An evaluation of slope stability classification

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Slopes in The Netherlands?

Jan van Goyen, View at Leiden, 1650 – Museum Lakenhal, Leiden

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Dykes have slopes!

(Brouwersdam, The Netherlands)

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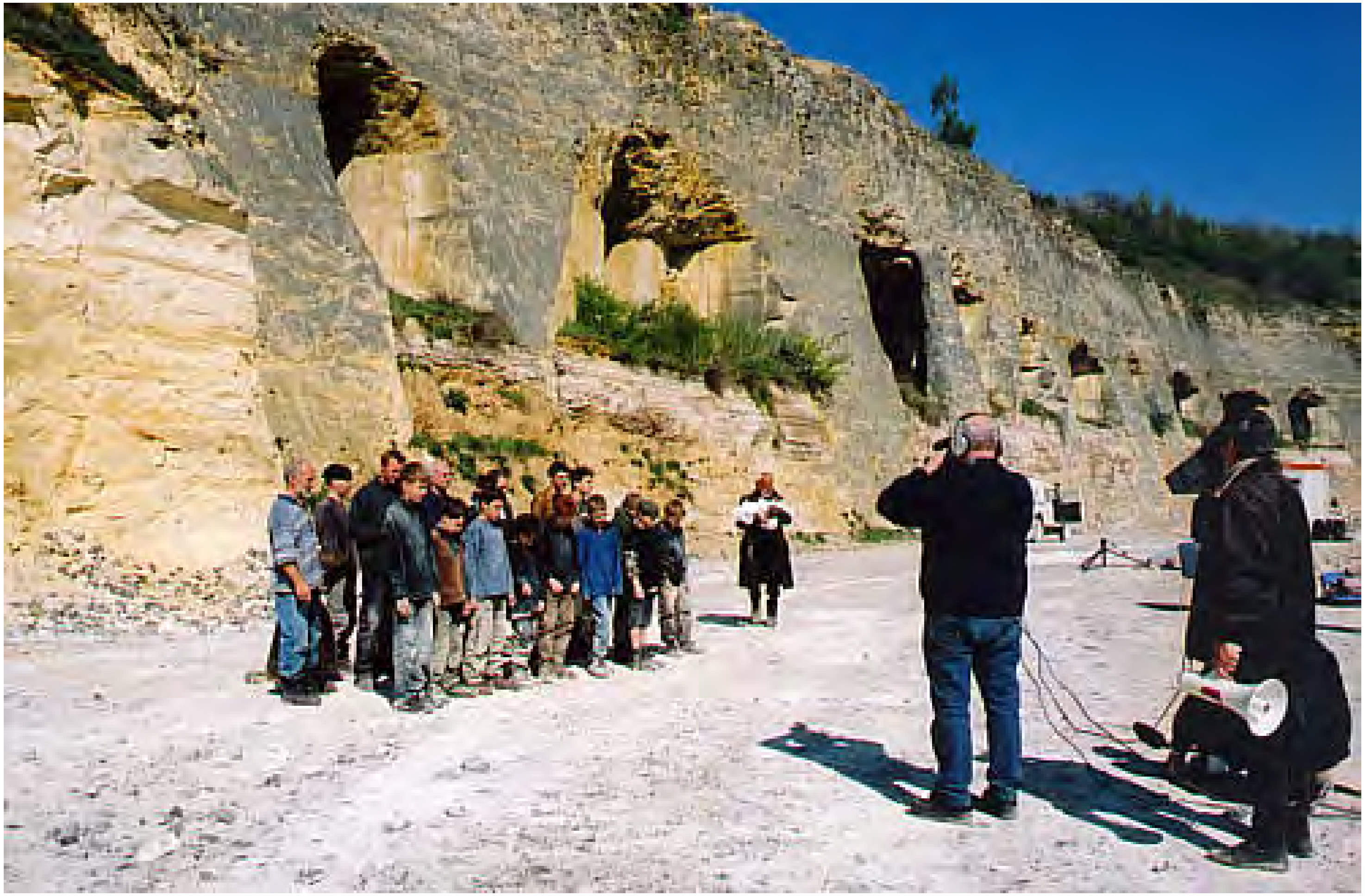
Dyke with basalt cover may be modelled with discontinuous rock mechanics

(seadyk with basalt cover: photo: Sytske Dijksen; http://www.waddenzee.nl/)

Also real rock slopes in the Southern part of The Netherlands!



(ENCI quarry; photo: http://www.beeldexpressie.be/film/)

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Other reasons to study slopes even if coming from a flat country

Slopes are an ideal study object for soil and rock mechanics in general because:

- **Soil or rock in tunnels and foundations often not visible**
- **Failures in tunnels or foundations not or difficult to study**
- **Slopes often easily accessible**
- **Often many slopes in a relatively small area**

and not very scientific, but highly important:

many Dutch civil engineering companies work worldwide with soil and rock slopes

Slope stability

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What is required to analyse the stability of a slope ?

- **soil and rock mass properties**
- **present and future geometry**
- **present and future geotechnical behaviour of soil or rock mass**
- **external influences such as earthquakes**

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Slope stability analyses done per geotechnical unit in a geometrically uniform slope geometry,
e.g. a slope analyses is done for a uniform material with uniform geometry

Is that possible ?

Variation

Heterogeneity of mass causes:

- variation in mass properties

Heterogeneity of slope geometry causes

- Variation in geometry

Mass versus geotechnical unit

- Mass is split in units such that homogenous geotechnical units are created that can be analysed with assumed uniform properties for the unit
- However, a certain variation in properties will always be present
- How to define a unit?

Example of geotechnical units

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Definition of a geotechnical unit is based on economical or environmental impact or the hazard the project forms for human live

- the more different units, the better the uniformity per unit and the better the analyses, but the higher the costs
- costs are balanced against the economical and environmental value of a project, and the potential hazard a project may impose on human live

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But no unit will be absolutely uniform

Hence, a certain variation will always be present in any geotechnical unit, causing an uncertainty in properties used for the analyses

Uncertainty

- Uncertainty in properties
- Uncertainty (error) in measurements of properties
- Uncertainties in geometry
- Uncertainty (error) in measurements of geometry (often small)
- Uncertainty in failure mechanisms applicable

Options for analysing slope stability

Analytical

Numerical

Classification

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Analysing slope stability

- **analytical: only in relatively simple cases possible for a discontinuous rock mass**
- **numerical: difficult and often cumbersome, however, possible with discontinuous numerical rock mechanics programs such as UDEC**

Hence, classification systems may be a good and simple alternative

What options from existing classification systems?

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Classification systems are empirical relations that relate rock mass properties either directly or via a rating system to an engineering application, e.g. a slope

Existing classification systems:

For underground:

Bieniawski (RMR)
Barton (Q)
Laubscher (MRMR)
etc.

For slopes:

Selby
Bieniawski (RMR)
Vecchia
Robertson (RMR)
Romana (SMR)
Haines
etc.

Development of existing rock mass classification systems

- First developed for underground excavations
- Most slope systems are based on underground systems adjusted to be used for slopes

Therefore a legacy in properties and parameters from underground systems

Development of existing rock mass classification systems

Most systems that are used at present are based on systems developed some 30 years ago

At that time “state-of-the-art” and new, but this is no reason not to investigate whether the systems are still as applicable or that new methodologies (for example, with the use of computers) allow for better systems

Existing rock mass classification systems

- Wide variation in rating systems, methodologies, parameters, calculation methods, boundaries, etc.
- Addition, multiplication, logarithmic, etc.
- Wide variation in the influence of parameters on the final result
- In some un-understandable ratings and relations

Strange influence parameters in some systems

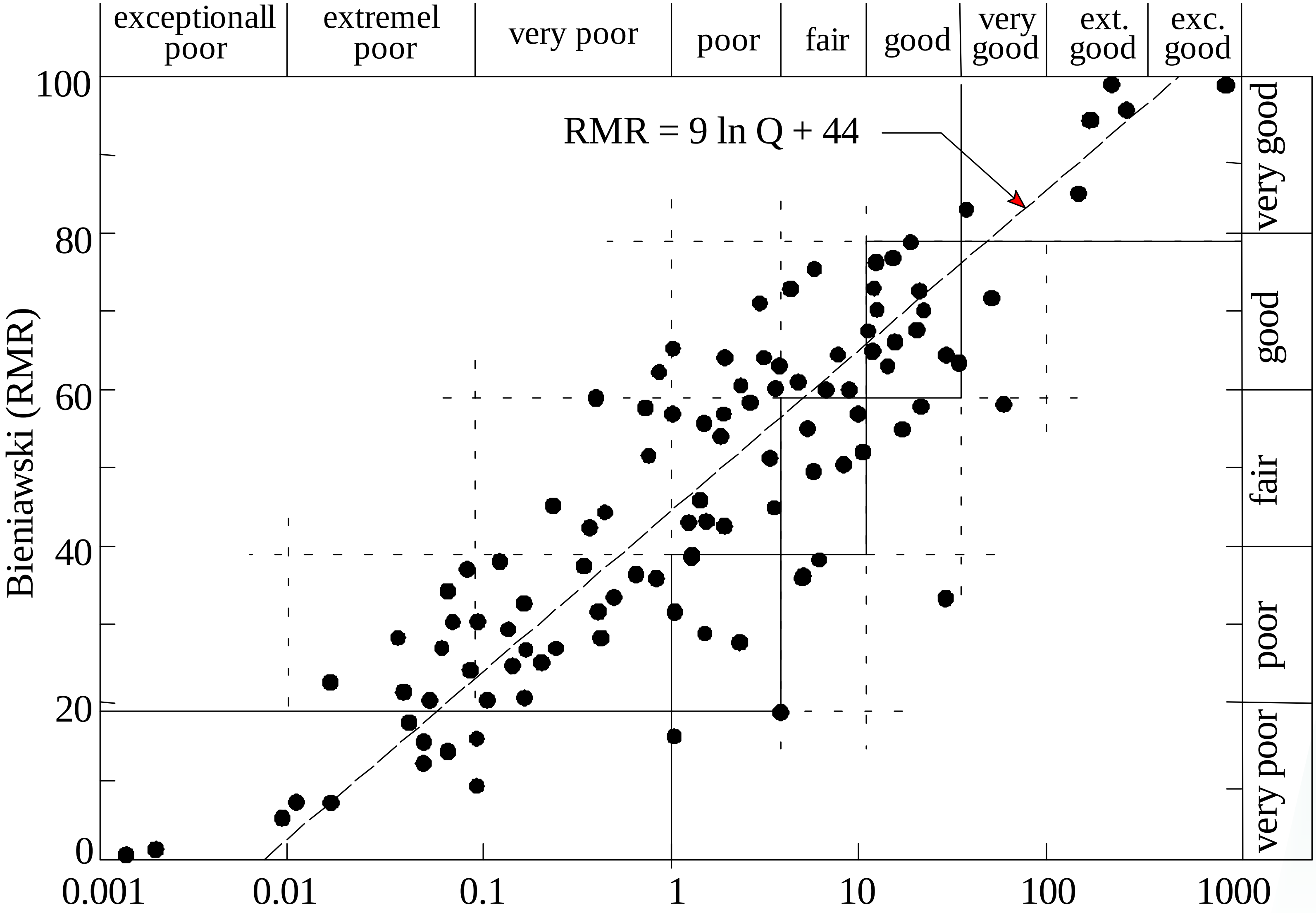
For example:

A slope in a rock mass with a high intact rock strength and one thick clay filled (gauge type) discontinuity set that will lead to sliding failure.

In some systems the intact rock strength will partially determine the stability rating, while the slope will be unstable due to the presence of the thick clay filled discontinuity and not at all be influenced by the intact rock strength.

How valid is such a system?

Correlation between RMR and Q ?



(after Bieniawski, 1989)

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Rock mass parameters of interest for engineering structures in or on rock

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geotechnical unit	intact rock strength			
	discon-tinuities		orientation (with respect to engineering structure)	
		rock block size and form	amount of disc. sets	
			spacing per disc. set	
			persistence per disc. set	
		shear strength along discontinuity (condition of discontinuity)	surface characteristics of discontinuity wall	material friction
				roughness (dilatancy)
				strength
				deformation
			infill material	
	susceptibility to weathering			
	deformation parameters of intact rock/rock mass			
engineering structure	geometry of engineering structure (size and orientation of a tunnel, height and orientation of a slope, etc.)			
external influences	water pressure/flow, snow and ice, stress relief, external stress, etc.			
	type of excavation			

Existing classification systems

- The absence of the intact rock strength (except for a low intact rock strength/environment stress ratio), in the Barton system.
- The absence of discontinuity spacing as quantitative parameter in the Barton system.
- The strong reduction in influence of the water parameter in the Laubscher and Haines systems as compared to the systems of Bieniawski and Barton.
- The absence of a water/water pressure parameter in the Robertson modification for slopes of the Bieniawski system and in the slope stability system of Vecchia.
- The strong influence of the susceptibility to weathering in the Laubscher system.
- The strong increase in influence of orientation of discontinuities in relation to the orientation of the walls and roof of underground excavations in the Laubscher system compared to the Bieniawski system.

