SLOPE STABILITY CLASSIFICATION OF TIME DEPENDENT DETERIORATING SLOPES

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Slopes in The Netherlands?

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

Rock slopes in The Netherlands?

Sassenheim between Leiden and Lisse

"A Field of Tulips in Holland", Claude Monet 1886, oil on canvas 65.5 x 81.5 cm, Musée d Orsay, Paris France

Dykes have slopes!

(Brouwersdam, The Netherlands)

Dyke with basalt cover can be modelled as a discontinuous rock mass

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

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

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

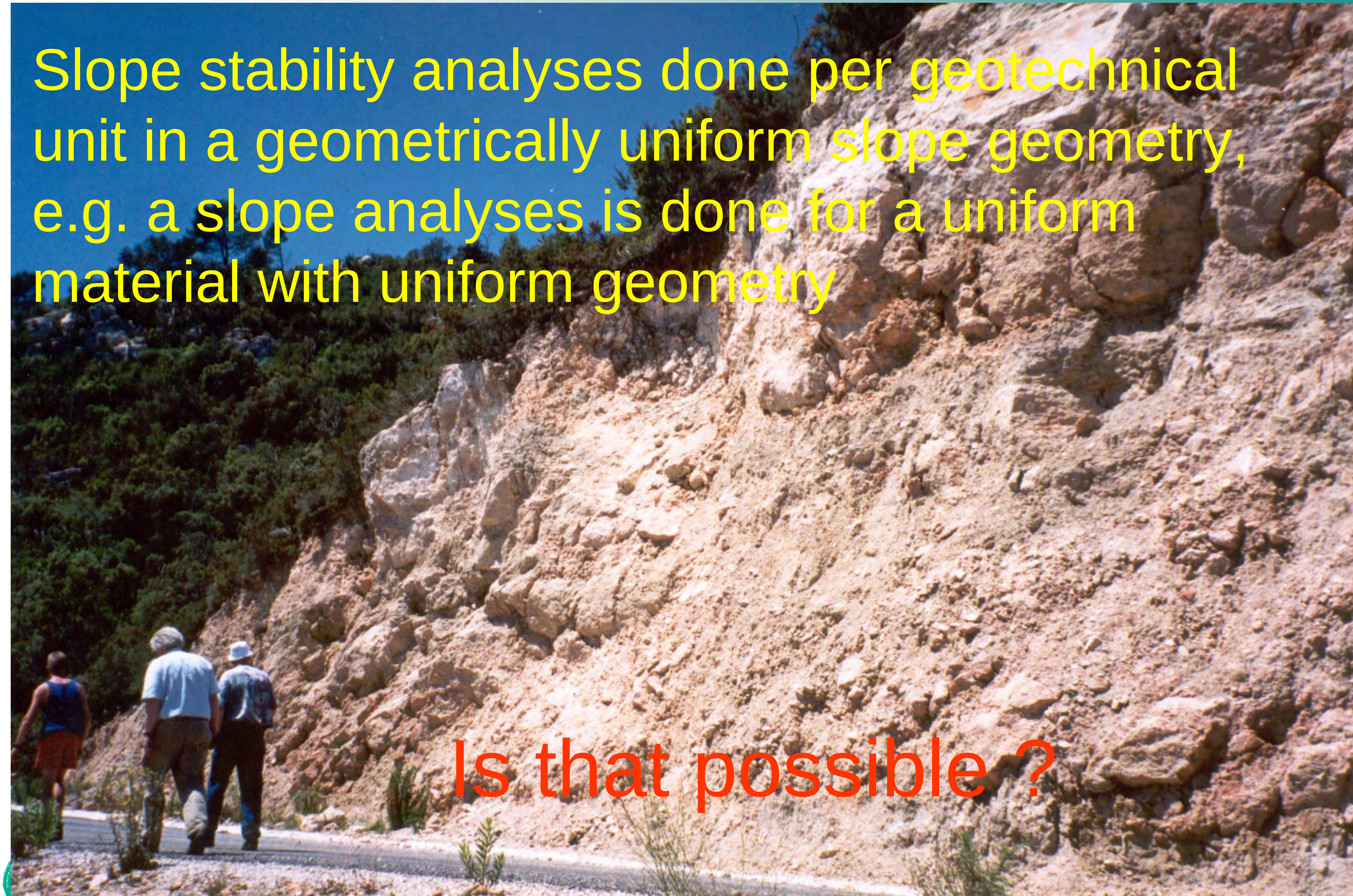
and not very scientific, but highly important:

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

Slope stability

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


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

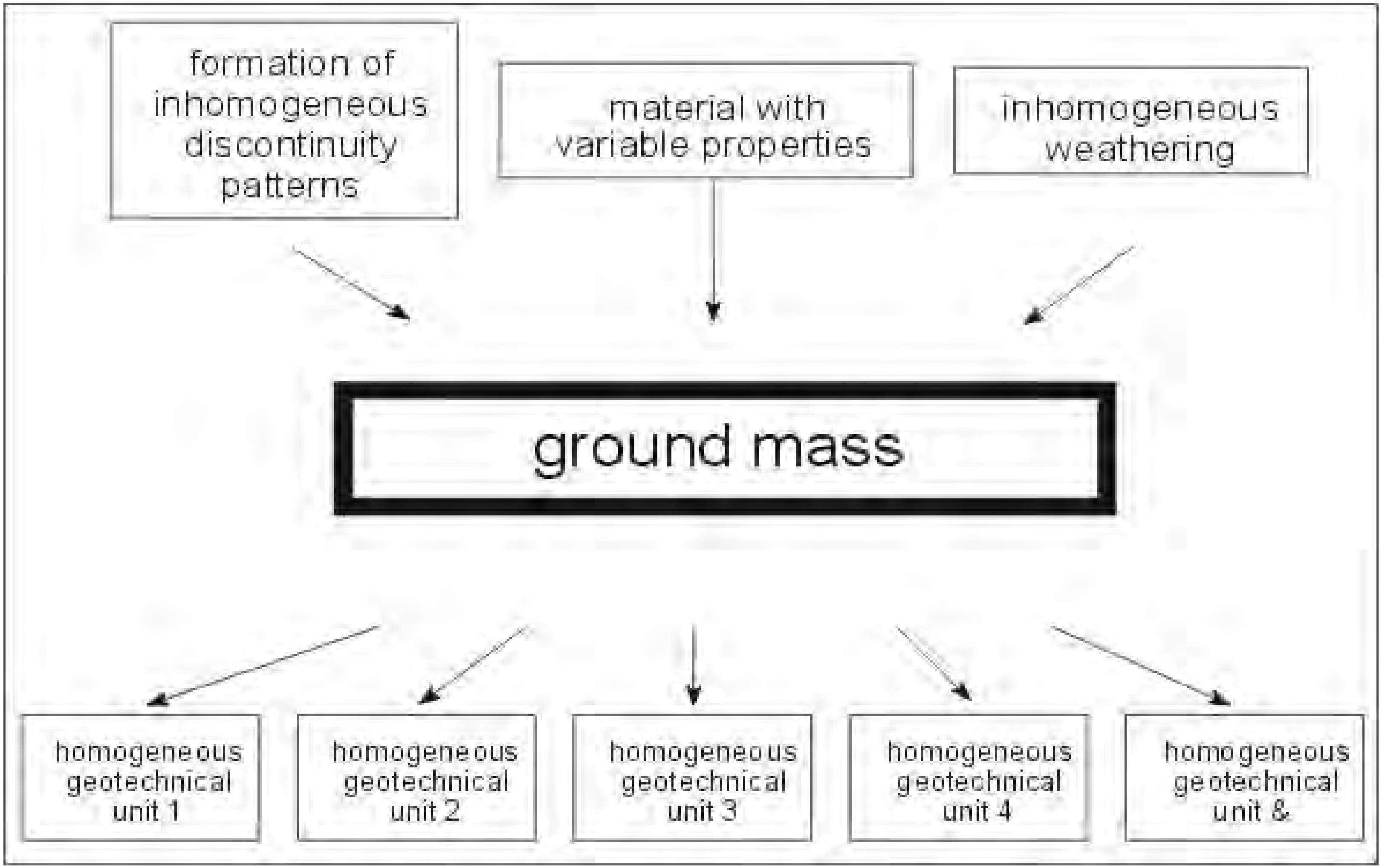
Heterogeneity of slope geometry causes

- Variation in geometry

Geotechnical unit:

A “geotechnical unit” is a unit in which the geotechnical properties are the same.

geotechnical units are based on the experience and expertise of the interpreter



“No geotechnical unit is really homogene….”

A certain amount of variation has to be allowed as otherwise the number of units will be unlimited

“The allowable variation of the properties within one geotechnical unit depends on:

- the degree of variability of the properties within a mass,
- the influence of the differences on engineering behaviour, and
- the context in which the geotechnical unit is used.

