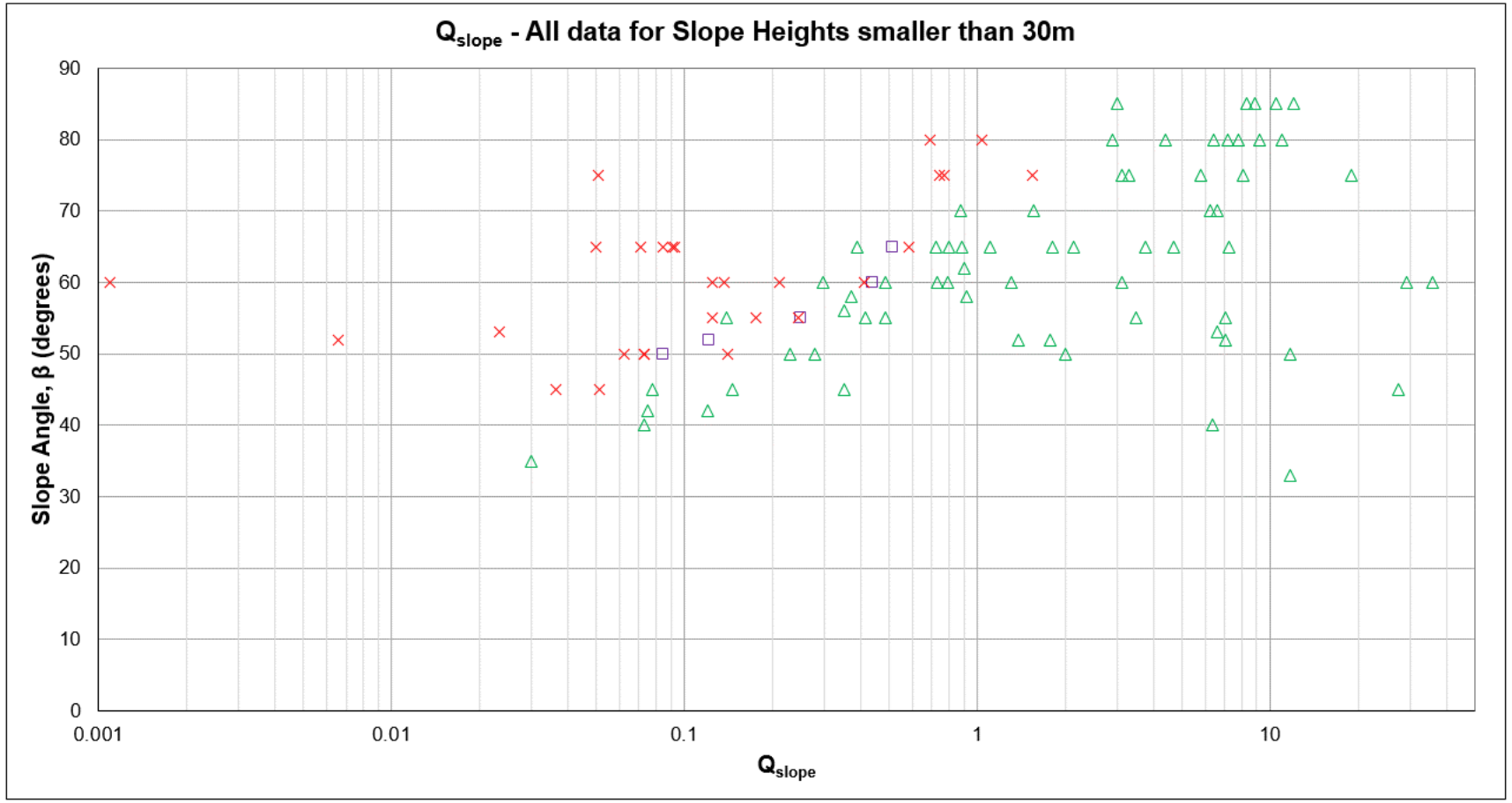
- Slope heights 5m to 30m
- Panama, Dominican Republic, Australia, Papua New Guinea & Laos

- **Rock types include**:
  - **Igneous** – basalt, diorite, dolerite, monzonite, monzodiorite, monzonite porphyry, agglomerate
  - **Sedimentary** – sandstone, siltstone, limestone, mudstone, conglomerate, banded iron formation
  - **Metamorphic** – shale, schist, skarns, phyllite

- **Saprolites** of some rock types have also been recorded.