Influence of intact rock strength and RQD

MAXIMUM NEGATIVE INFLUENCE OF PARAMETERS (in percentage from final maximum rating)(1)(2)

classification system(2)	rating range	intact rock strength	RQD	
EARLY SYSTEMS (for underground excavations)				
Deere (RQD)	0 - 100		100	
Wickham (RSR)	19 - 120			
RECENT SYSTEMS (for underground excavations)				
Bieniawski (RMR)	0 - 100	15	20	
Barton(3) (Q)	0.00006 - 2666	with rock load parameter(3)		
Laubscher	0 - 120	17 (no change of class)	13(5)	
SLOPE SYSTEMS				
Selby	0 - 100	20		
Bieniawski (RMR)	0 - 100	15	20	
Vecchia	0 - 100			
Robertson (RMR)(10)	0 - 100	30	20	
Romana (SMR)	0 - 115	13	17	
Haines	0 - 100	17	13(5)	

Influence of water and method of excavation

MAXIMUM NEGATIVE INFLUENCE OF PARAMETERS (in percentage from final maximum rating)		
classification system	water	excavation methods
EARLY SYSTEMS (for underground excavations)		
Deere (RQD)		
Wickham (RSR)	7	17
RECENT SYSTEMS (for underground excavations)		
Bieniawski (RMR)	15	
Barton(3) (Q)	95	
Laubscher	3	20
SLOPE SYSTEMS		
Selby		
Bieniawski (RMR)	15	
Vecchia		
Robertson (RMR)(10)		
Romana (SMR)	13	13
Haines	3	20

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Classification systems: Problems with Intact rock strength

If intact rock is defined as Unconfined Compressive Strength (UCS):

1. Inclusion of discontinuities within 10 cm length
2. Samples tested in the laboratory tend to be of better quality (or of lower quality if rock is very strong)
3. The intact rock strength measured depends on the sample orientation if the intact rock exhibits anisotropy.
4. UCS is not a valid parameter because, in reality, most rock will be stressed under circumstances resembling conditions of triaxial tests rather than UCS test conditions

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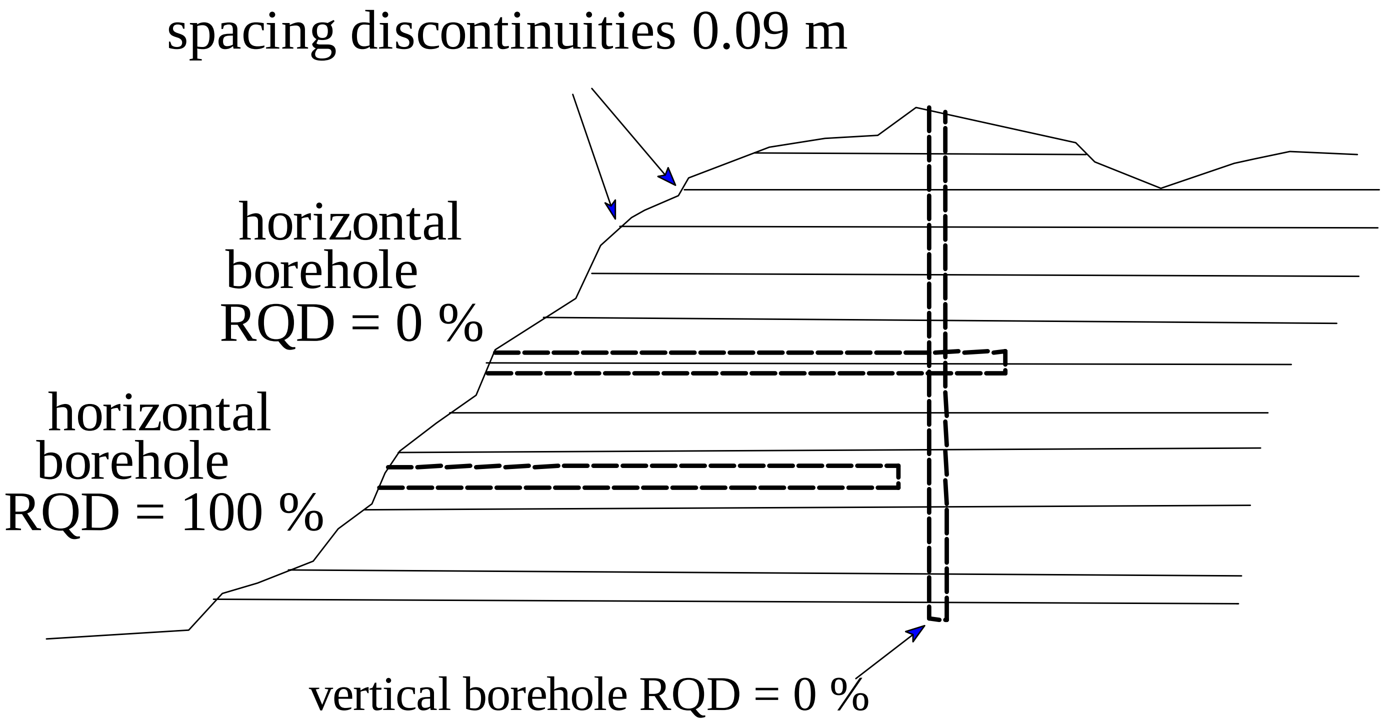
Classification systems: Problems with RQD (1)

1. Arbitrary length of 10 cm

2/3. Orientation of borehole in relation with discontinuity spacing



spacing discontinuities 0.09 m

horizontal borehole RQD = 0 %

horizontal borehole RQD = 100 %

vertical borehole RQD = 0 %

Classification systems: Problems with RQD (2)

4. Weak rock pieces (weathered pieces of rock or infill material) that are not sound should not be considered for determining the RQD (Deere et al., 1967, 1988). To exclude infill material will usually not be too difficult; however, excluding pieces of weathered, not sound rock is fairly arbitrary.

5. The RQD value is influenced by drilling equipment, drilling operators and core handling. Especially RQD values of weak rocks can be considerably reduced due to inexperienced operators or poor drilling equipment.

Classification systems: Problems with RQD (3)

6. No standard core barrel - single, double, or triple barrel ?

7. Diameter of boreholes

8. Drilling fractures should be re-fitted, but what are drilling fractures?

9. RQD should be determined per lithology, but where is the lithology boundary if washed away?

Classification systems: Problems with RQD (5)

Some systems allow for replacing RQD by fracture frequency or equivalent

or use a relation to calculate an RQD value from discontinuity measurements on an exposure

Why should then the RQD be used as parameter?

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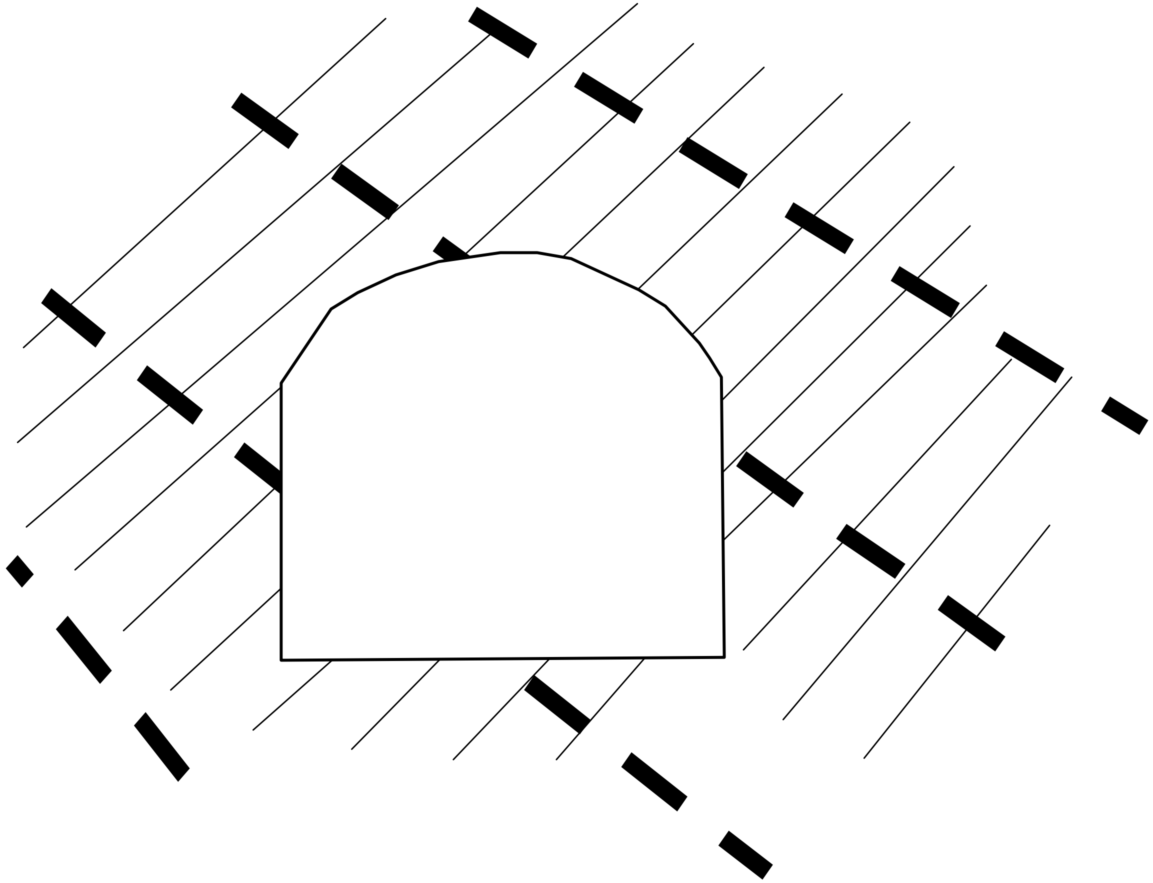
Many classification systems allow for only one rating for discontinuity set spacing and shear strength; this then to be the spacing and shear strength of the most unfavourable discontinuity set

What is the most unfavourable discontinuity set ?

——— discontinuity set with good condition; e.g. high shear strength

▬ ▪ discontinuity set with very poor condition; e.g. low shear strength



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Classification systems problem:(1)

In many systems the following parameters are absent:

- Anisotropic roughness of discontinuities
- Discontinuity karst features
- Susceptibility to weathering
- Deformation of intact rock and rock mass, stress relief
- Relative orientation of slope and discontinuities
- Slope height
- Water, influence of ice and snow

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Classification systems problem: Water (1)

If water parameter defined on amount of water:

1 Amount of water depending on intersected number of discontinuities, hence, on the size of the excavation

2 The amount of water is not the pressure of water (which is the important parameter)

3 Amount and pressure not constant throughout the slope; e.g. lower in the slope higher pressure than high in the slope

4 Difference in underground excavations and slopes for pressure regime

Classification systems problem: Water (2)

5 Water transport in discontinuities mainly via channels: if also applicable to pressure: resulting pressure on a discontinuity considerably less than pressure over full discontinuity surface

6 Run-off water over the slope face degrades slope face and may lead to instability

7 Not constant over time - wait for maximum rainfall?

Classification systems problem: Water (3)

Practical problems with determining water:

1. How to differentiate between run-off water over the slope face and water under pressure out of a discontinuity?
2. How to measure the quantity of water out of a slope (tunnel with weir) and differentiate with surface run-off
3. Terminology often subjective: dripping <> wet

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No clear differentiation “as is” and “as will be”

External influences as weathering and method of excavation will have influenced the site characterized but will also (and likely differently) influence the new slope in the future

Bias and familiarization

- Often not clear how many different persons developed a system and whether designer bias may be present
- Those using a system and being satisfied with the system may be so familiarized that they do not see the flows anymore

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Slope Stability probability Classification (SSPC)

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SSPC

- three step classification system
- based on probabilities
- independent failure mechanism assessment