Smaller allowed variability of the properties in a geotechnical unit results in:

- higher accuracy of geotechnical calculations
- less risk that a calculation or design is wrong

Smaller allowed variability of the properties in a geotechnical unit:

- requires collecting more data and is thus more costly
- geotechnical calculations are more complicated and complex, and cost more time

Hence:

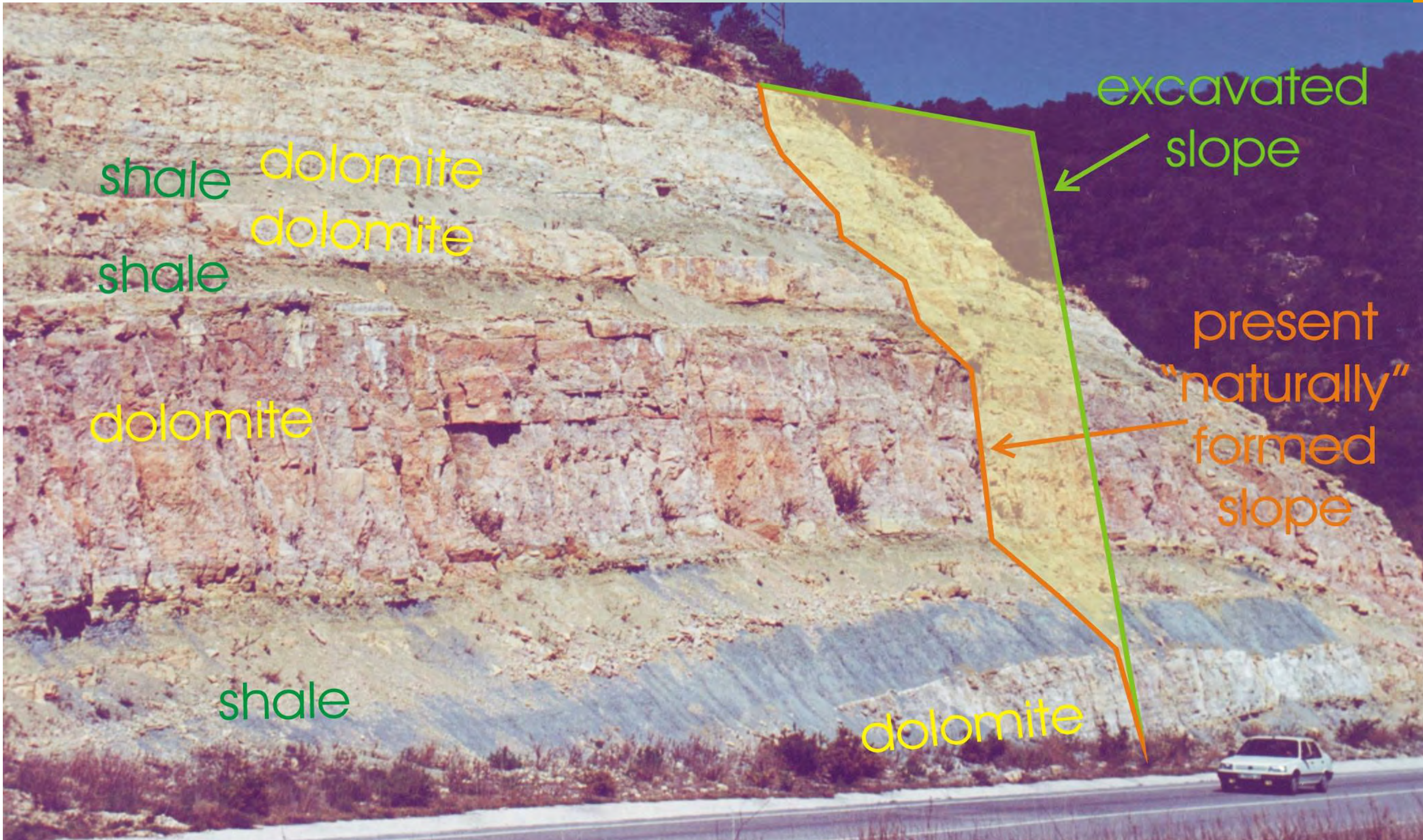
- the variations allowed within a geotechnical unit for the foundation of a highly sensitive engineering structure (for example, a nuclear power station) is smaller
- the variations allowed within a geotechnical unit in a calculation for the foundation of a standard house will be larger

Examples

What are the implications if wrong?

Original situation

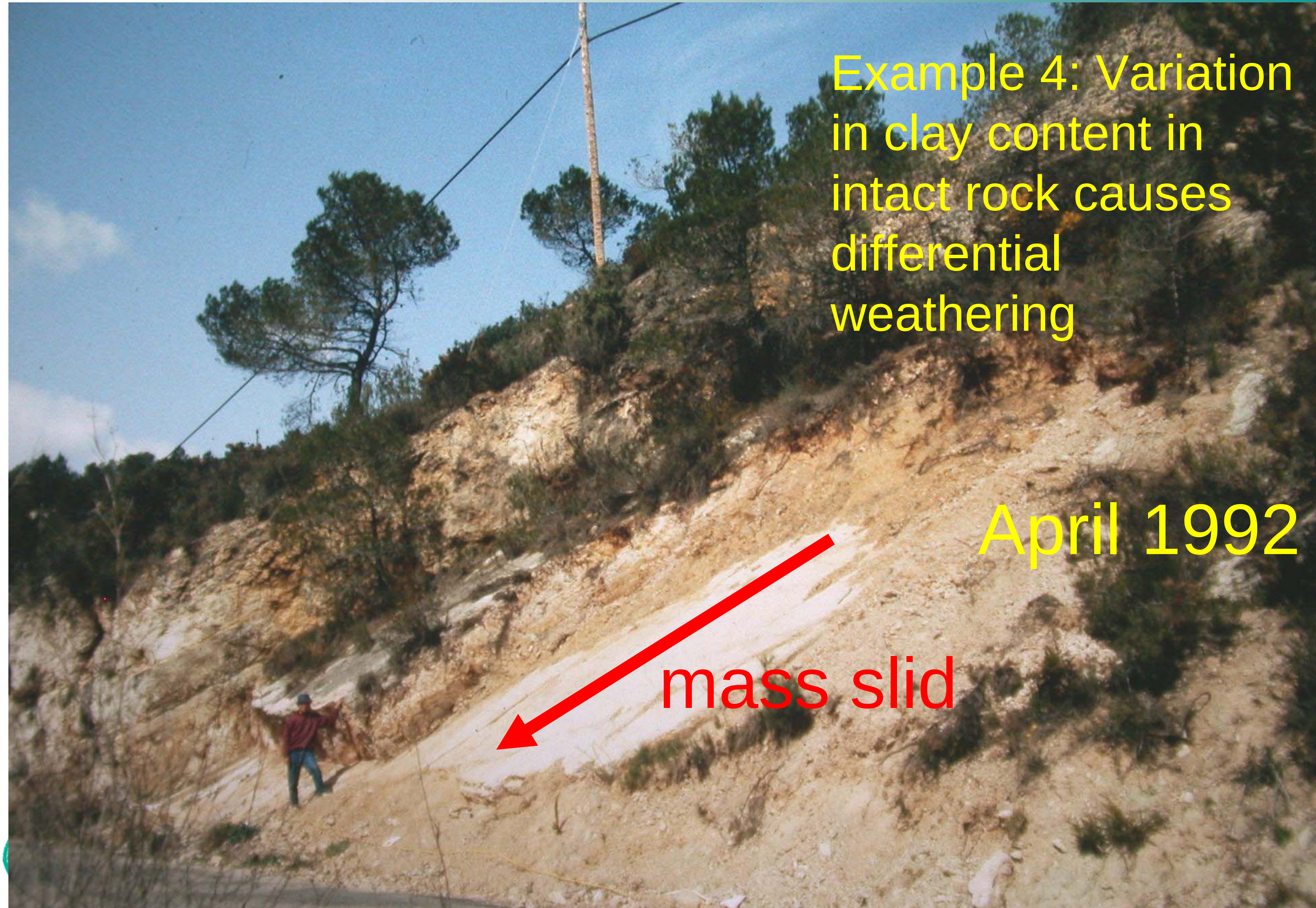
design error



Example 2: Many discontinuity sets with large variation in orientation (too many for the design engineer?)


Example 3: Many discontinuity sets with large variation in orientation


Example 4: Variation in clay content in intact rock causes differential weathering
bedding planes
April 1990
Slightly higher clay content


Example 4: Variation in clay content in intact rock causes differential weathering
April 1992
mass slid

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
- Uncertainty in future environment (for example, weathering)

Options for analysing slope stability

Analytical

Numerical

Classification

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?

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. 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

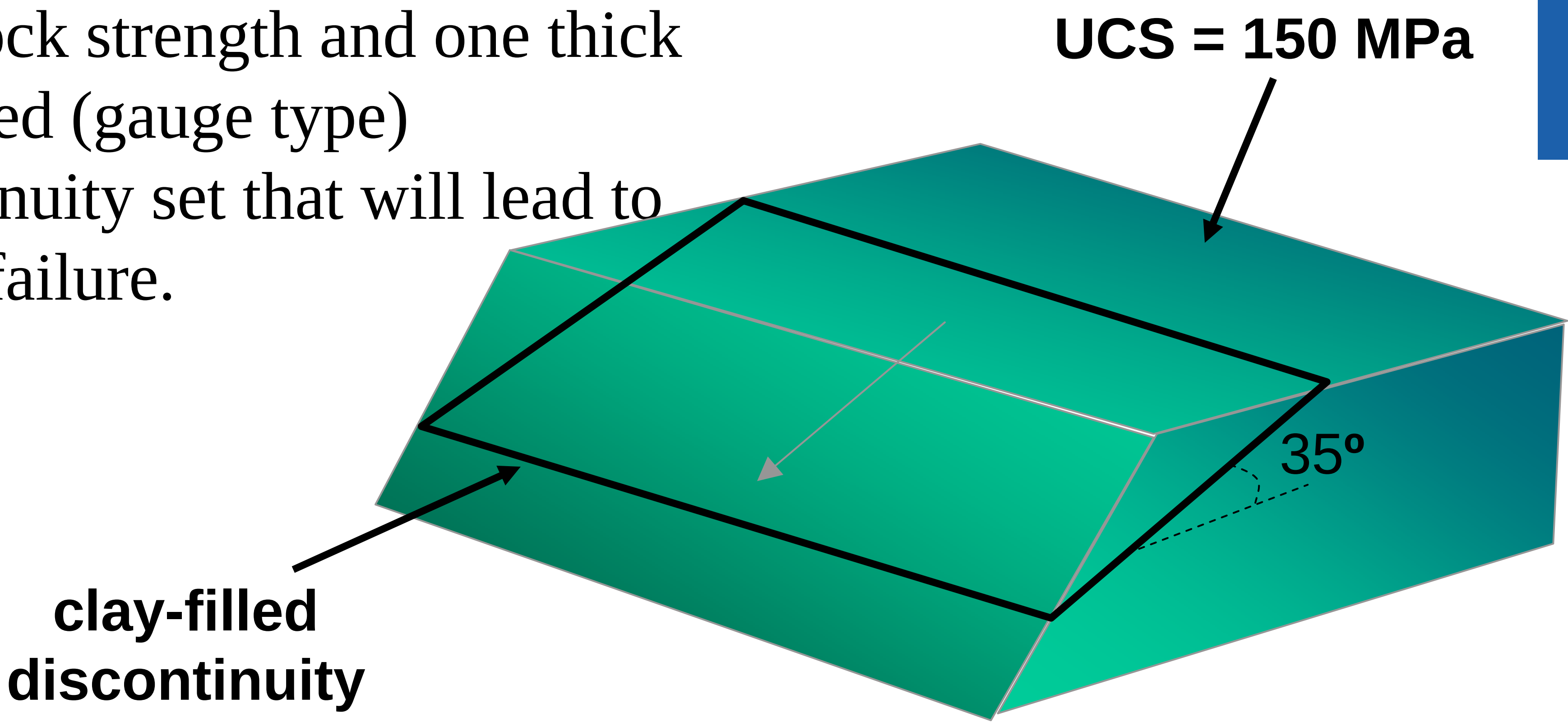
Existing rock mass classification systems