Q-slope Data for Slope Heights smaller than 30m

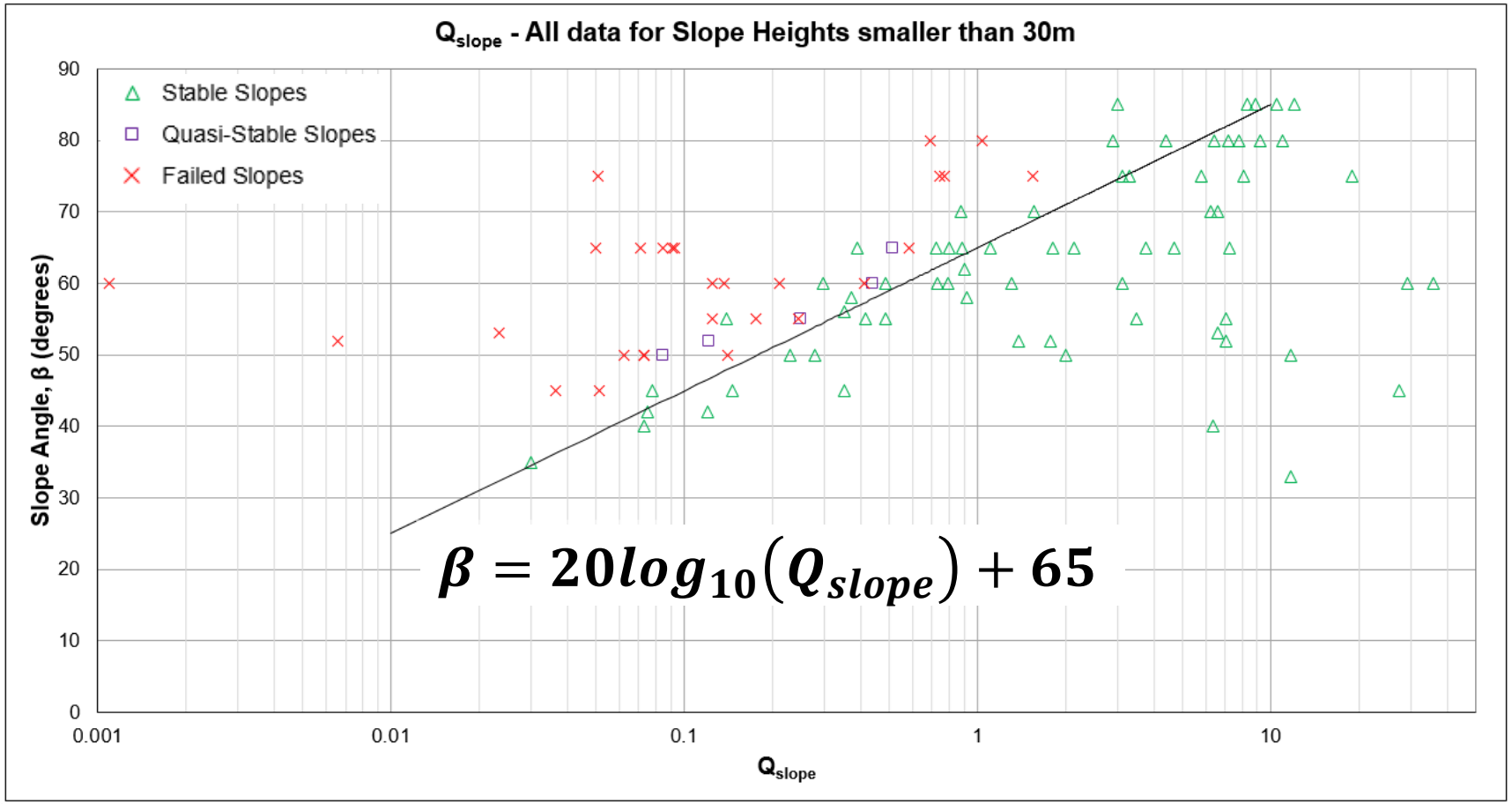
- Over 100 case studies:
  - △ Stable Slopes
  - □ Quasi-Stable Slopes
  - × Failed Slopes
- X-axis is log scale