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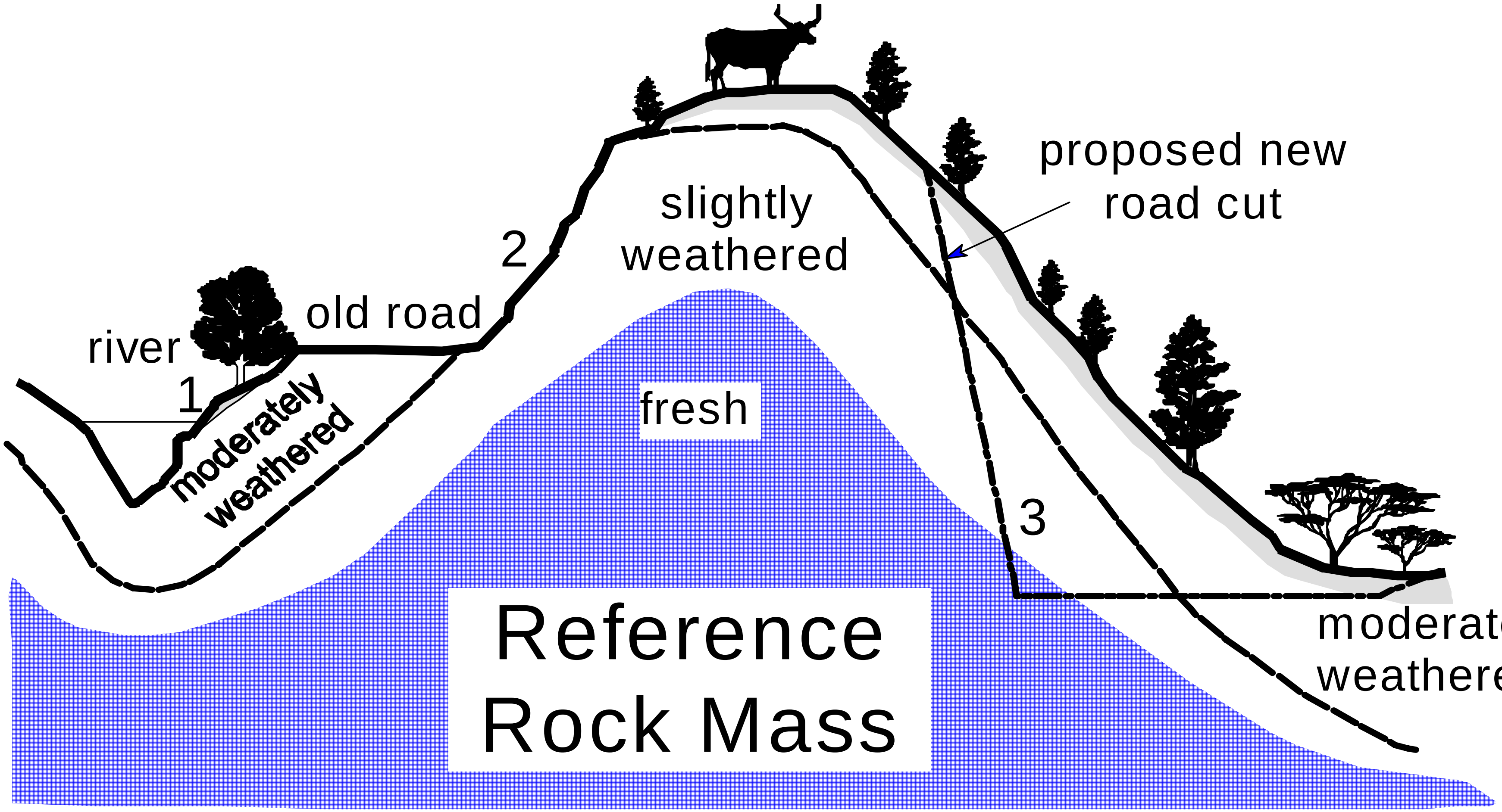
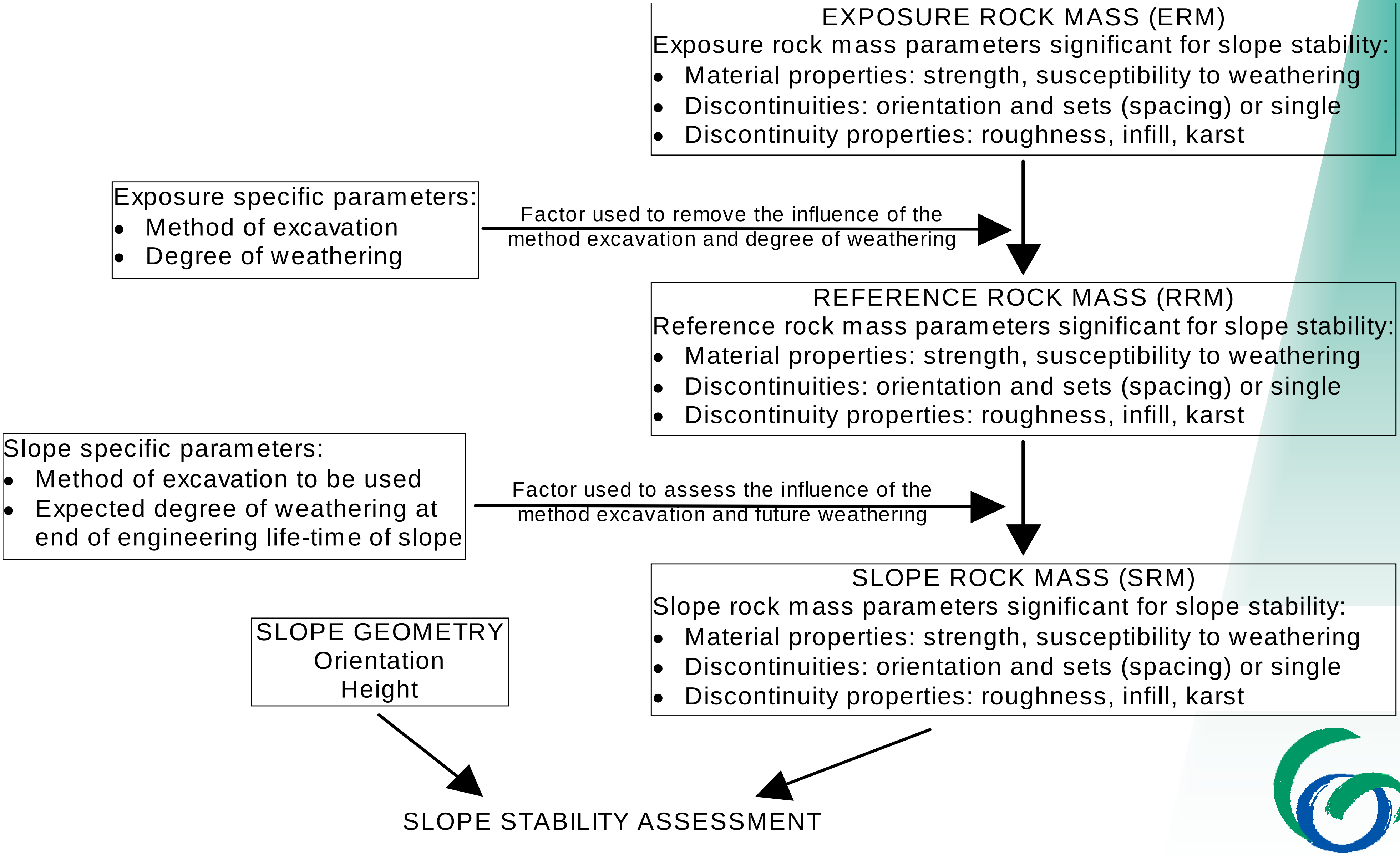
Three step classification system (1)



1: natural exposure made by scouring of river, moderately weathered; 2: old road, made by excavator, slightly weathered; 3: new to develop road cut, made by blasting, moderately weathered to fresh.

Three step classification system (2)



EXPOSURE ROCK MASS (ERM)

Exposure rock mass parameters significant for slope stability:
- Material properties: strength, susceptibility to weathering
- Discontinuities: orientation and sets (spacing) or single
- Discontinuity properties: roughness, infill, karst

Exposure specific parameters:
- Method of excavation
- Degree of weathering

Factor used to remove the influence of the method excavation and degree of weathering

REFERENCE ROCK MASS (RRM)

Reference rock mass parameters significant for slope stability:
- Material properties: strength, susceptibility to weathering
- Discontinuities: orientation and sets (spacing) or single
- Discontinuity properties: roughness, infill, karst

Slope specific parameters:
- Method of excavation to be used
- Expected degree of weathering at end of engineering life-time of slope

Factor used to assess the influence of the method excavation and future weathering

SLOPE ROCK MASS (SRM)

Slope rock mass parameters significant for slope stability:
- Material properties: strength, susceptibility to weathering
- Discontinuities: orientation and sets (spacing) or single
- Discontinuity properties: roughness, infill, karst

SLOPE GEOMETRY
Orientation
Height

SLOPE STABILITY ASSESSMENT

Excavation specific parameters for the excavation which is used to characterize the rock mass

- **Degree of weathering**
- **Method of excavation**

Rock mass Parameters

- Intact rock strength
- Spacing and persistence discontinuities
- Shear strength along discontinuity
  - Roughness
    - large scale
    - small scale
    - tactile roughness
  - Infill
  - Karst
- Susceptibility to weathering

Slope specific parameters for the new slope to be made

- **Expected degree of weathering at end of lifetime of the slope**
- **Method of excavation to be used for the new slope**

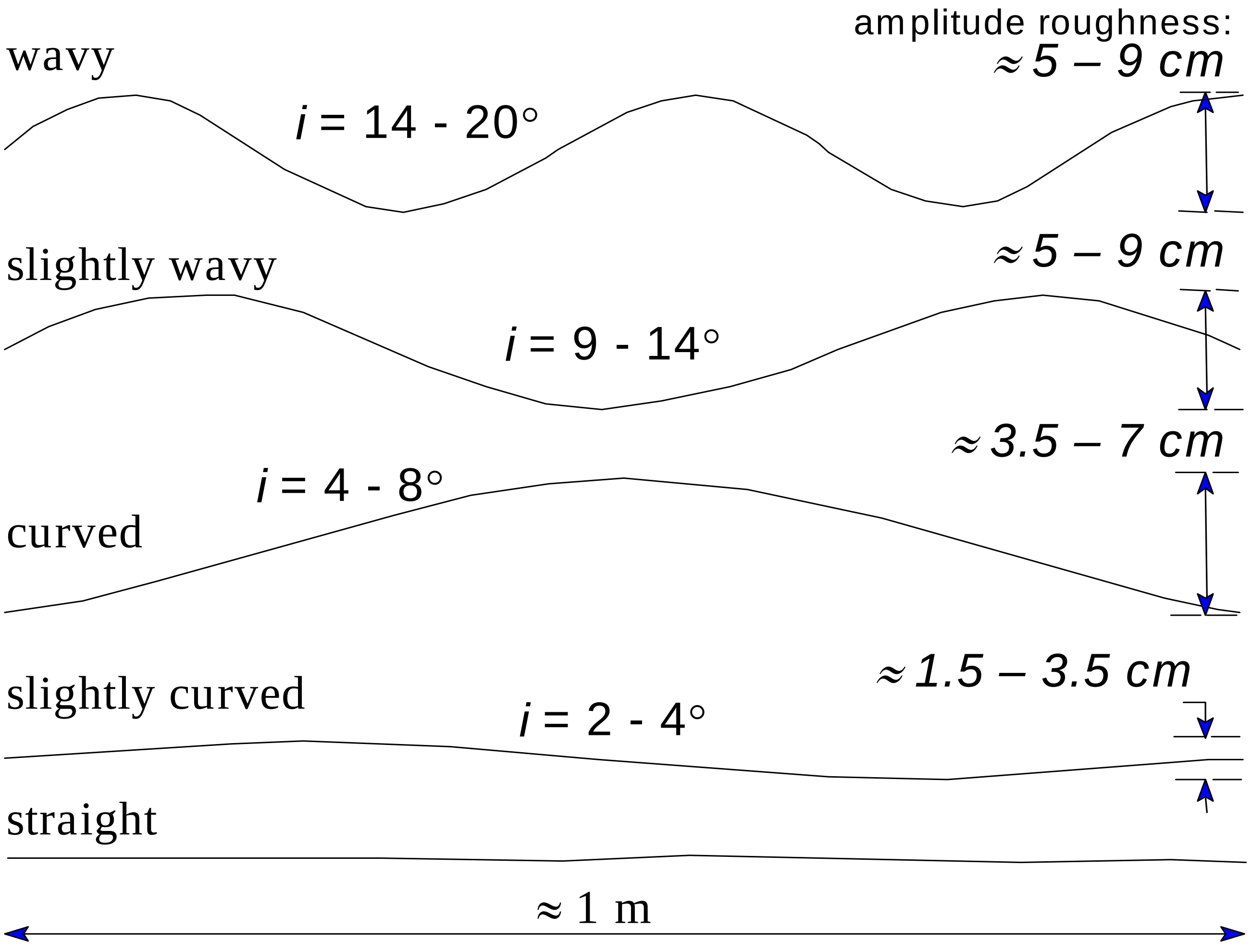
Intact rock strength

By simple means test - hammer blows, crushing by hand, etc.

Spacing and persistence of discontinuities

Based on the block size and block form by first visual assessment and then quantification of the characteristic spacing and orientation

Shear strength - roughness large scale



(*i*-angles and dimensions only approximate)

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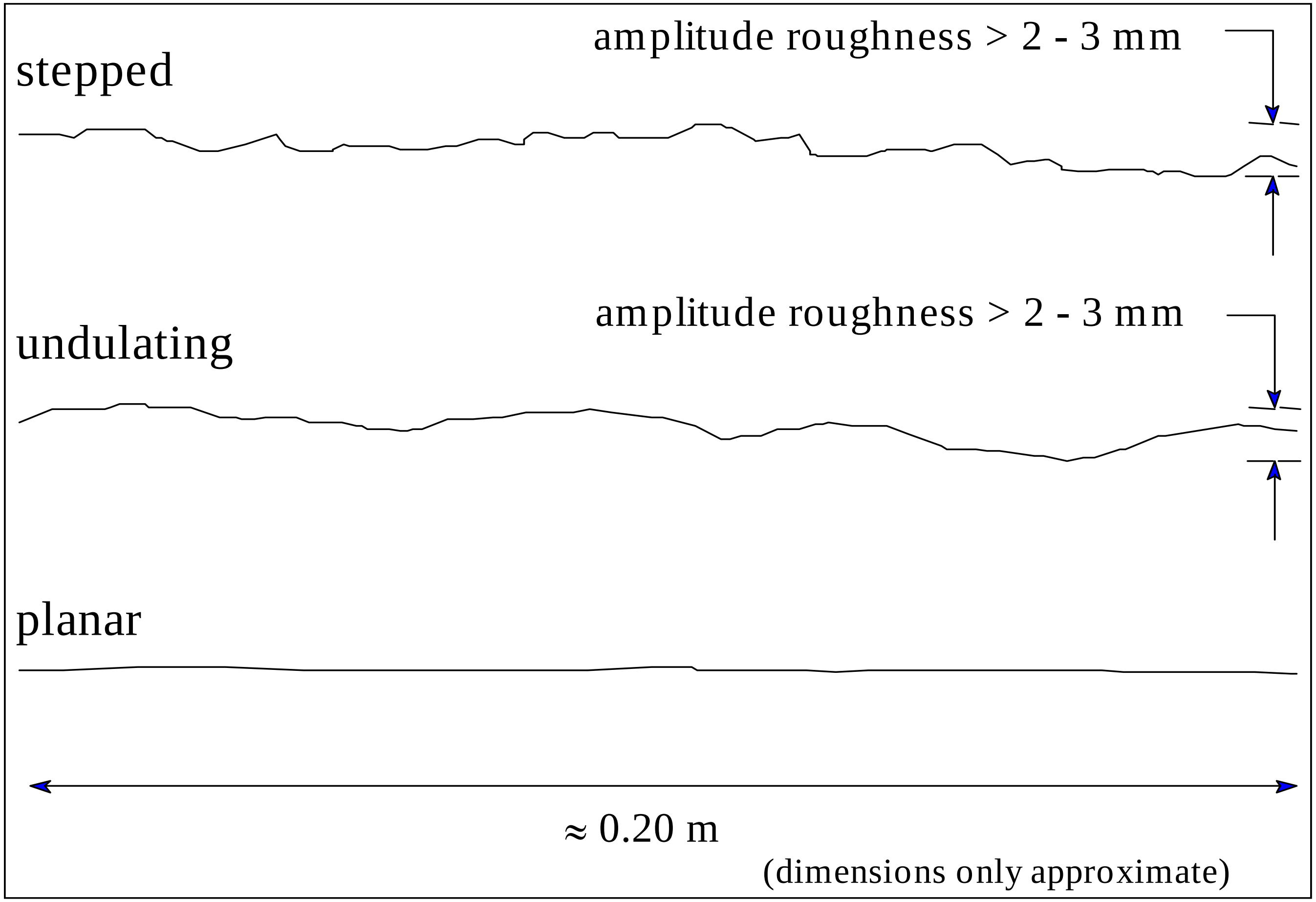
Shear strength - roughness small scale