- 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

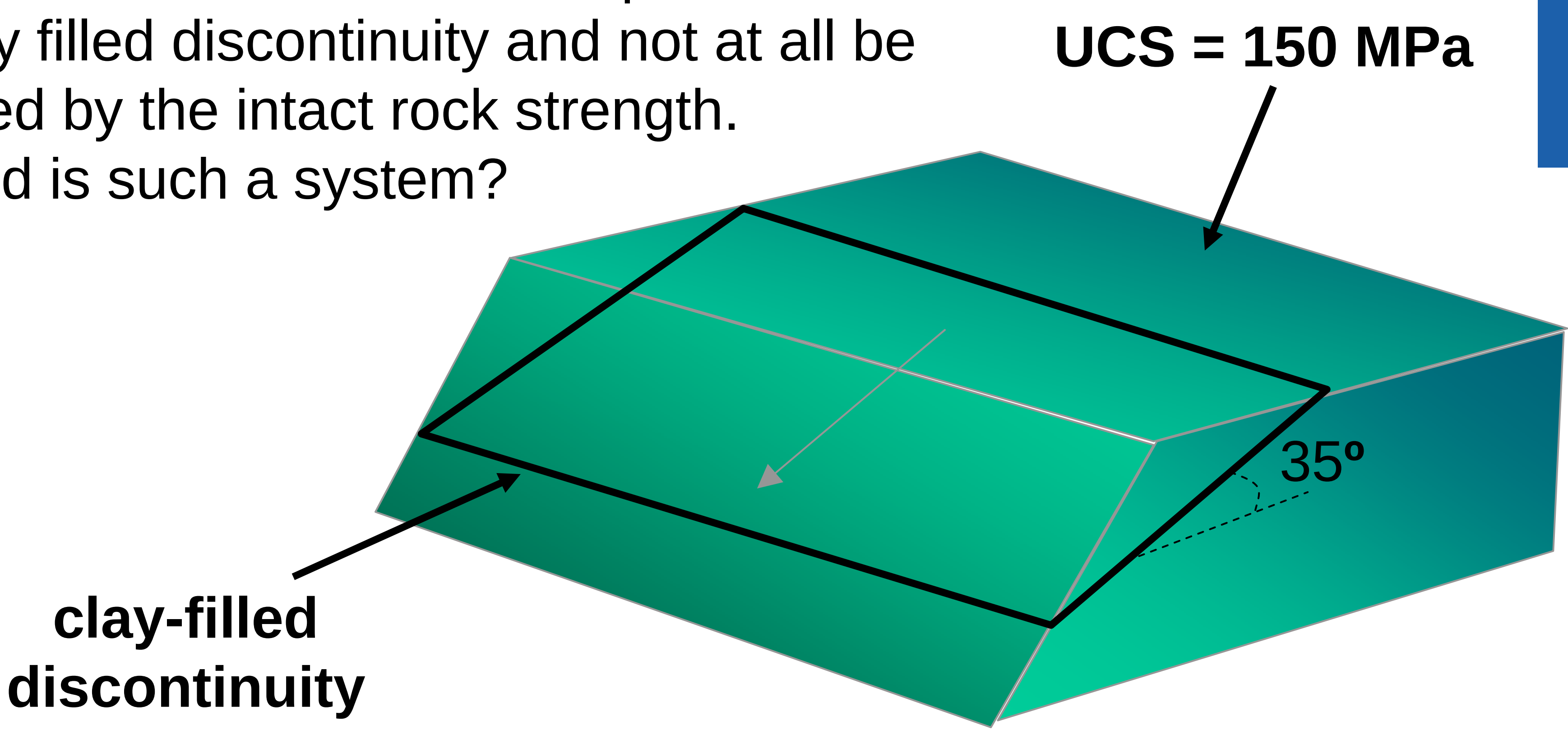
For example:

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.



Strange influence parameters in some systems

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?



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

<table>
<tr><td rowspan="12">geotechnical unit</td><td colspan="4">intact rock strength</td></tr>
<tr><td rowspan="9">discon-tinuities</td><td></td><td colspan="2">orientation (with respect to engineering structure)</td></tr>
<tr><td rowspan="3">rock block size and form</td><td colspan="2">amount of disc. sets</td></tr>
<tr><td colspan="2">spacing per disc. set</td></tr>
<tr><td colspan="2">persistence per disc. set</td></tr>
<tr><td rowspan="5">shear strength along discontinuity (condition of discontinuity)</td><td rowspan="4">surface characteristics of discontinuity wall</td><td>material friction</td></tr>
<tr><td>roughness (dilatancy)</td></tr>
<tr><td>strength</td></tr>
<tr><td>deformation</td></tr>
<tr><td colspan="2">infill material</td></tr>
<tr><td colspan="4">susceptibility to weathering</td></tr>
<tr><td colspan="4">deformation parameters of intact rock/rock mass</td></tr>
<tr><td>engineering structure</td><td colspan="4">geometry of engineering structure (size and orientation of a tunnel, height and orientation of a slope, etc.)</td></tr>
<tr><td rowspan="2">external influences</td><td colspan="4">water pressure/flow, snow and ice, stress relief, external stress, etc.</td></tr>
<tr><td colspan="4">type of excavation</td></tr>
</table>

Existing classification systems (1)

- 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.

Existing classification systems (2)

- 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 parame-ter(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

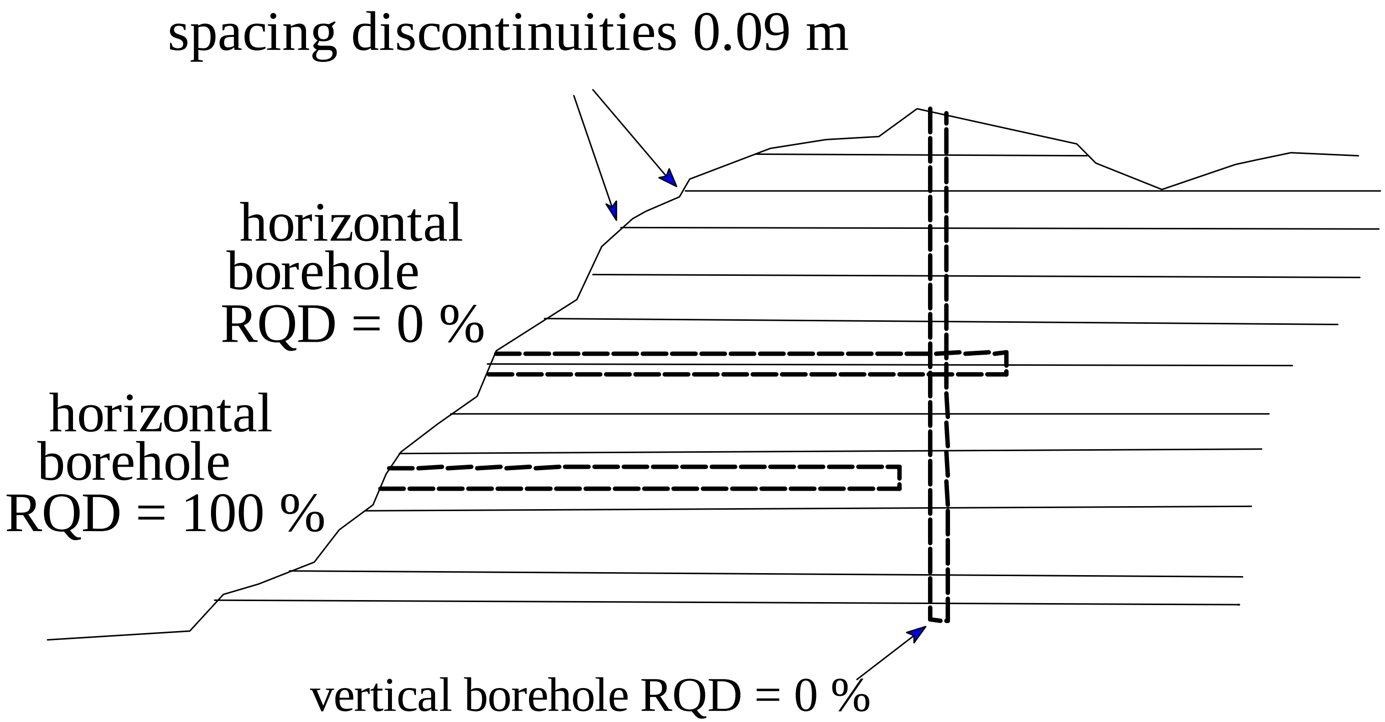
Classification systems: Problems with Intact rock strength

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

- Inclusion of discontinuities within 10 cm length
- Samples tested in the laboratory tend to be of better quality (or of lower quality if rock is very strong)
- The intact rock strength measured depends on the sample orientation if the intact rock exhibits anisotropy.
- 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

Classification systems: Problems with RQD (1)

- Arbitrary length of 10 cm
- Orientation of borehole in relation with discontinuity spacing



Classification systems: Problems with RQD (2)

- 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.
- 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)

- No standard core barrel - single, double, or triple barrel ?
- Diameter of boreholes
- Drilling fractures should be re-fitted, but what are drilling fractures?
- RQD should be determined per lithology, but where is the lithology boundary if washed away?