Q-slope Data for Slope Heights smaller than 30m

- Line of best fit for stable slopes

Q-slope	β (slope angle °)
0.01	**25**
0.1	**45**
1	**65**
10	**85**

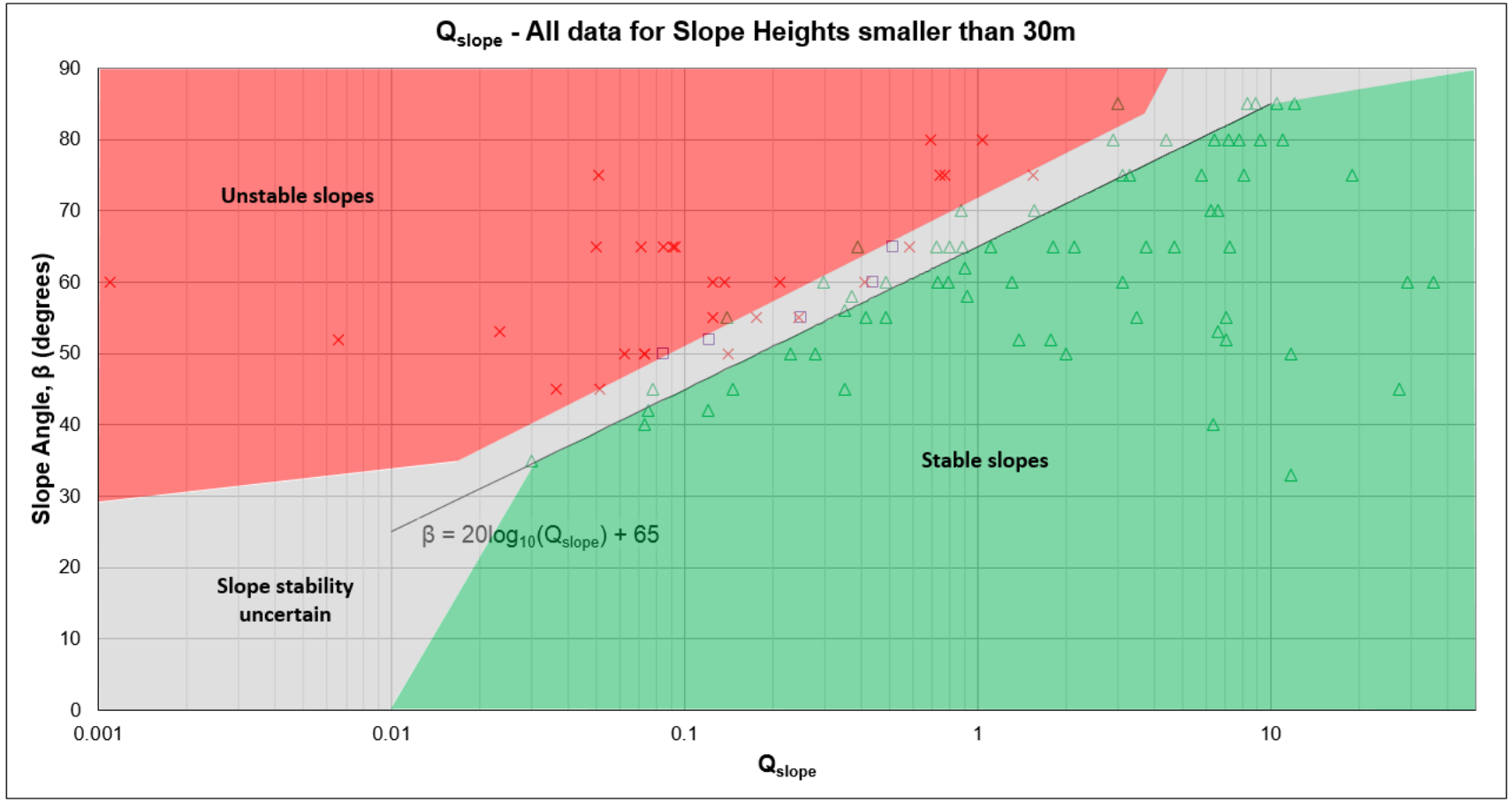


Barton and Bar, 2015. Q-slope

Q-slope Data for Slope Heights smaller than 30m

Slope stability zones:

- **Unstable (red)**
- **Uncertain (grey)**
- **Stable (green)**

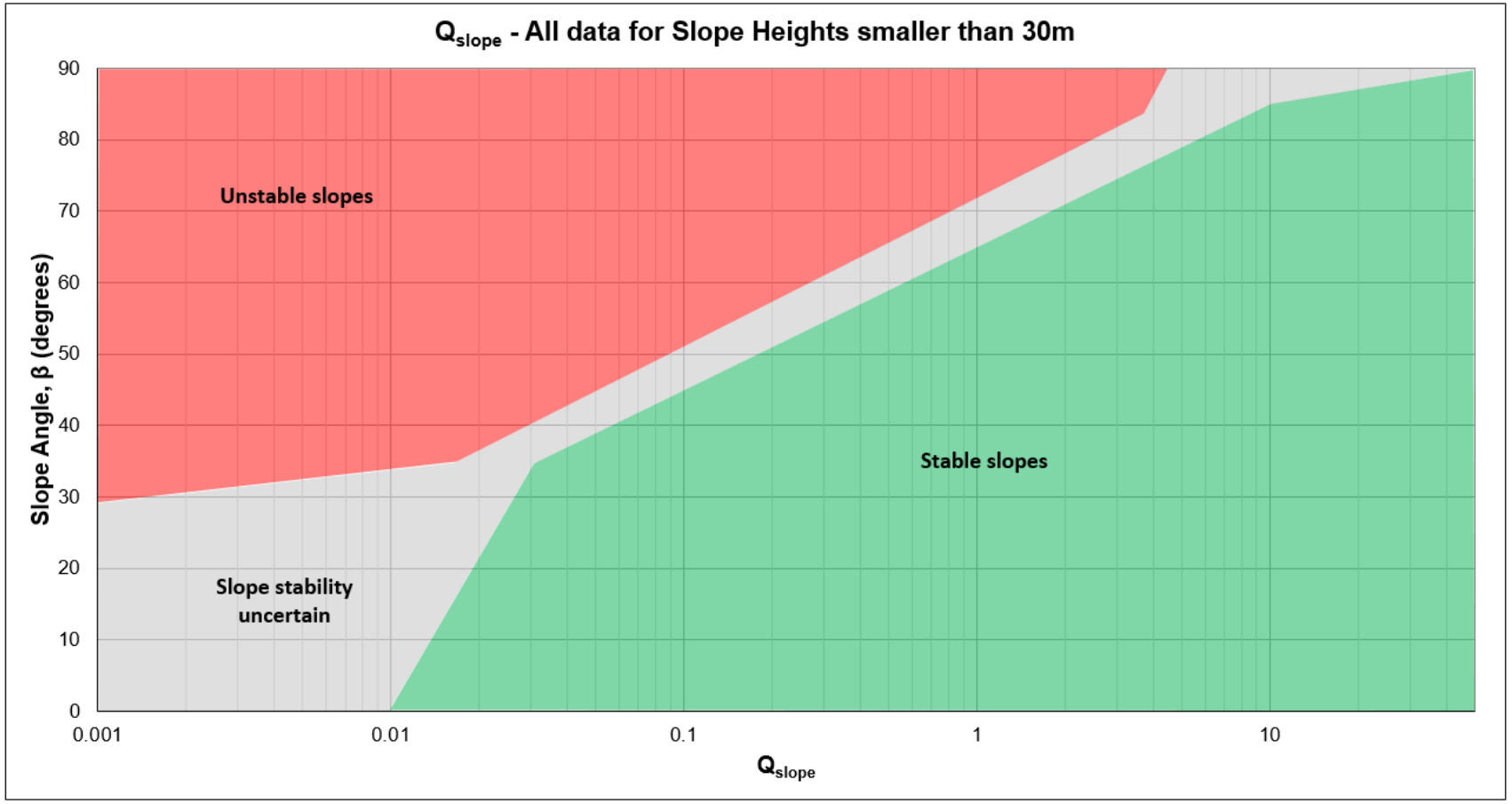


Barton and Bar, 2015. Q-slope

Q-slope Data for Slope Heights smaller than 30m

Slope stability zones:

- **Unstable (red)**
- **Uncertain (grey)**
- **Stable (green)**



Barton and Bar, 2015. Q-slope

Case Study 1: Plane failure

- Pre-failure bench angle = 75°
- Failure plane angle ≈ 60°
- Wet environment
- RQD 75-90%
- Competent rock, UCS~90MPa
- Generally stable structure (i.e. failure is localised due to slope orientation change)