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Shear strength - roughness tactile

Three classes:

rough

smooth

polished

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Infill:

- cemented
- no infill
- non-softening (3 grain sizes)
- softening (3 grain sizes)
- gauge type (larger or smaller than roughness amplitude)
- flowing material

Shear strength - Infill

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Shear strength - karst

Karst or no karst

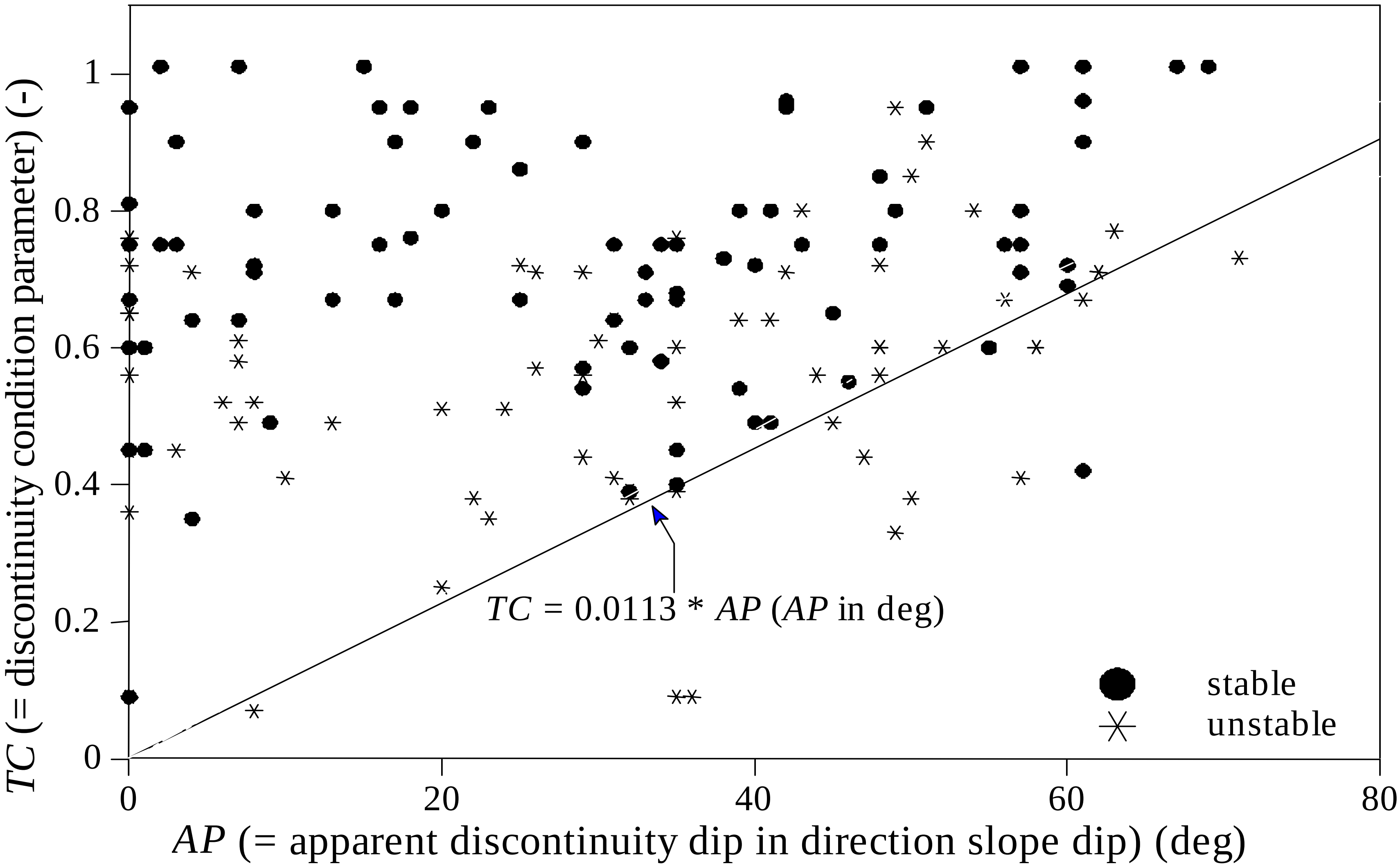
Shear strength - condition factor

Discontinuity condition factor (*TC*) is a multiplication of the rating for small- and large scale roughness, infill and karst (similar to method used by Laubscher)

Orientation dependent stability

Stability depending on relation between slope and discontinuity orientation

How did we develop it? - sliding criterion:



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Sliding criterion

$$\text{sliding occurs if :}$$

$$TC < 0.0113 * AP$$

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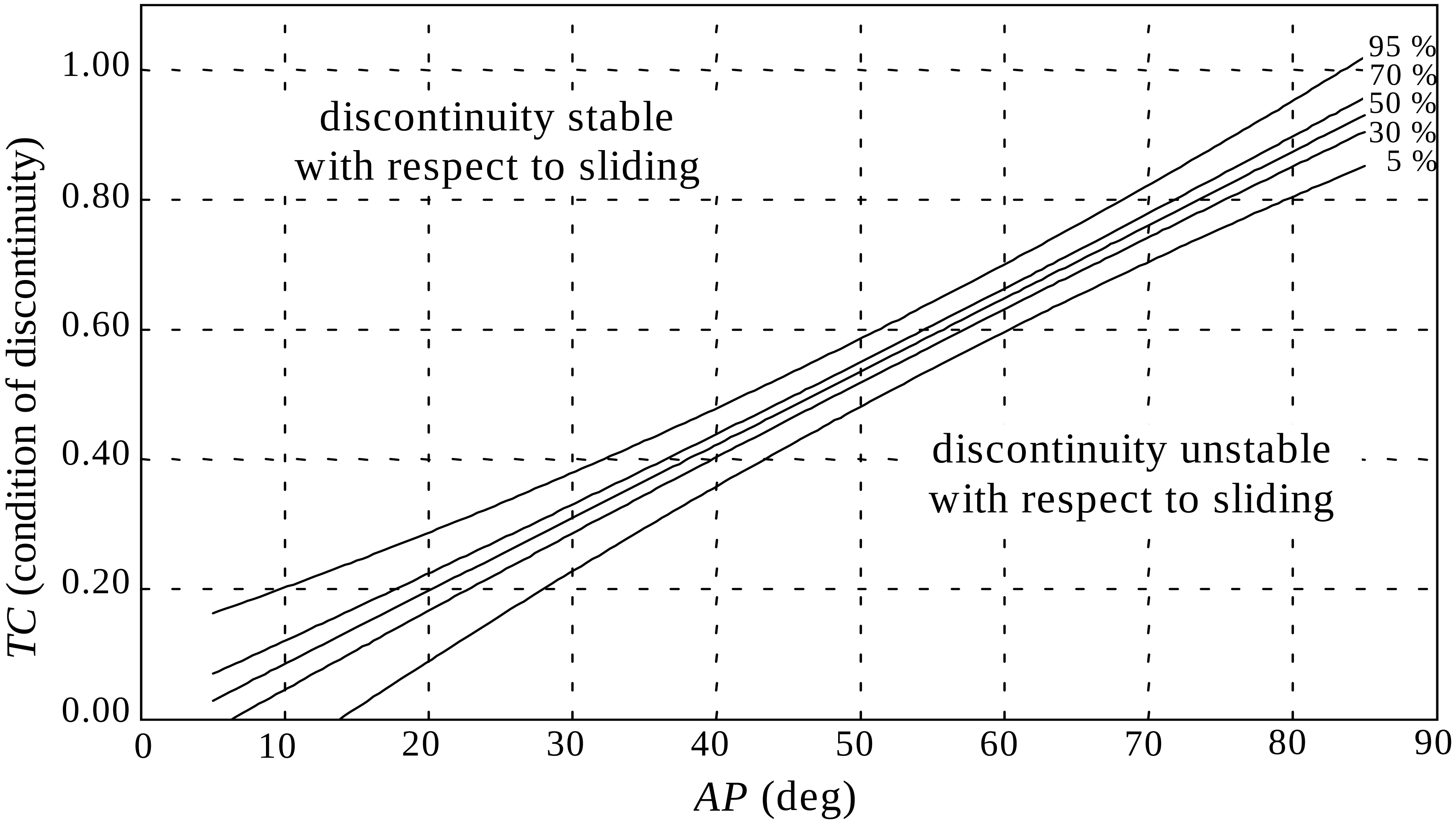
Sliding probability



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Toppling criterion

$$TC < 0.0087 * \left(- 90^{\circ} - AP + dip_{discontinuity} \right)$$

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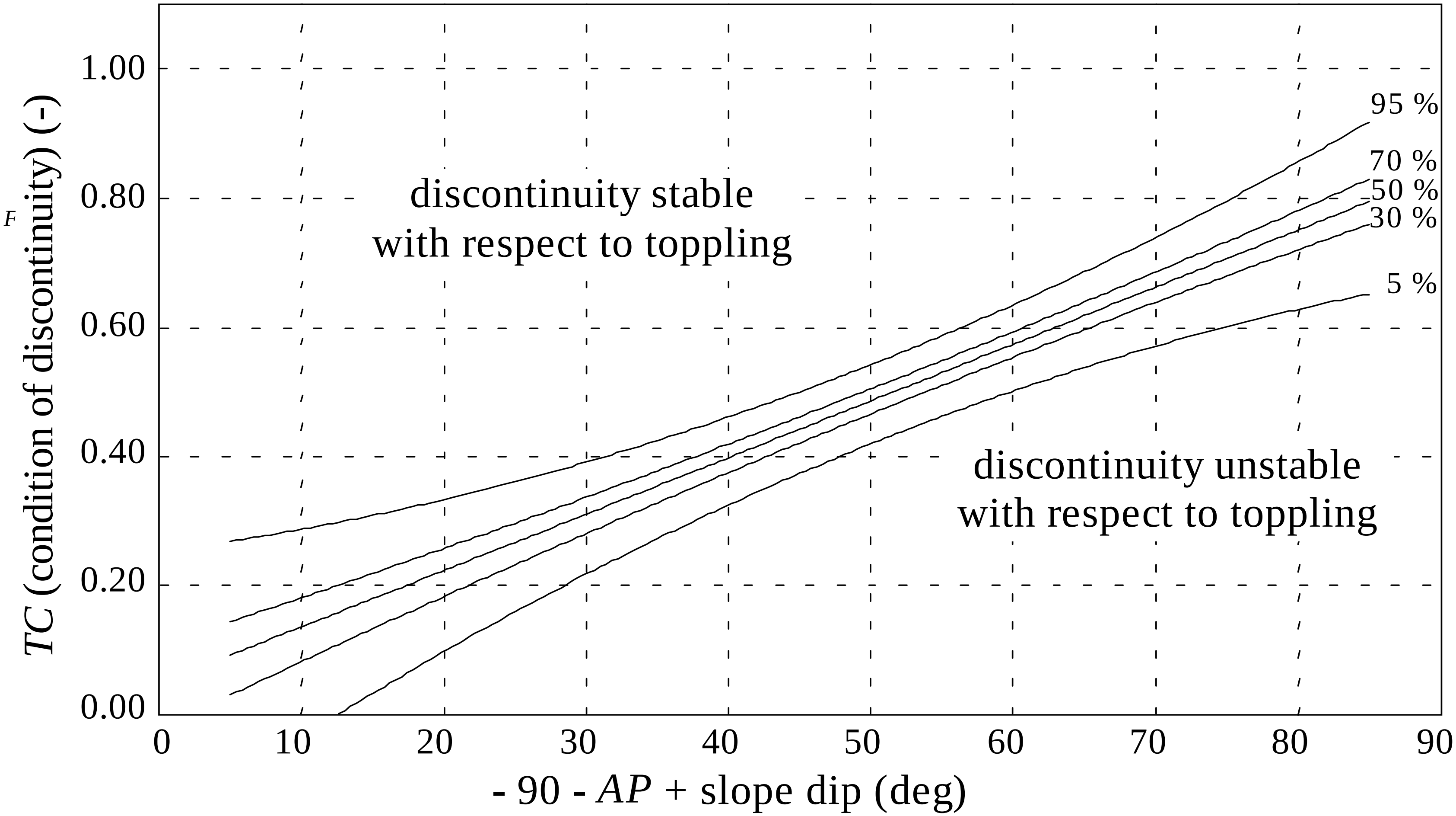
Toppling probability



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Orientation independent stability