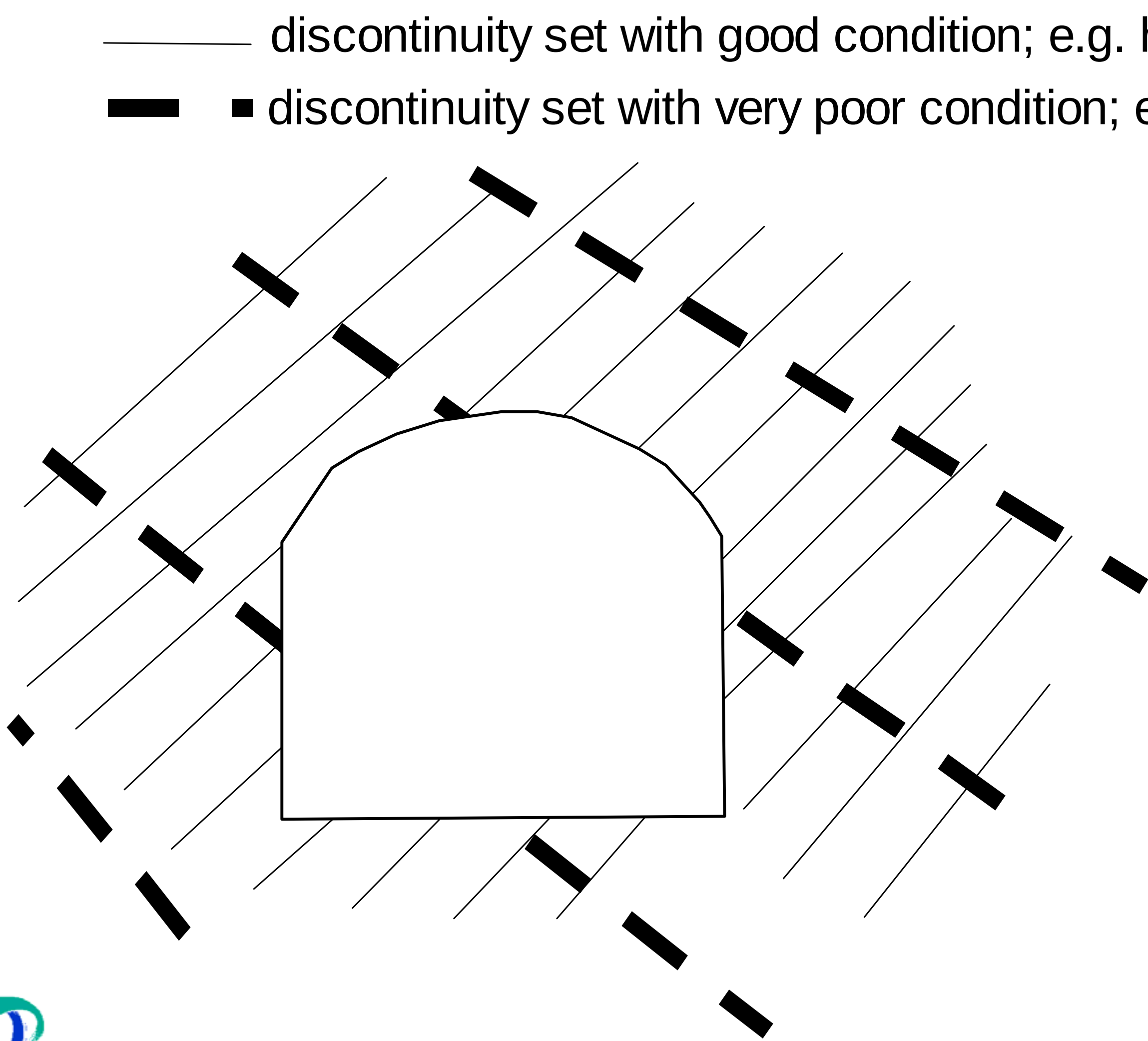
Classification systems: Problems with RQD (5)

- 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?

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 ?



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

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

No clear differentiation between “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

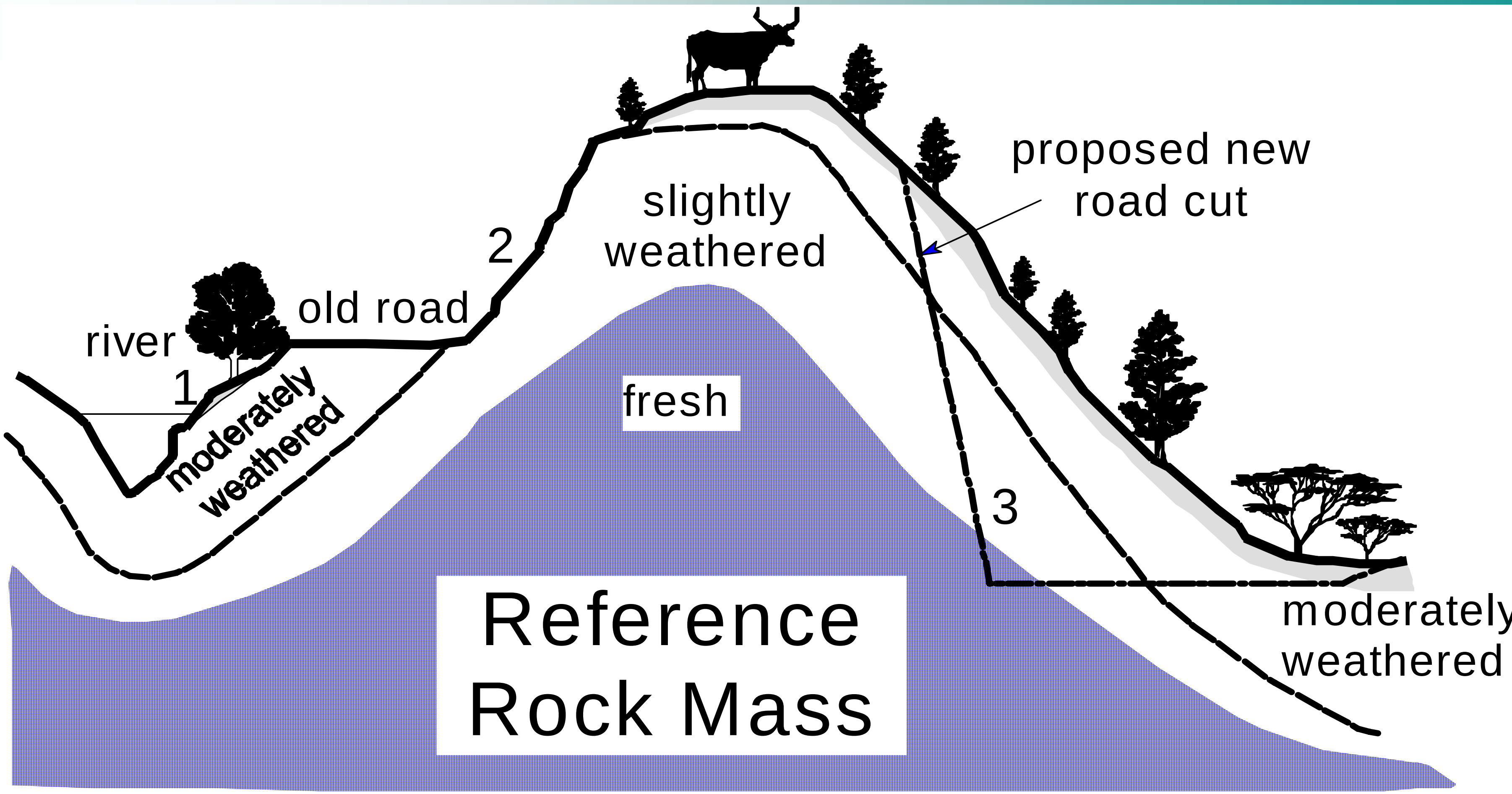
- Often not clear how many different persons developed a system and whether designer bias may be present
- Those using a system and being satisfied with the system may be so familiarized that they do not see the flows anymore

Slope Stability probability Classification (SSPC)