- 2 joint sets and random joints

Barton and Bar, 2015. Q-slope

Case Study 1: Plane failure

RQD (%)	Jn	Jr		Ja		0-factor		Jwice	SRFa	SRFb	SRFc
		SET A	SET B	SET A	SET B	SET A	SET B				
75-90	6	1.5		2		0.25		0.7	2.5	1	

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

$$= \frac{82.5}{6} x \left(\frac{1.5}{2} x 0.25\right) x \frac{0.7}{2.5}$$

$$= \mathbf{0.722}$$

$$\boldsymbol{\beta} = 20 log_{10} Q_{slope} + 65$$

$$= 20 log_{10}(0.722) + 65$$

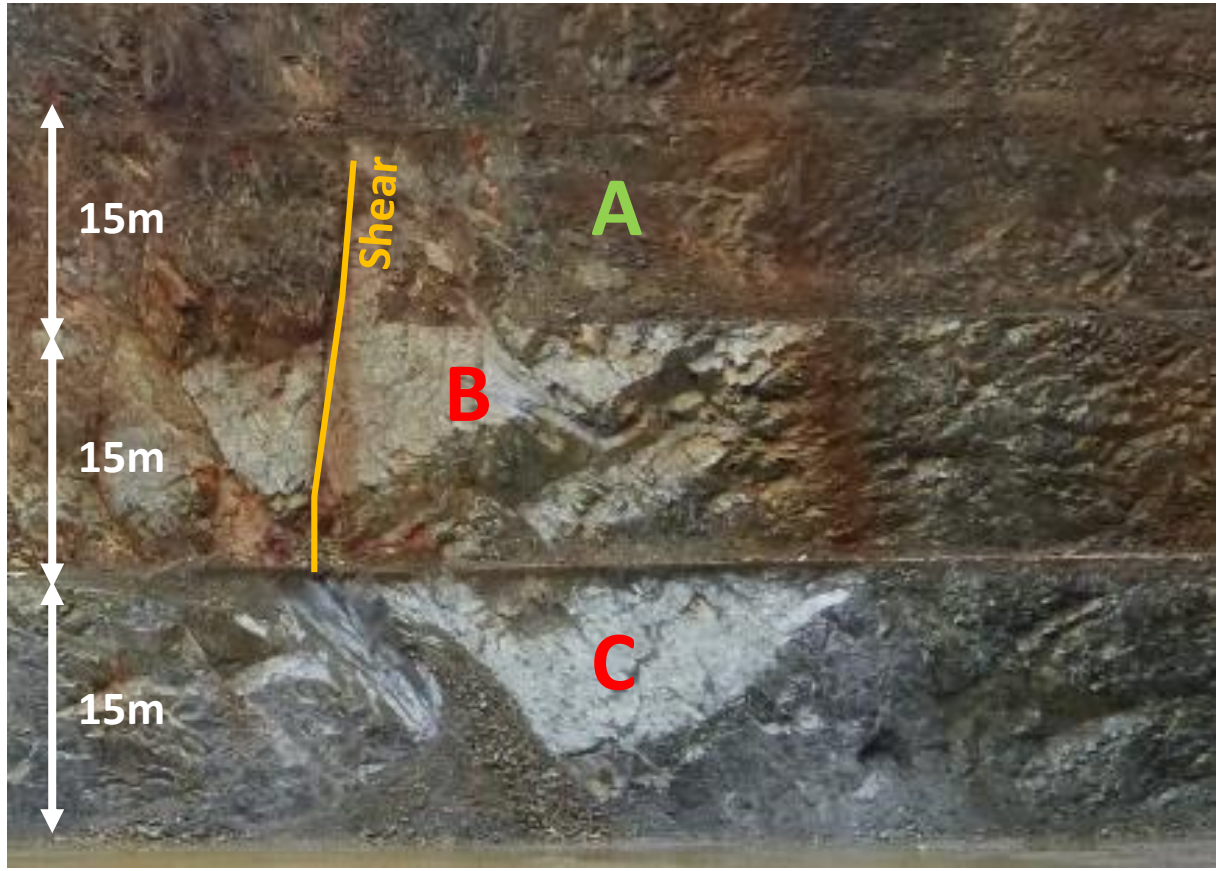
$$= \mathbf{62°} \quad (steepest\ slope\ angle)$$