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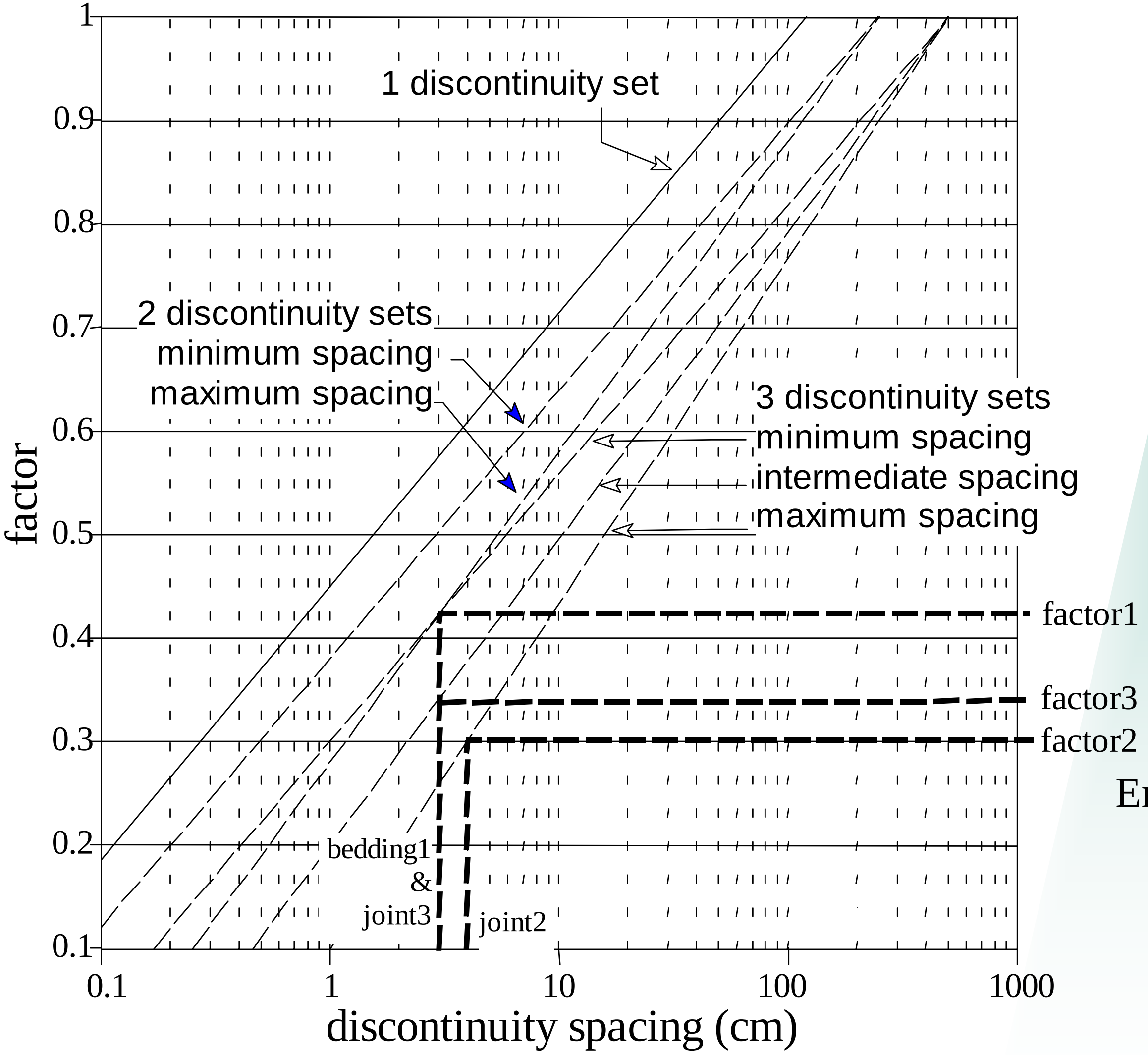
Overall spacing of discontinuity sets

Block size and form relations from Taylor



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Overall condition of discontinuity sets

$$CD = \frac{\frac{TC_1}{DS_1} + \frac{TC_2}{DS_2} + \frac{TC_3}{DS_3}}{\frac{1}{DS_1} + \frac{1}{DS_2} + \frac{1}{DS_3}}$$

$TC_{1,2,3}$ are the condition, and $DS_{1,2,3}$ are the spacings of discontinu ity sets 1, 2, 3

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Shear plane failure following Mohr-Coulomb for rock mass

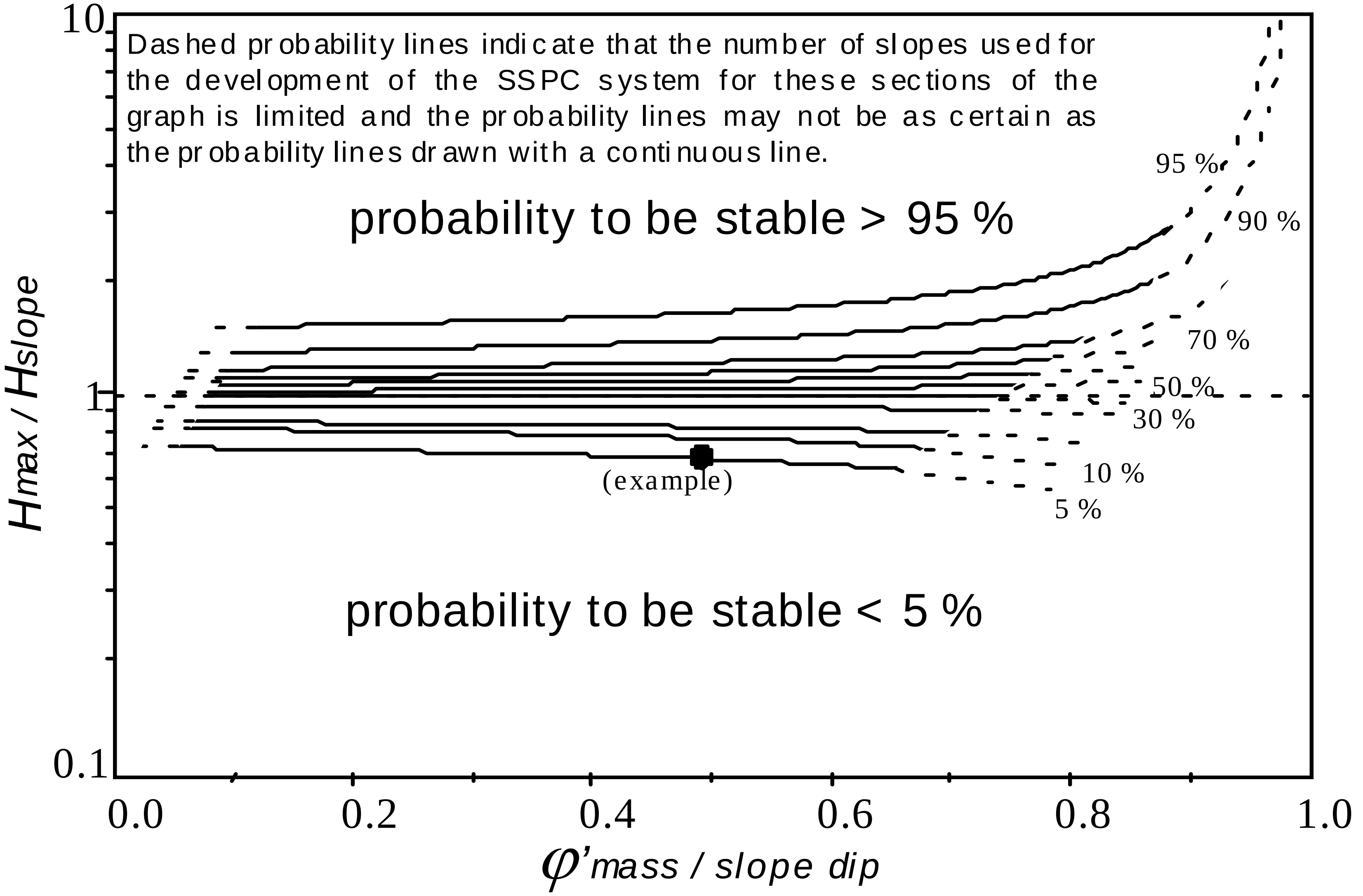
If the $dip_{slope} \leq \varphi'_{mass}$:

the maximum slope height (H_{max}) is infinite

else

$$H_{\max} = 1.6 * 10^{-4} * coh'_{mass} * \frac{\sin\left(dip_{slope}\right) * \cos\left(\varphi'_{mass}\right)}{1 - \cos\left(dip_{slope} - \varphi'_{mass}\right)}$$

Probability orientation independent failure



Dashed probability lines indicate that the number of slopes used for the development of the SSPC system for these sections of the graph is limited and the probability lines may not be as certain as the probability lines drawn with a continuous line.

probability to be stable > 95 %

probability to be stable < 5 %

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How did we do this?

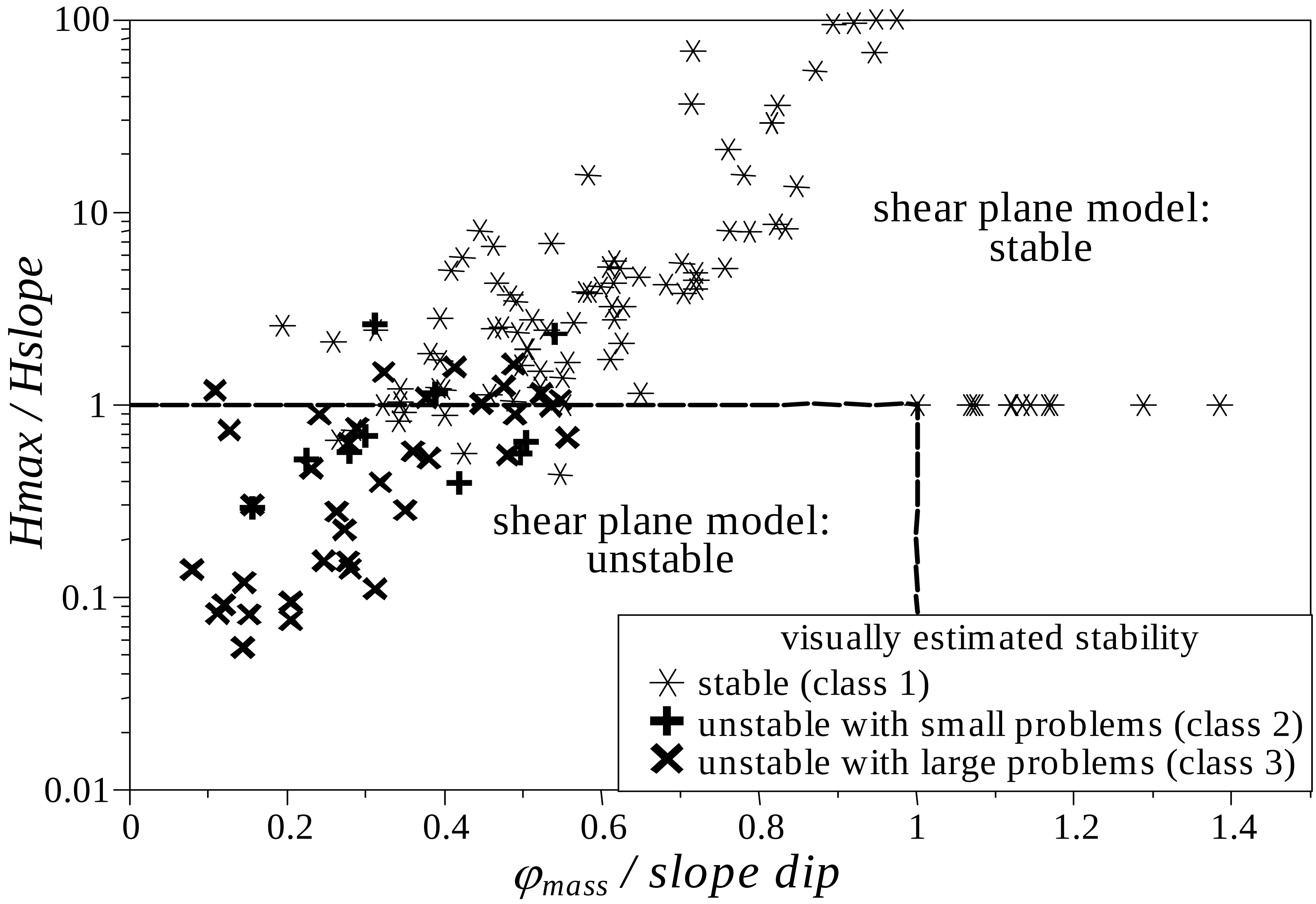
$\text{For each slope } j:$

$$\text{visually estimated stability} = \text{class } 1 \quad \begin{cases} \dfrac{\varphi_{mass}}{dip_{slope}} \geq 1 \quad (stable) \to er = 1 \\ \dfrac{\varphi_{mass}}{dip_{slope}} < 1 \begin{cases} \dfrac{H_{max}}{H_{slope}} \geq 1 \quad (stable) \to er = 1 \\ \dfrac{H_{max}}{H_{slope}} < 1 \quad (unstable) \to er = \dfrac{H_{slope}}{H_{max}} \end{cases} \end{cases}$$

$$\text{visaually estimated stability} = \text{class } 2 \text{ or } 3 \quad \begin{cases} \dfrac{\varphi_{mass}}{dip_{slope}} \geq 1 \quad (stable) \to er = \dfrac{\varphi_{mass}}{dip_{slope}} \\ \dfrac{\varphi_{mass}}{dip_{slope}} < 1 \begin{cases} \dfrac{H_{max}}{H_{slope}} \leq 1 \quad (unstable) \to er = 1 \\ \dfrac{H_{max}}{H_{slope}} > 1 \quad (stable) \to er = \dfrac{H_{max}}{H_{slope}} \end{cases} \end{cases}$$

$$ER = \sum_j er_j$$

How did we do this?