SSPC

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

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

ITC

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

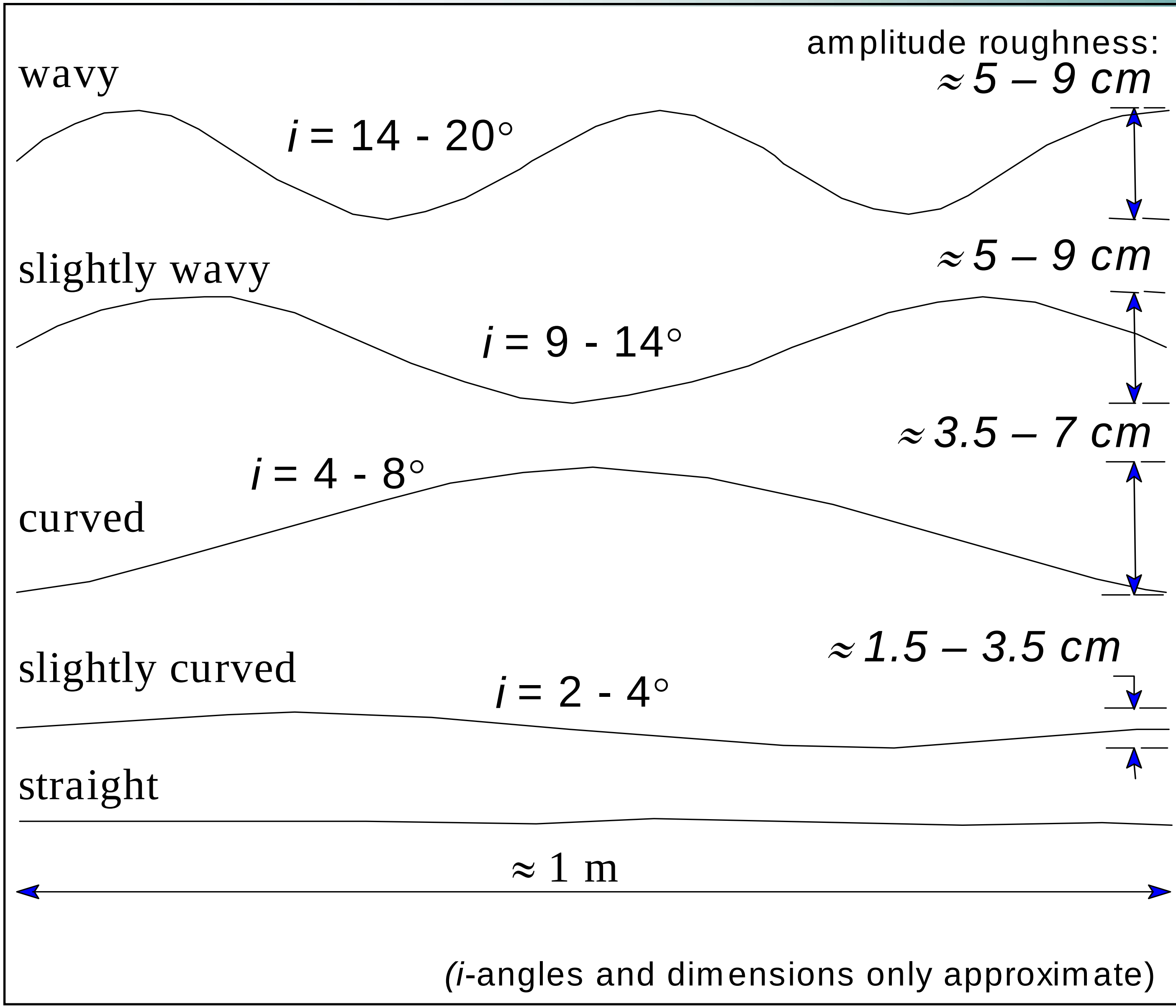
Intact rock strength

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

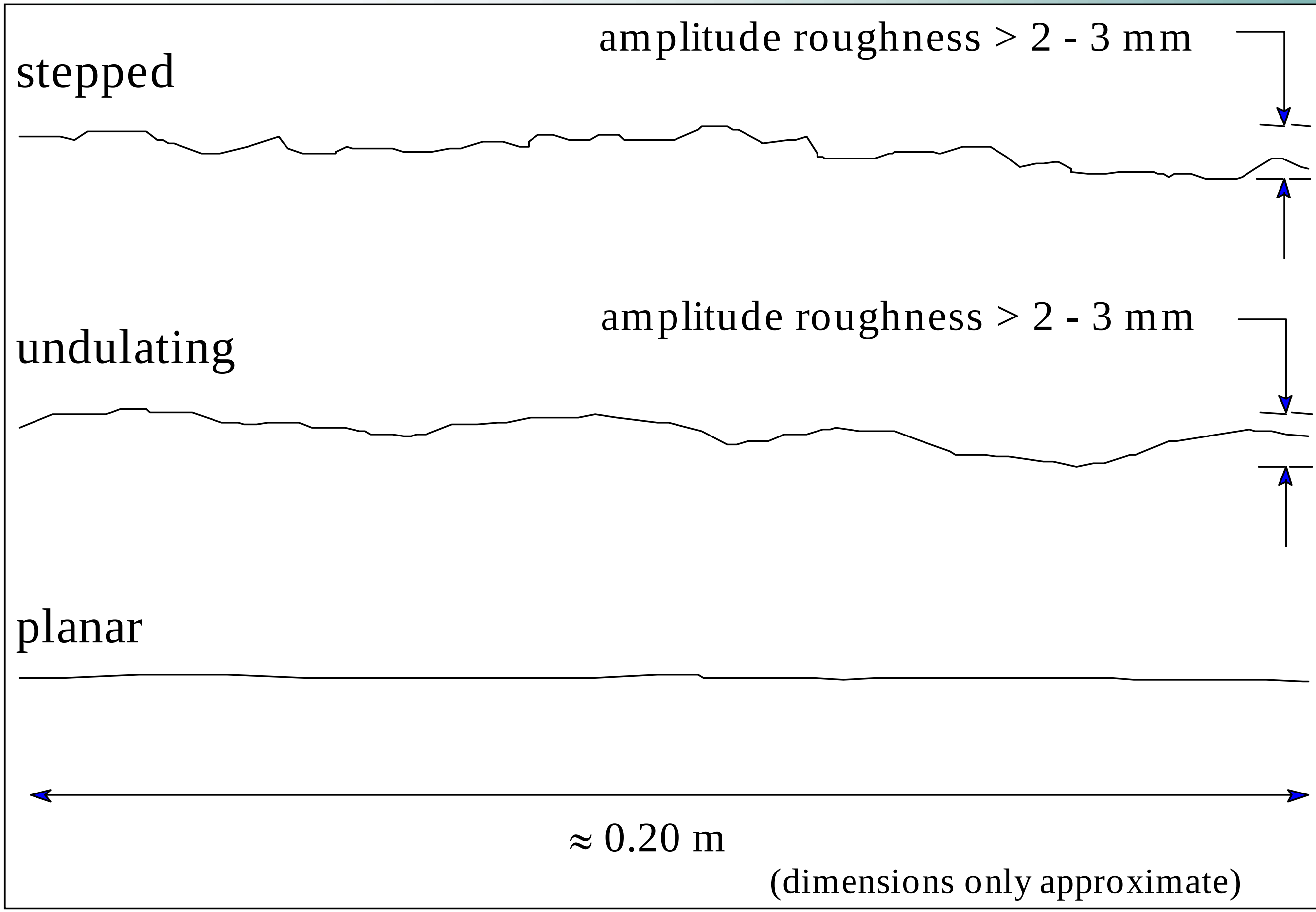
Spacing and persistence of discontinuities

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



Shear strength - roughness small scale



Shear strength - roughness tactile

Three classes:

- rough
- smooth
- polished

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

Shear strength - karst

Karst or no karst

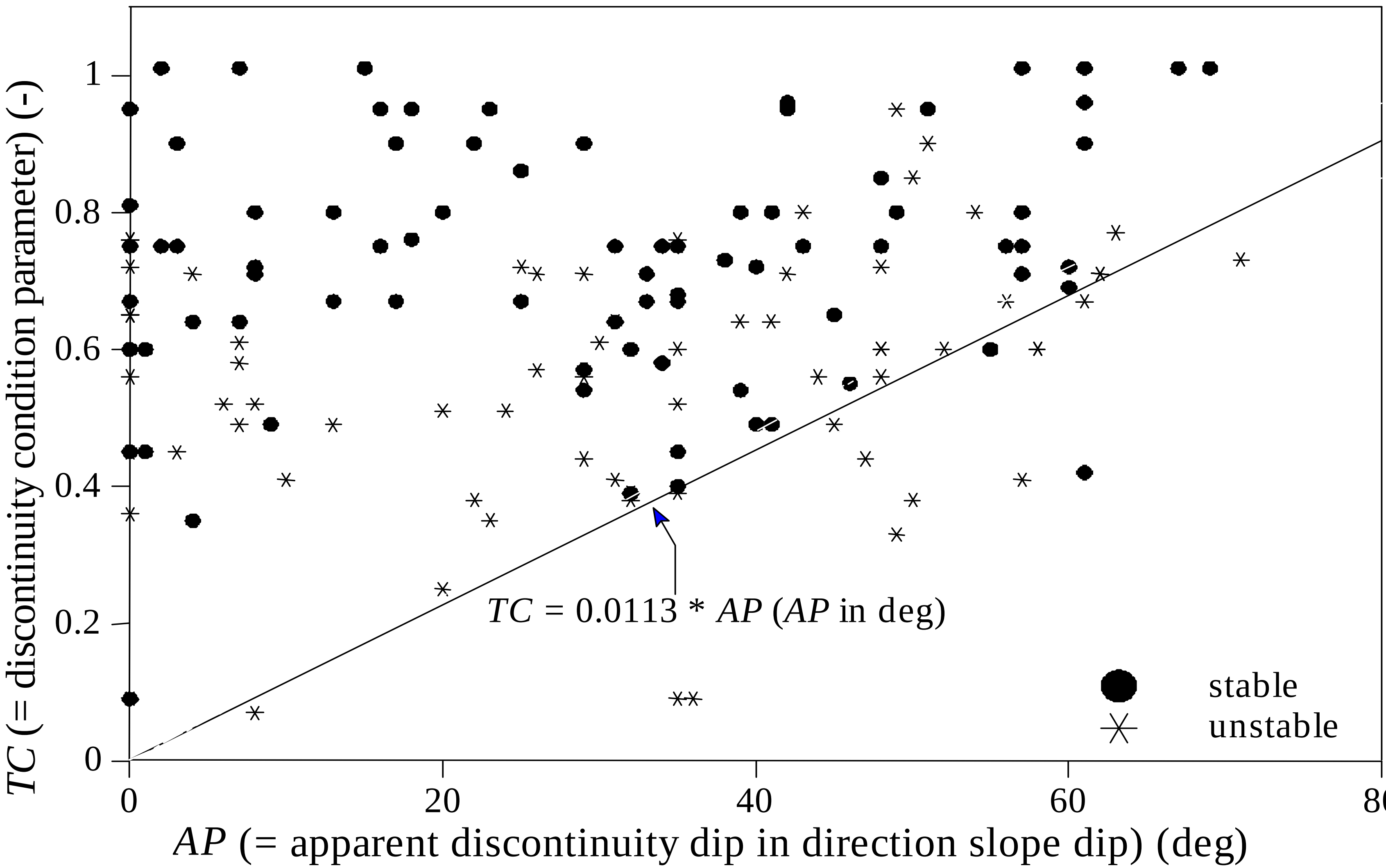
Shear strength - condition factor

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:

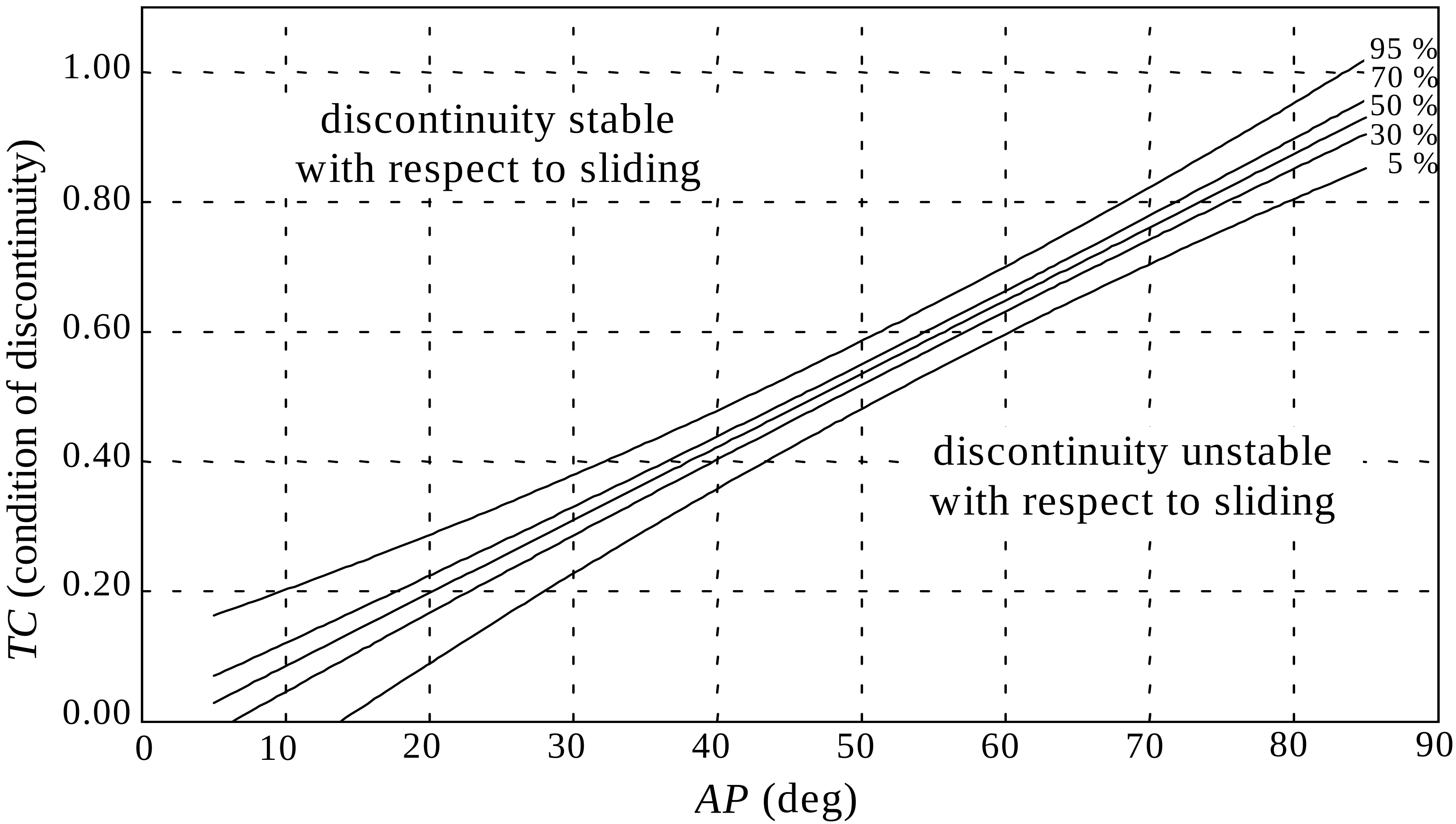


Sliding criterion

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

$$TC < 0.0113 * AP$$

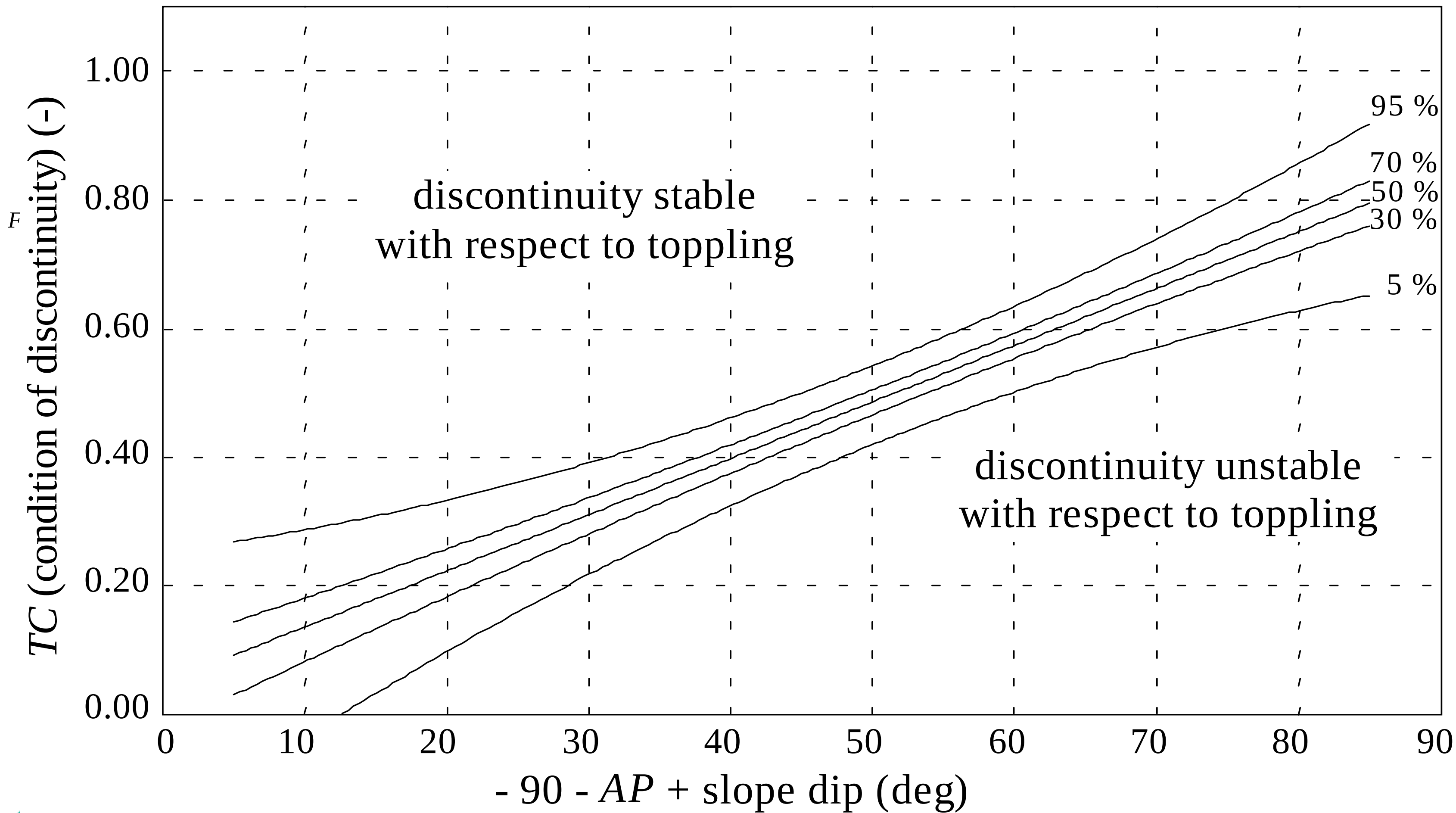
Sliding probability



Toppling criterion

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

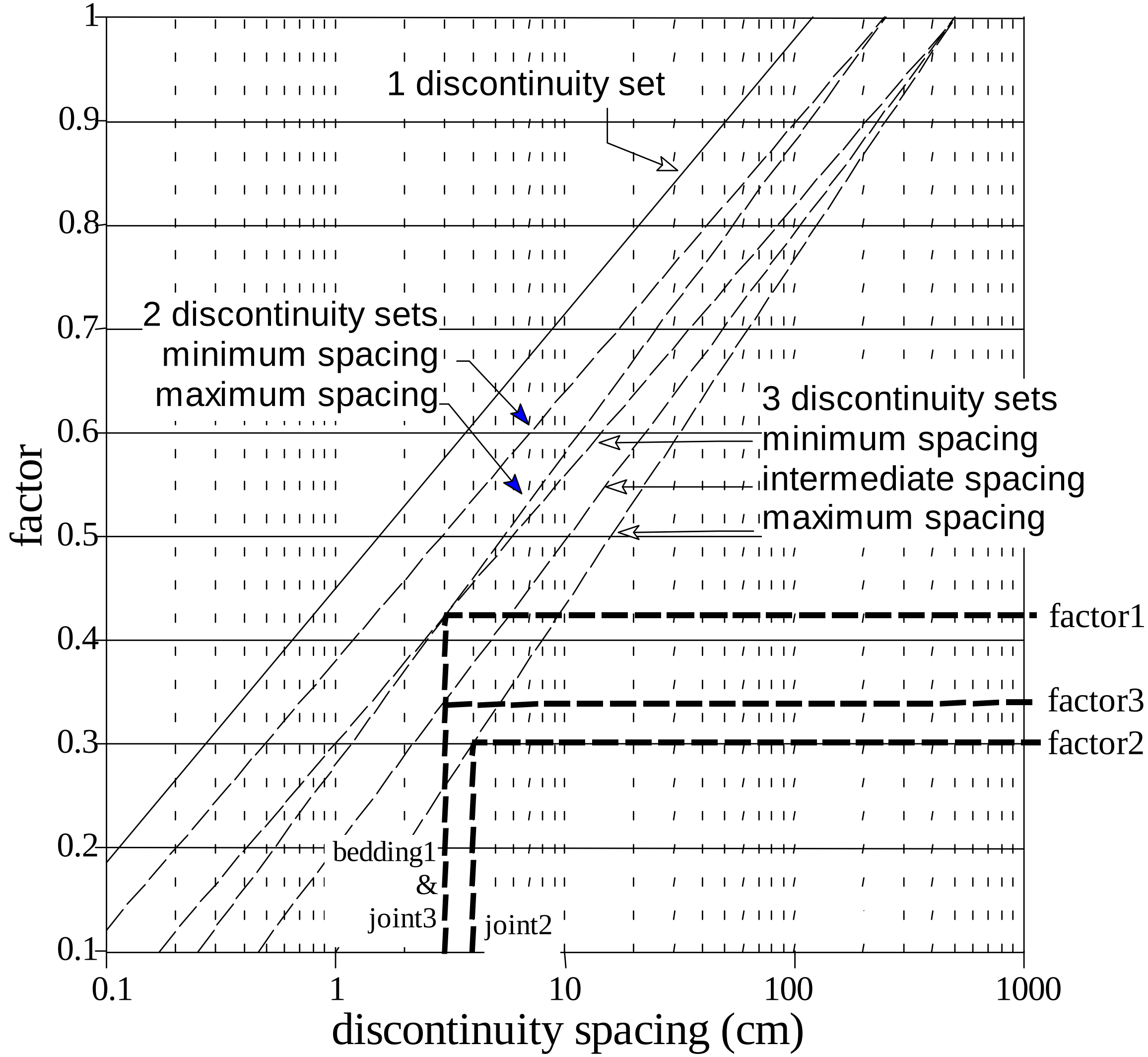
Toppling probability



Orientation independent stability

Overall spacing of discontinuity sets

Block size and form relations from Taylor



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

Shear plane failure following Mohr-Coulomb for rock mass

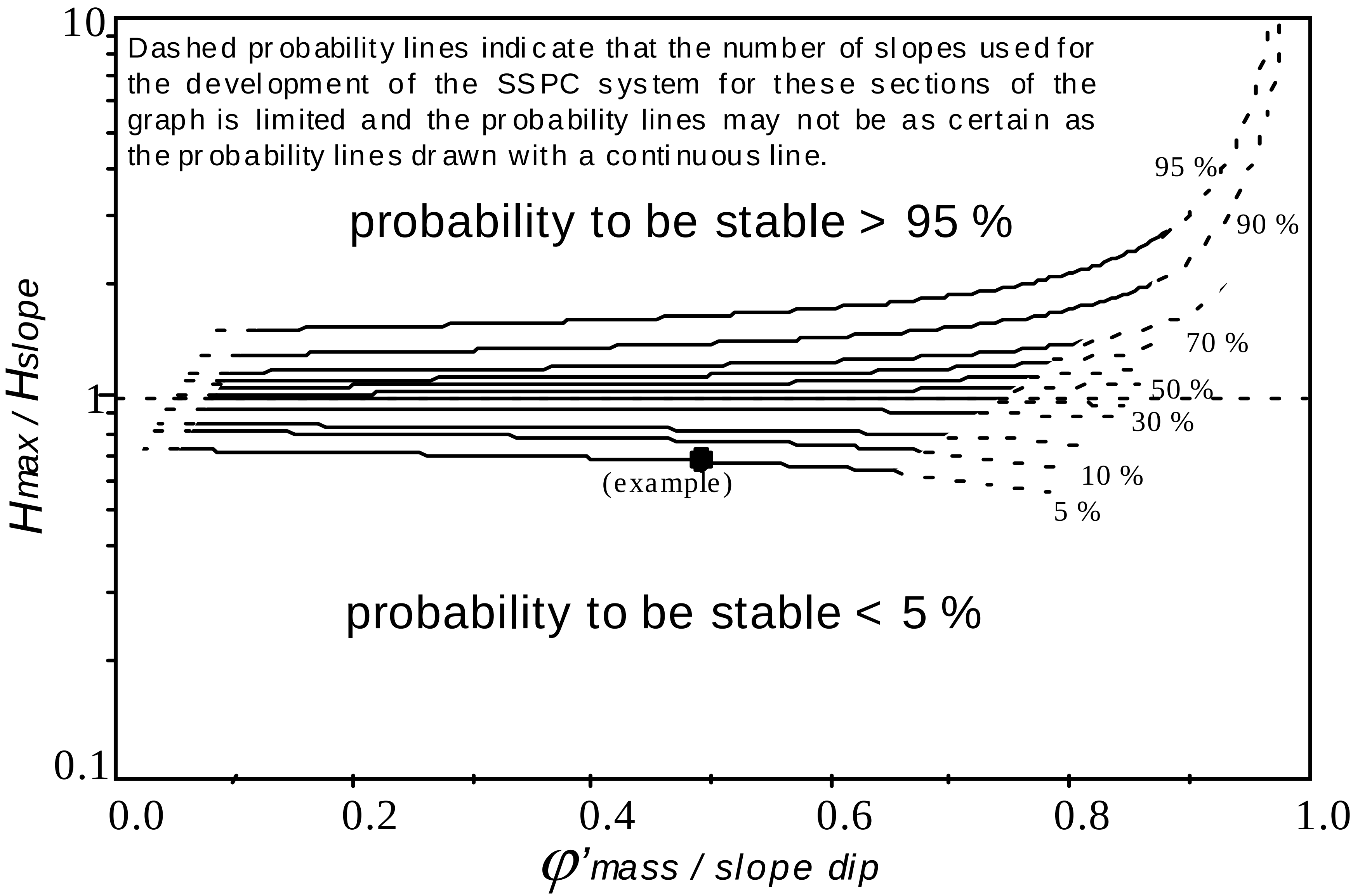
$$\text{If the } dip_{slope} \leq \varphi'_{mass} :$$