Pre-failure slope angle was 75°

Barton and Bar, 2015. Q-slope

Case Study 2: Wedge failures

- Wedges ‘B’ & ‘C’ failed separately within days of each excavation.
  Location ‘A’ stable.
- Excavated bench angle = 65°
- Bench height = 15m (individual slope height)
- Wet environment in Papua New Guinea
- RQD 70-90%
- Competent rock, UCS~70MPa
- Unstable structure (wedge forming)
- Typically 3 joint sets
- Localised shear involved in the failure
- Horizontal weep holes (‘A’ & ‘B’)



Barton and Bar, 2015. Q-slope

Case Study 2: Wedge failures (Location B)

RQD (%)	Jn	Jr		Ja		0-factor		Jwice	SRFa	SRFb	SRFc
		SET A	SET B	SET A	SET B	SET A	SET B				
70-90	12	1	1.5	2	3	0.25	0.9	0.6x1.5	2.5	1.5	1

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

$$= \frac{80}{12} x \left(\underbrace{\frac{1}{2} x 0.25}_{\text{Set A}} x \underbrace{\frac{1.5}{3} x 0.9}_{\text{Set B}}\right) x \frac{(0.6x1.5)}{2.5}$$

Drainage measures

$$= \mathbf{0.135}$$

$$\boldsymbol{\beta} = 20log_{10}Q_{slope} + 65$$

$$= 20log_{10}(0.135) + 65$$

$$= \mathbf{48°} \quad (steepest\ slope\ angle)$$

Pre-failure slope angle was 65°

Barton and Bar, 2015. Q-slope

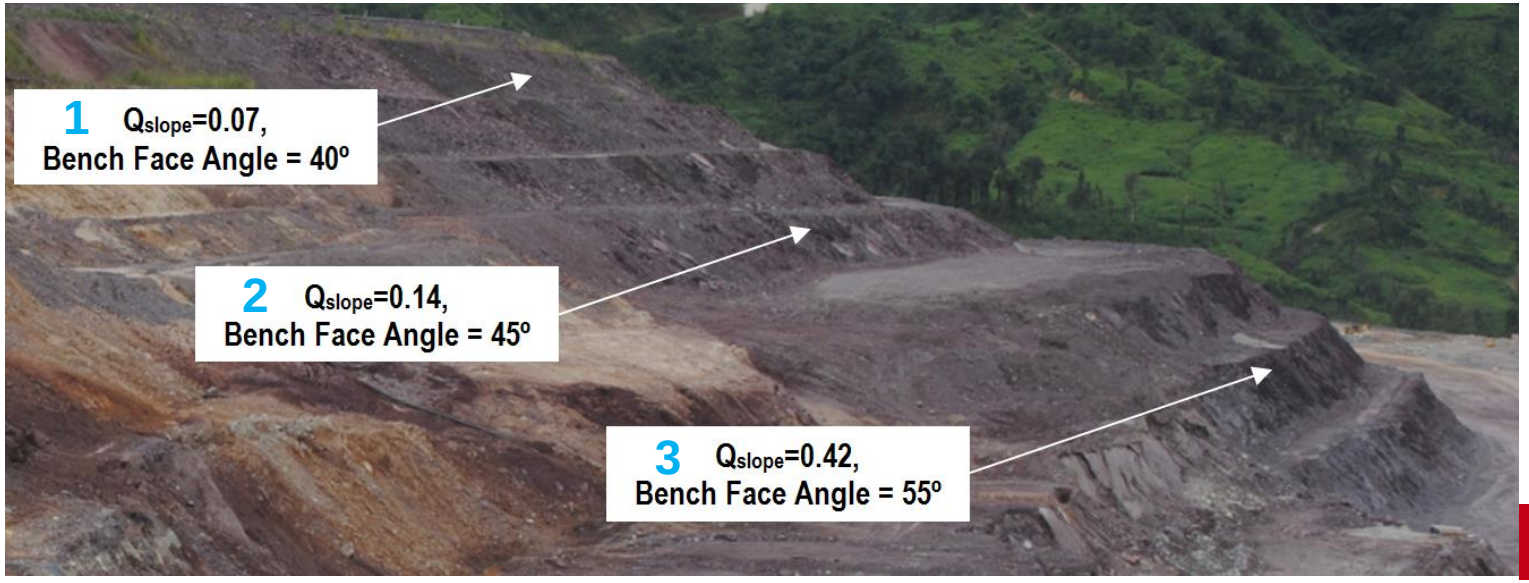
Case Study 3: Q-slope mining application

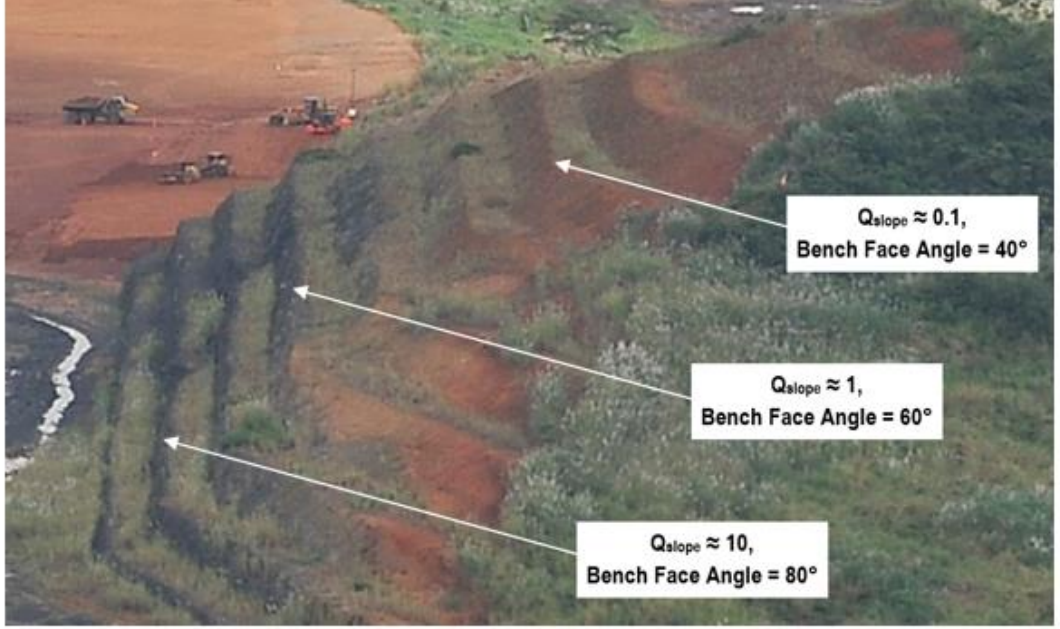
- Thinly bedded, folding siltstone dipping into excavation (dip: 35°-70°)
- Bedding dip becomes more favourable lower in the slope & RQD slightly improves
- Bench face angles adjusted accordingly. Stable bench designs achieved.