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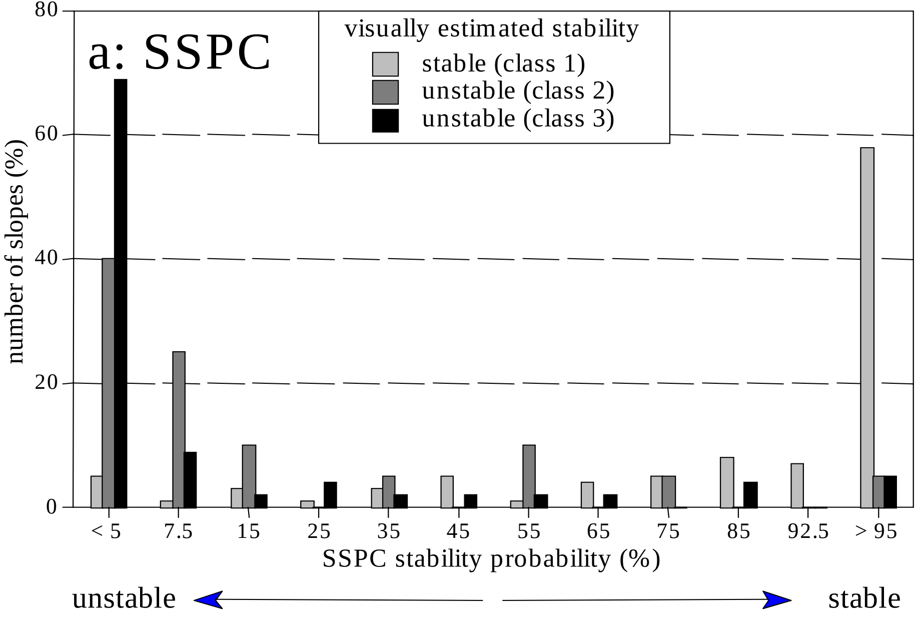

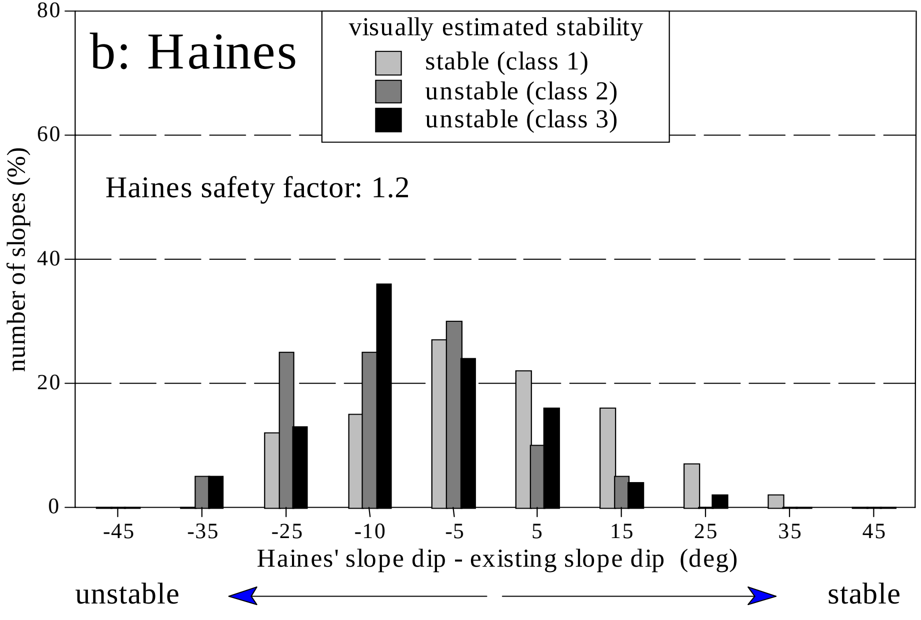

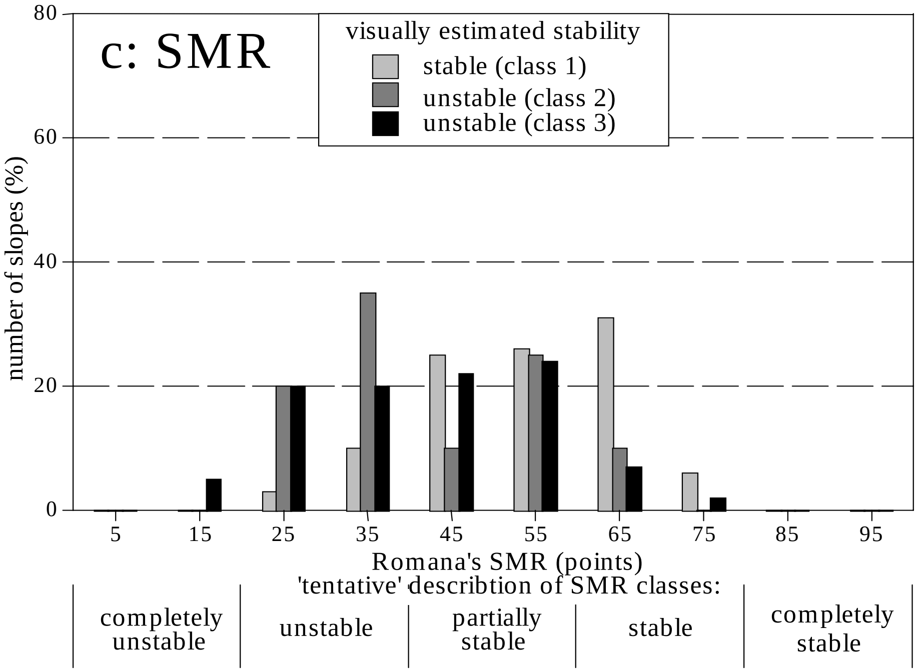

Percentages are from total number of slopes per visually estimated stability class.

visually estimated stability:

class 1: stable; no signs of present or future slope failures (number of slopes: 109)
class 2: small problems; the slope presently shows signs of active small failures and has the potential for future small failures (number of slopes: 20)
class 3: large problems; The slope presently shows signs of active large failures and has the potential for future large failures (number of slopes: 55)

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Comparison

Poorly blasted slope

Poorly blasted slope

General impression: extremely poor. The stability of the new road cut with a height of 13.8 m, with a degree of rock mass weathering of 'moderately' and 'dislodged blocks' due to blasting, results in a stability assessment of about 8 % for a slope dip of 70° in 1996. This is in agreement with the visual observed stability at that time. The rock mass is clearly not able to support a slope with a dip of 70°. According to the SSPC system, stability will be achieved if the slope dip is decreased to about 45°. In 2002 the slope dip had been reduced to about 55° and visually assessed the slope is still unstable.

OLD ROAD CUTS (> 40 years old) in same thin bedded limestone: SSPC system probability to be stable of > 95 % with a slope dip of 70° and a height of 5 m. The same rock mass characteristics are used for the new slope. Hence, both slopes are assumed to have been made in the same 'reference' rock mass as far as the thin-bedded units are considered.

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Plane sliding failure

40 year old road cut, Spain

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Plane sliding failure (2)

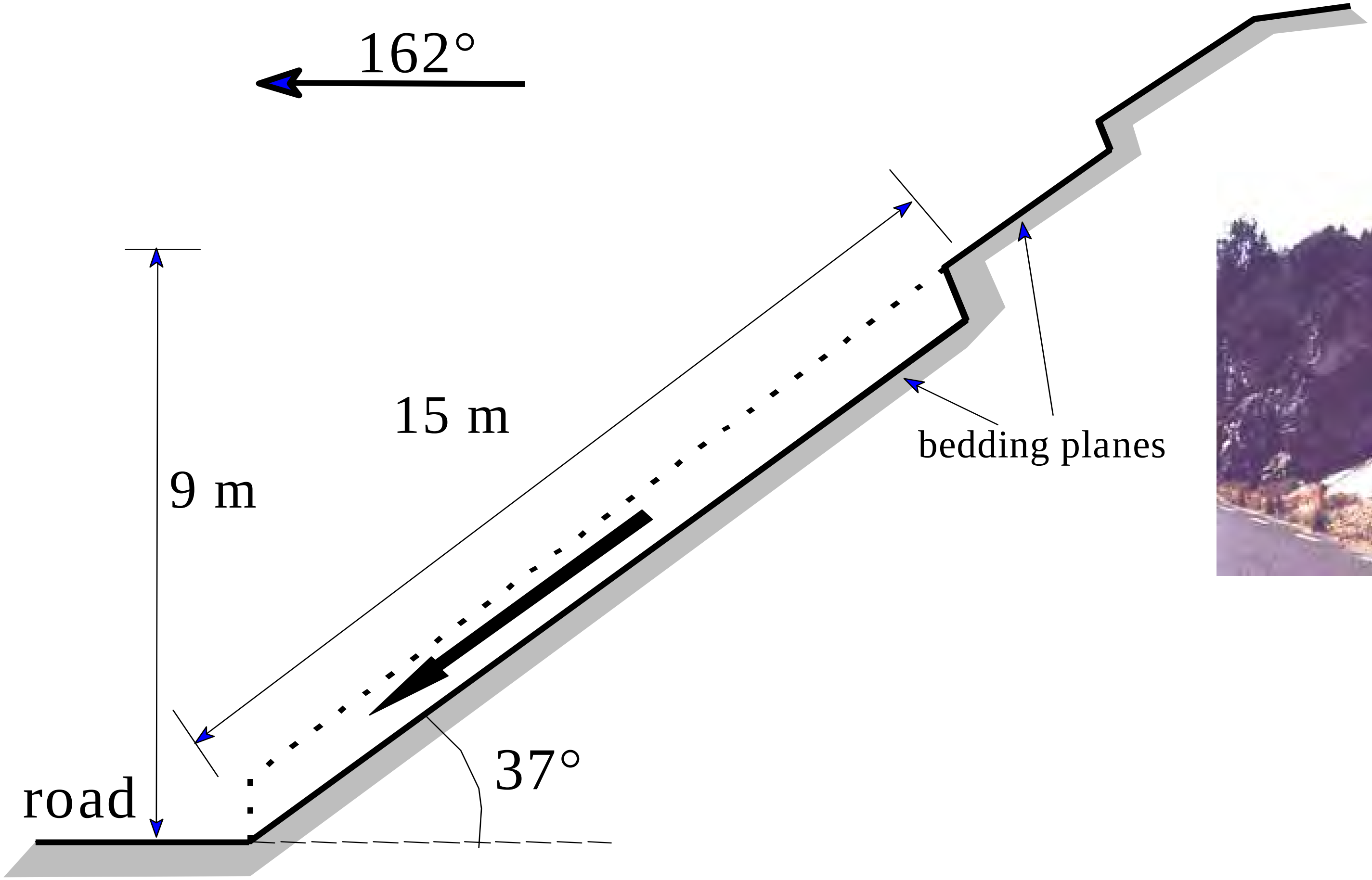

Fig. 108. Geometrical cross section of the slope.

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Plane sliding failure (3)

- **Laboratory test: ϕ=45°**
- **SSPC: ϕ≈35°**
- **Stability assessed using:**
  - SSPC – 55% stability probability, failure imminent (ϕ≈35°)

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Slope Stability probability Classification (SSPC)

Saba case - Dutch Antilles

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Landslide in harbour

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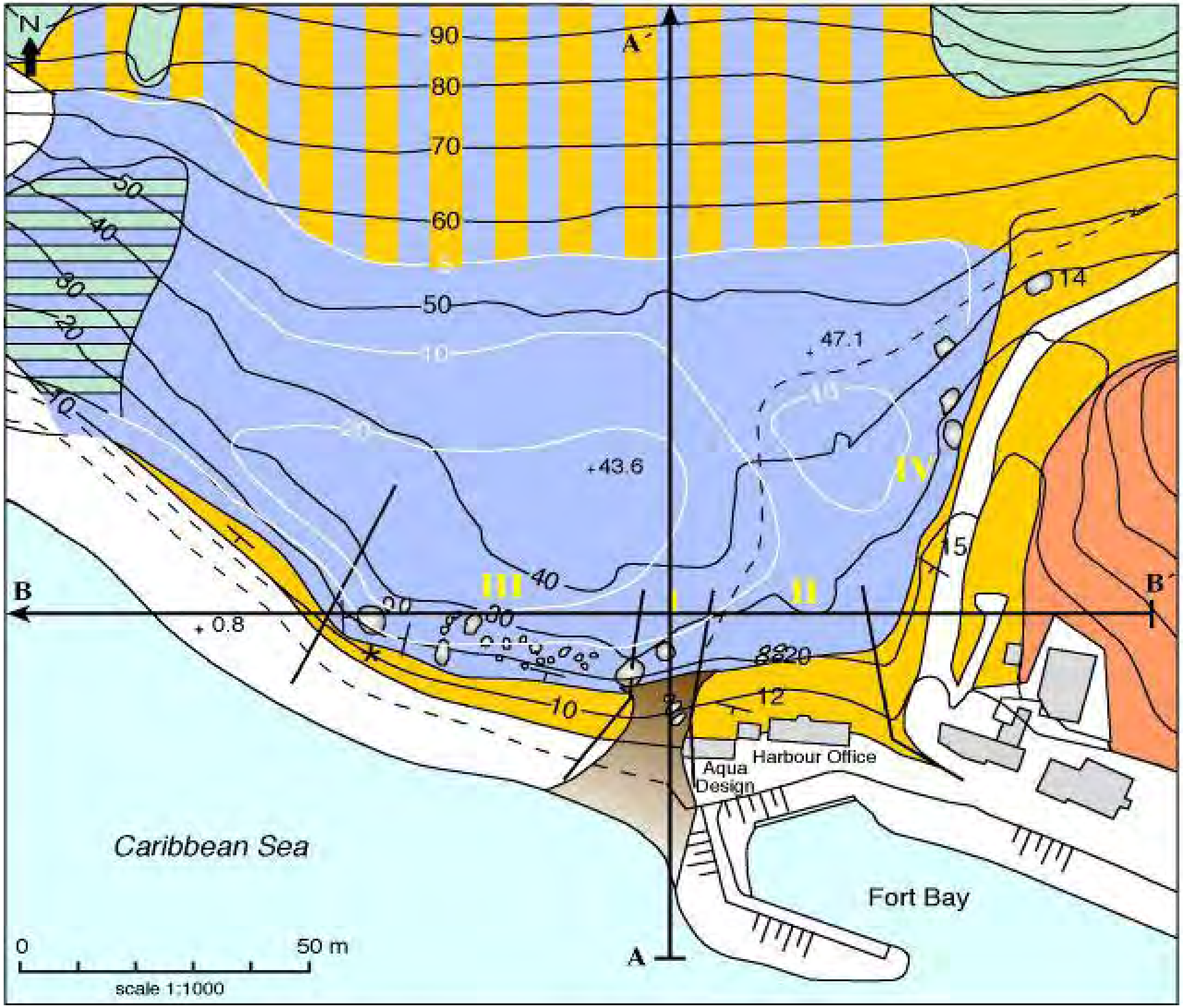
Geotechnical zoning