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

else

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

Probability orientation independent failure



How did we do this?

For each slope j:

visually estimated stability = class 1

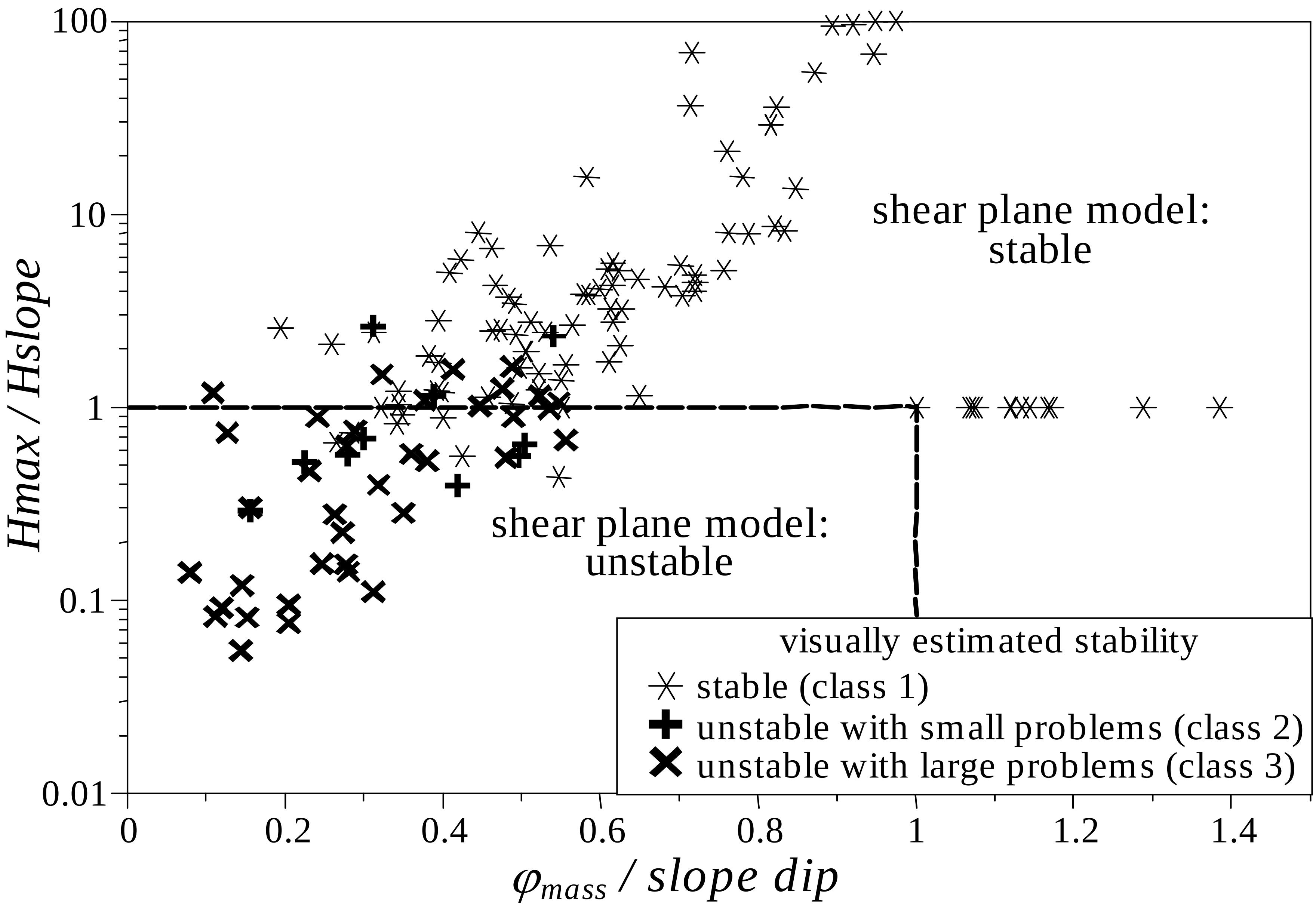
$$\begin{cases} \dfrac{\varphi_{mass}}{dip_{slope}} \geq 1 \quad (stable) \rightarrow er = 1 \\ \dfrac{\varphi_{mass}}{dip_{slope}} < 1 \begin{cases} \dfrac{H_{max}}{H_{slope}} \geq 1 \quad (stable) \rightarrow er = 1 \\ \dfrac{H_{max}}{H_{slope}} < 1 \quad (unstable) \rightarrow er = \dfrac{H_{slope}}{H_{max}} \end{cases} \end{cases}$$