Case Study 3: Q-slope mining application

Local	RQD (%)	Jn	Jr	Ja	0-factor	Jwice	SRFa	SRFb	SRFc	Q-slope	β (slope angle °)
1	10-25	6	1	4	0.5	0.5	2.5	1	N/A	0.0729	**42**
2	10-25	6	1	3	0.75	0.5	2.5	2	N/A	0.1458	**48**
3	25-50	9	2	3	0.75	0.5	2.5	2	N/A	0.4166	**57**

- RQD improves with depth
- Orientation factor improves with depth (bedding)

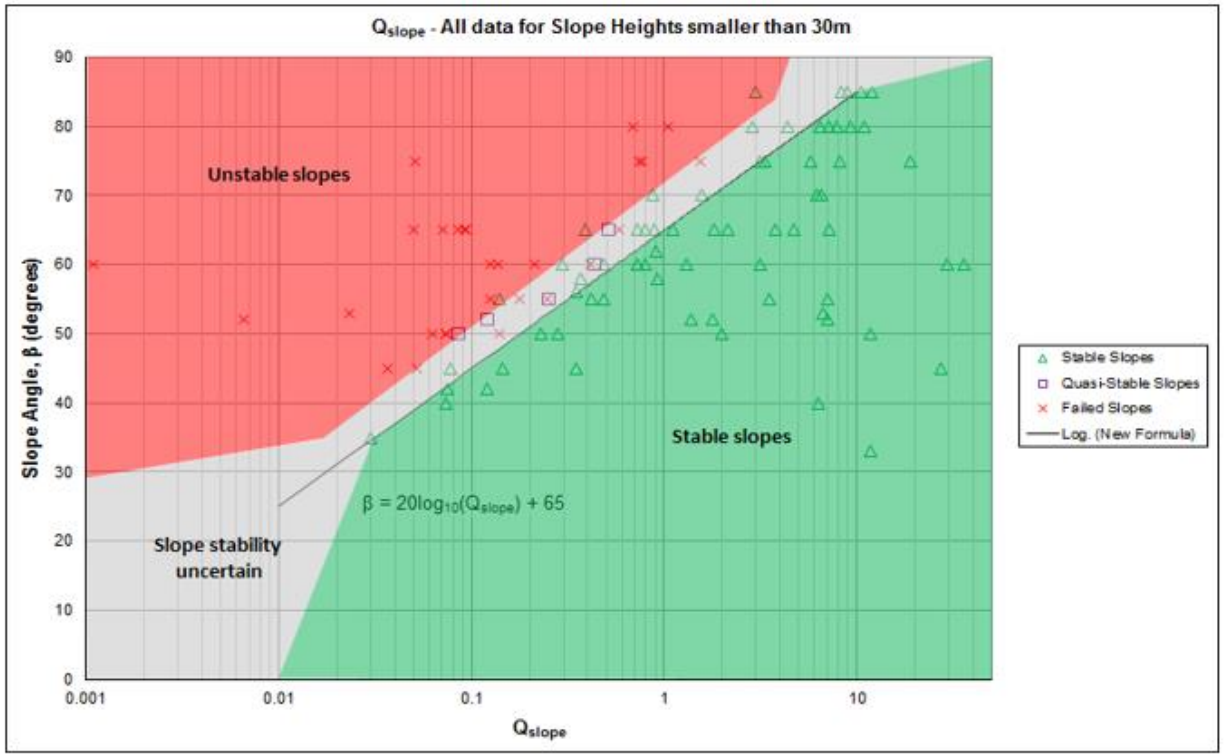




Q-SLOPE METHOD

(Barton and Bar, 2015)

Q-slope = 0.01 : slope angle ≈ 25°
Q-slope = 0.1 : slope angle 45°
Q-slope = 1.0 : slope angle 65°
Q-slope = 10 : slope angle 85°

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

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