🟩	Brown-red, massive lava (andesite)
🟨	Pyroclastic deposits (eruptive material)
🟧	Light-grey andesite (pipe)
🟦	Slope debris deposit, consolidated
▤	Unconsolidated slope debris (recent)
20	Dip direction and dip
★	Spring
10	Contour thickness slope debris (m)
◭	Land slide of February 1997
●	Instable blocks
I-II-III-IV	Geotechnical zone
– 20 –	Topography (m)

SSPC results

Pyroclastic deposits	**Calculated SSPC**	**Laboratory / field**
Rock mass friction	35°	27° (measured)
Rock mass cohesion	39kPa	40kPa (measured)
Calculated maximum possible height on the slope	13m	15m (observed)

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Failing slope in Manila, Philippines

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Failing slope in Manila (2)

- tuff layers with near horizontal weathering horizons (about every 2-3 m)
- slope height is about 5 m
- SSPC non-orientation dependent stability about 50% for 7 m slope height
- unfavourable stress configuration due to corner

Earthquake influence on rock slopes

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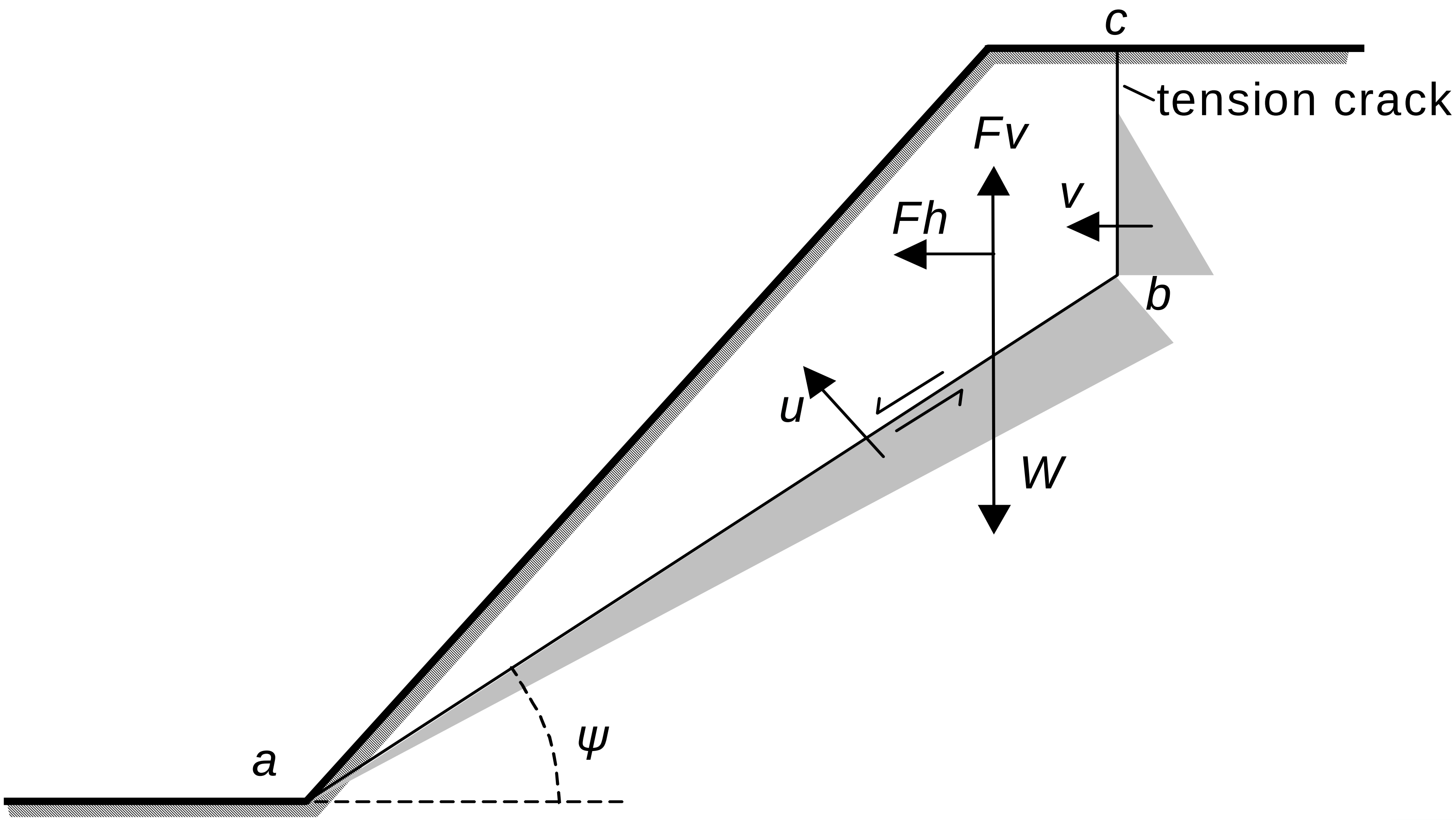
During an earthquake may occur either together or subsequently:

- reduction normal stress and consequently also shear strength
- breaking of cementation in discontinuities
- breaking of asperities on discontinuity planes
- displacement of discontinuities - leading to non-fitting of discontinuity roughness
- resonance effects - increasing accelerations and displacements
- (breaking of intact rock - generally only if intact rock strength is very weak)

The results of an earthquake

- permanent reduction of shear and tensile strength (if present) along discontinuities
- opening of discontinuities; allowing water influx, etc.
- (increase in number of discontinuities because of fracturing of intact rock)

Stability calculation - pseudo-static analysis (1)



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Stability calculation - pseudostatic analyses (2)

$$F = \frac{\text{resisting force}}{\text{driving force}} =$$

$$= \frac{coh_{ab} + \left(\left(W - Fv\right)\cos\psi - Fh\sin\psi - u_{ab}\right) * \tan\varphi}{\left(W - Fv\right)\sin\psi + Fh\cos\psi + v_{bc}\cos\psi}$$

$$coh_{ab}, \varphi = \text{cohesion force, respectivily friction along discontinuity}$$

$$\text{W} = \text{weight of block}$$

$$u_{ab}, v_{bc} = \text{the water forces in the discontinuities}$$

$$Fv, Fh = \text{horizontal and vertical force due to eathquake acceleration}$$

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Stability calculation - pseudostatic analyses (3)

$$Fh = \frac{a_h W}{g} \qquad Fv = \frac{a_v W}{g} =$$

$$\mathrm{W} = \text{weight of block}$$

$$a_h, \mathrm{a}_\mathrm{v} = \text{accelerati ons}$$

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Stability calculation - pseudostatic analyses (4)

- **choice of a_h and a_v**

- difficult

- no clear rules what to use

- Terzaghi (1950): a_h = 0.1 g for severe, = 0.2 g for violent, and = 0.5 g for catastrophic earthquakes

- Marcuson (1981): a_h and a_v about 1/3 to 1/2 of a_{peak}

- Franklin (1980): a_h = 0.5 a_{peak} *(to avoid “dangerously large deformations”)*

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Drawbacks of a pseudo-static analyses

- Reduction shear strength during the earthquake only due to reduction in normal stresses
- No breaking of cementation or asperities
- No displacement effects and subsequent reduction in shear strength
- No deformation or rotation of blocks
- No resonance effects
- (no breaking of intact rock)

Stability analysis - Newmark (1)

- **Criterion of displacement rather than stress equilibrium**
- **Displacement of a ridged block over a surface**
- **Displacement depends on**

- Frequency (number of pulses in which yield acceleration is exceeded)

- Maximum acceleration per peak

Stability analysis - Newmark (3)

Possible to include “strain hardening” or “strain softening” constitutive models for the sliding plane (later may be very applicable to rock slopes - permanent reduction shear strength, etc.)

Drawbacks of Newmark - displacement methodologies

- Only plane sliding
- No deformation or rotation of blocks
- No resonance effects
- (no breaking of intact rock)

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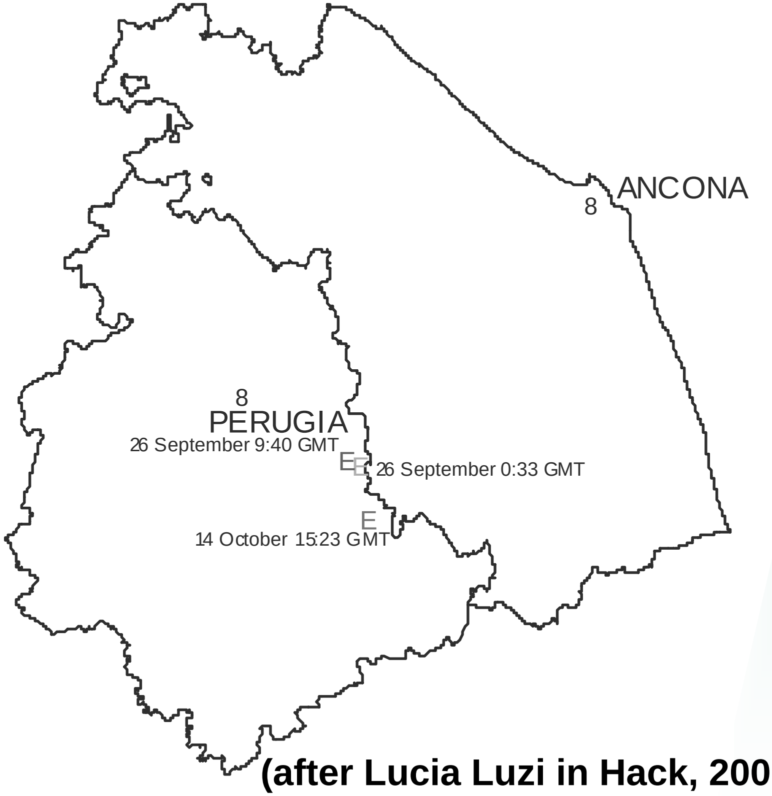
Simple empirical relations

Umbria-Marche earthquake of 26 September 1997



(after Lucia Luzi in Hack, 2002)

Simple empirical relations (2)

Umbria-Marche earthquake of 26 September 1997

$$f(D) = A \cdot g(s) + B \cdot h(k) + C$$

D = the landslide displacement; $g(s)$ = the seismic parameter

$h(k)$ = the landslide susceptibility to failure; A, B, C = constants

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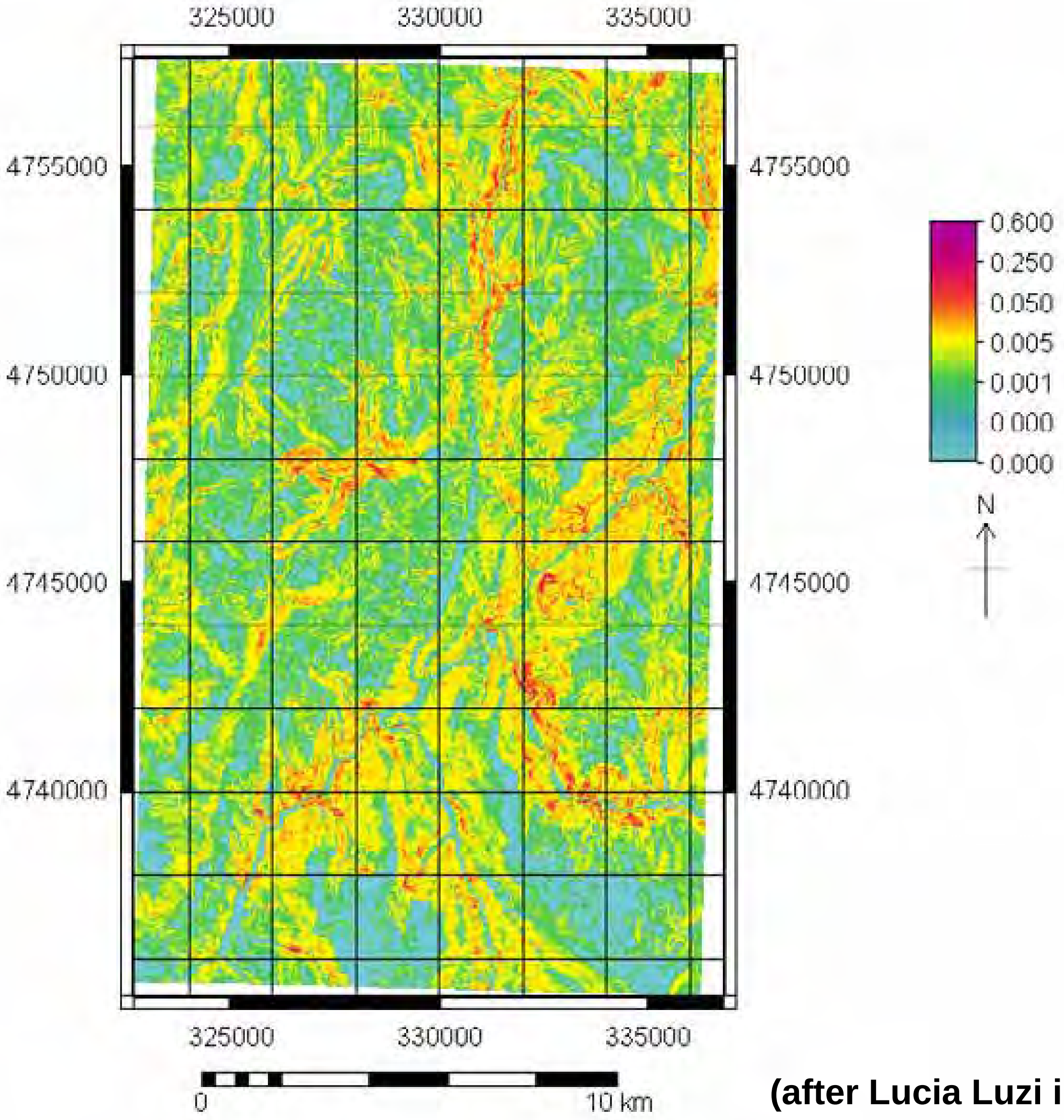
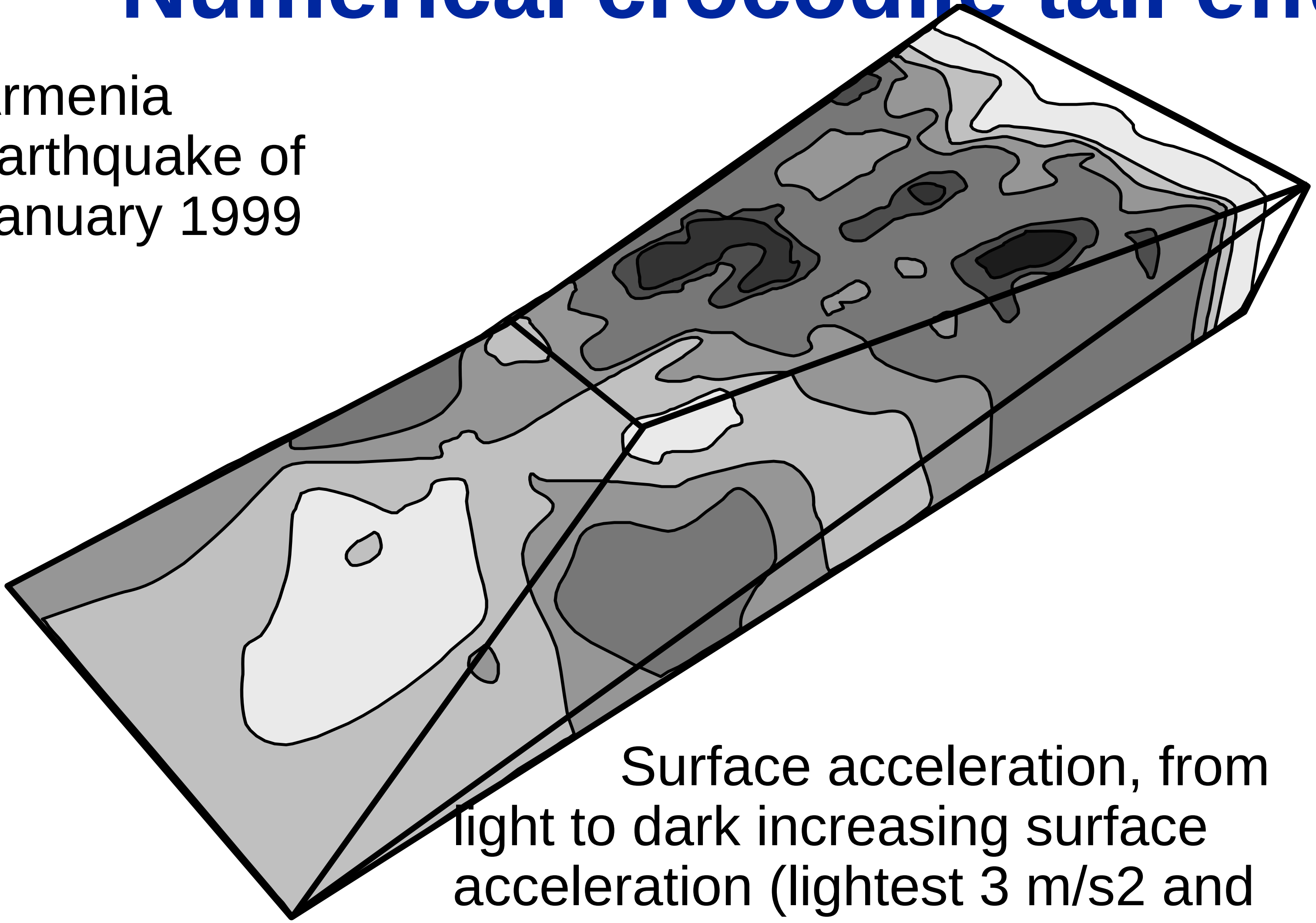
(after Lucia Luzi in Hack, 2002)

Simple empirical relations (3)



(after Lucia Luzi in Hack, 2002)

Numerical crocodile tail effect



Armenia
earthquake of
January 1999

Surface acceleration, from light to dark increasing surface acceleration (lightest 3 m/s2 and darkest 17 m/s2)

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Discussion earthquakes

- **slope stability analyses with earthquake influence far more difficult than without**
- **simplifications in accepted calculation methods such that it is questionable whether they make sense**
- **why are there no classification system for earthquake prone areas?**

Heterogeneity

- even if uncertainty is included this is only up to a certain extend – what extend is to the discretion of the engineer
- can heterogeneity be defined by an automatic procedure , e.g. for example Lidar

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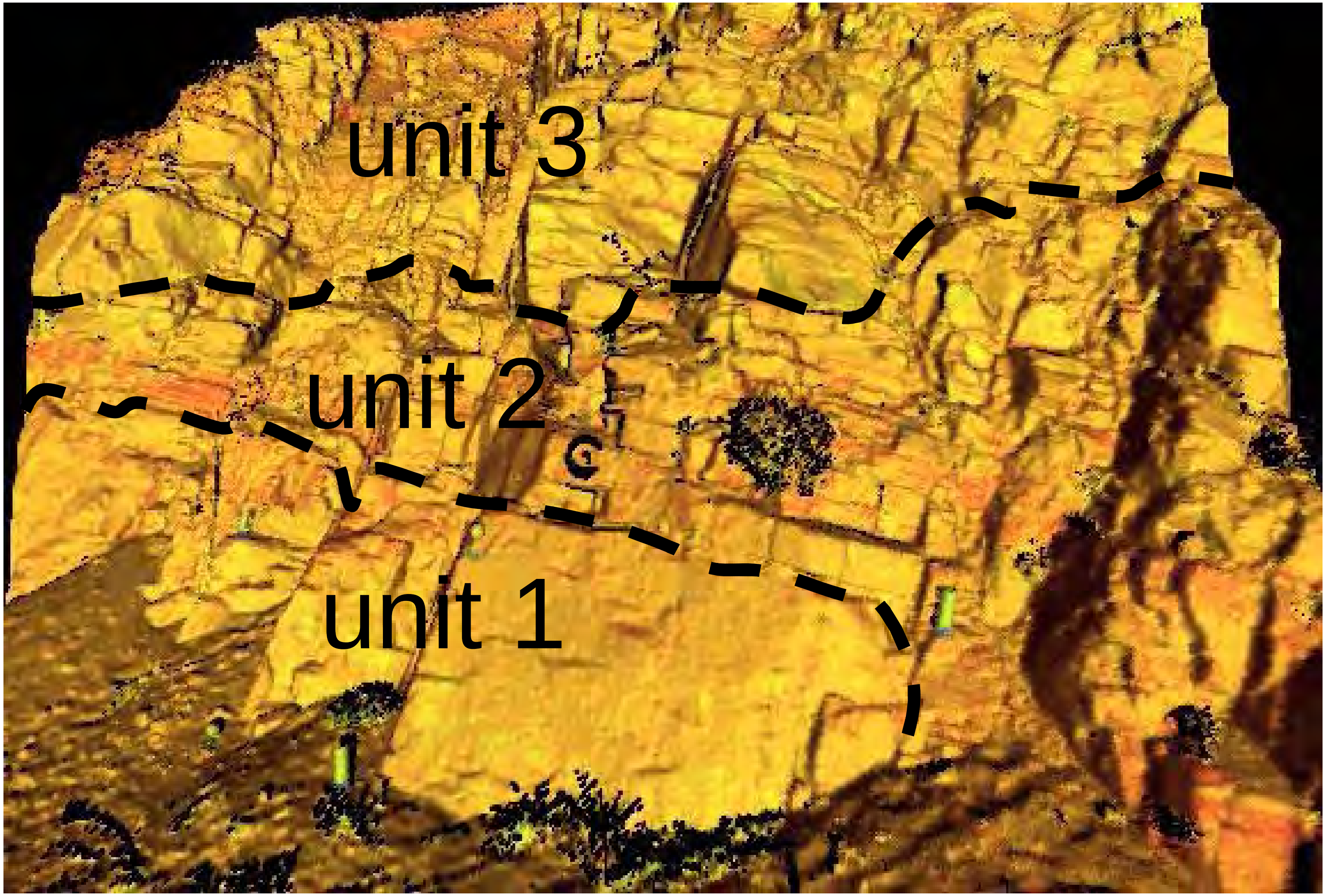
Heterogeneity (2)



(modified after Slob et al, 2002)

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Future degradation of soil or rock due to weathering, ravelling, etc.

no reliable quantitative relations exist to forecast the future geotechnical properties of soil or rock mass

Future degradation (2)

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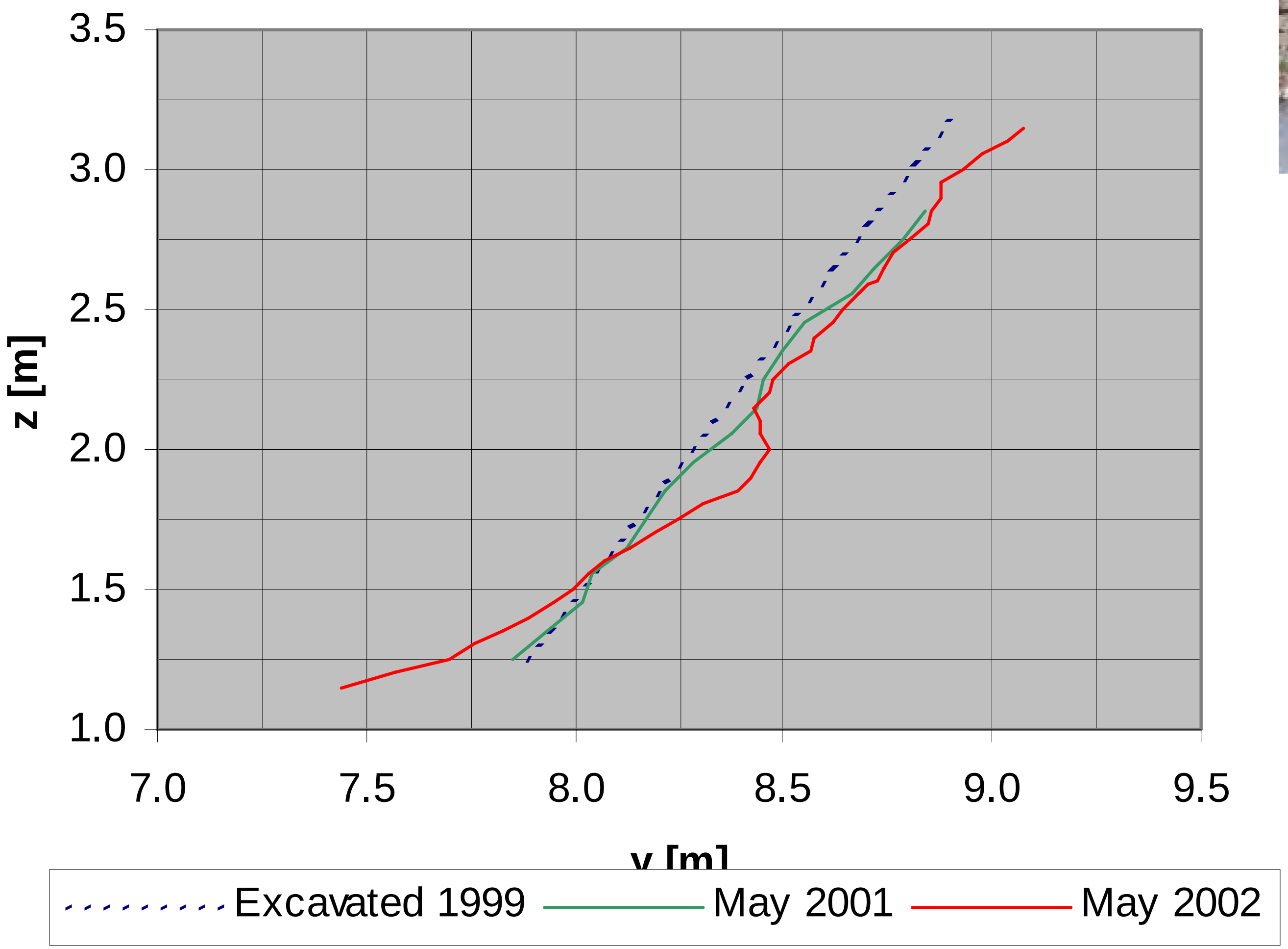
Future degradation (3)



Reduction in slope angle due to weathering, erosion and ravelling (after Huisman)

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Conclusions

- **classification works for slope stability**
- **classification can incorporate uncertainty**
- **classification can be improved by using more elaborate relations**
- **computers can be used to optimise complicated relations**
- **be not afraid to abandon inherited methodologies and parameters**

Future

- definition of heterogeneity
- expressions for quantification of future geotechnical properties
- classification systems for earthquake areas
- influence of snow and ice
- submersed marine slopes ?

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