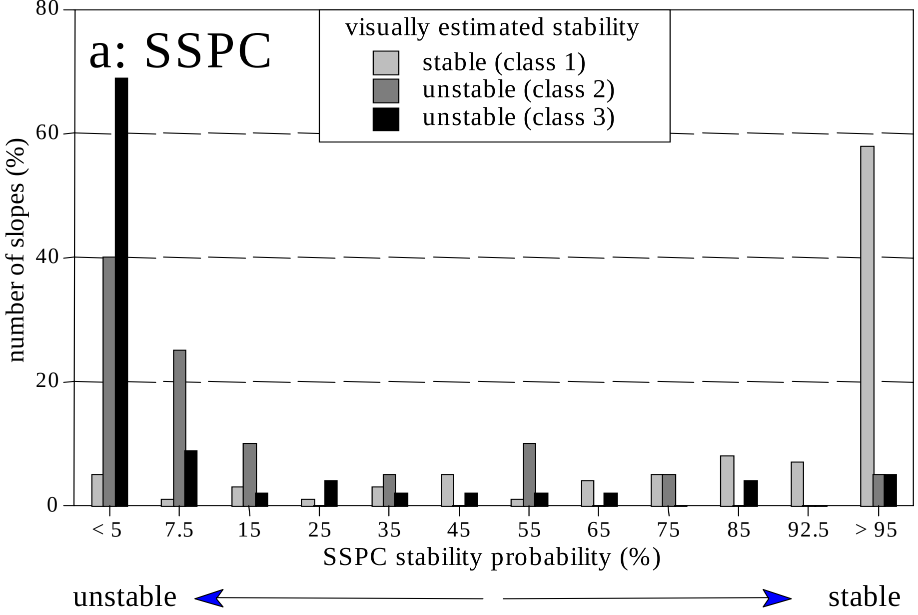
visaually estimated stability = class 2 or 3

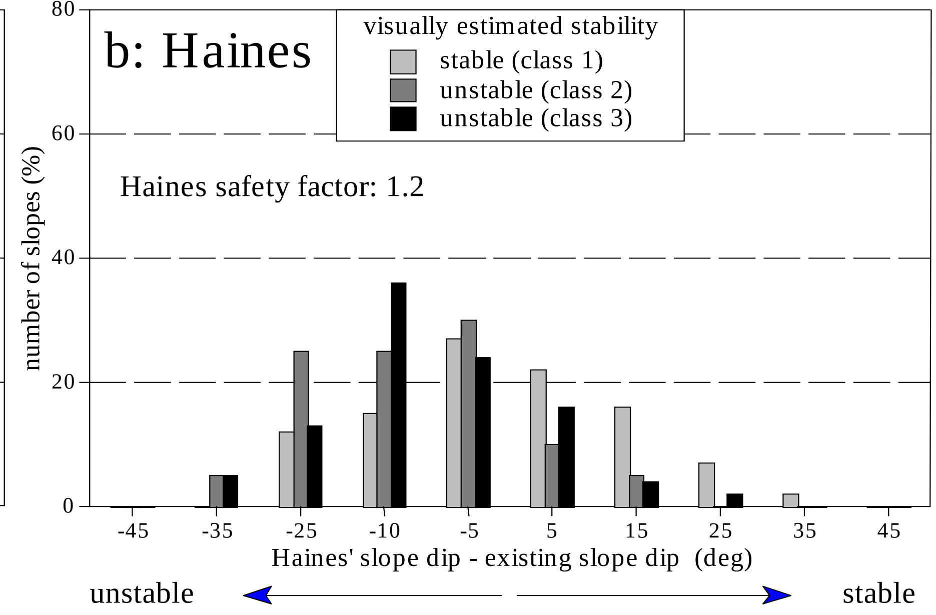
$$\begin{cases} \dfrac{\varphi_{mass}}{dip_{slope}} \geq 1 \quad (stable) \rightarrow er = \dfrac{\varphi_{mass}}{dip_{slope}} \\ \dfrac{\varphi_{mass}}{dip_{slope}} < 1 \begin{cases} \dfrac{H_{max}}{H_{slope}} \leq 1 \quad (unstable) \rightarrow er = 1 \\ \dfrac{H_{max}}{H_{slope}} > 1 \quad (stable) \rightarrow er = \dfrac{H_{max}}{H_{slope}} \end{cases} \end{cases}$$

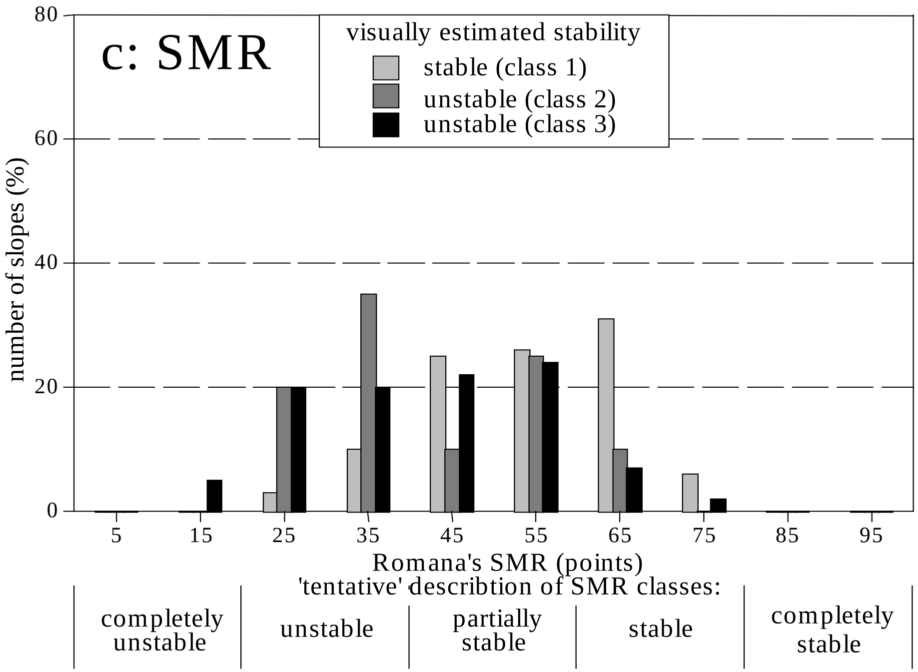
$$ER = \sum_j er_j$$

How did we do this?









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)

Comparison


Poorly blasted slope

Poorly blasted slope

New cut (in 1990):
Visual assessed: extremely poor instable.
SSPC stability < 8% (13.8 m high, dip 70°, rock mass weathering: 'moderately' and 'dislodged blocks' due to blasting).

Forecast in 1996: SSPC stability: slope dip 45°.

In 2002: Slope dip about 55° (visually assessed unstable).

In 2005: Slope dip about 52° (visually assessed unstable – big blocks in middle photo have fallen).

Plane sliding failure

40 year old road cut, Spain

Plane sliding failure (2)

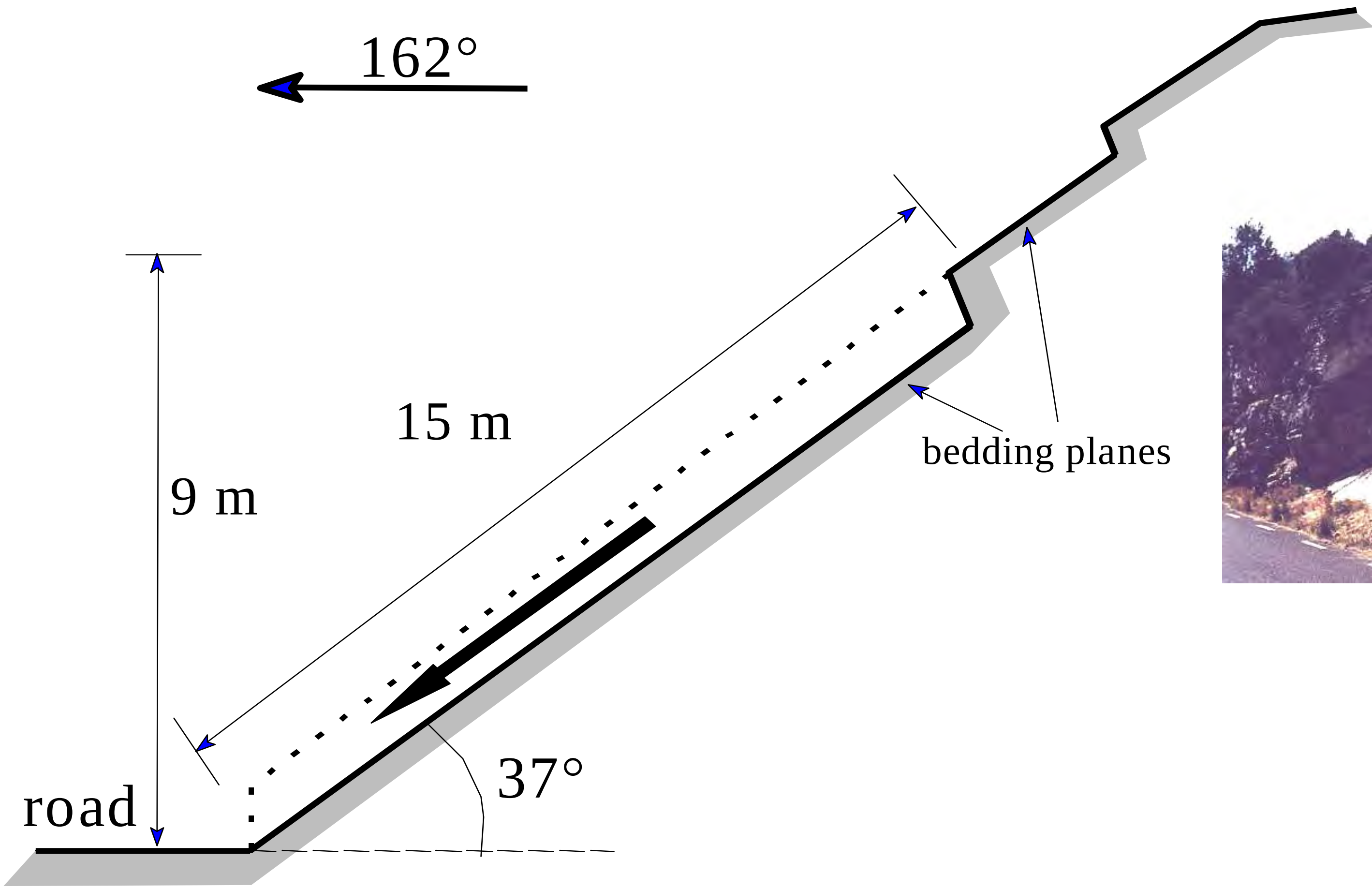


Fig. 108. Geometrical cross section of the slope.

Plane sliding failure (3)

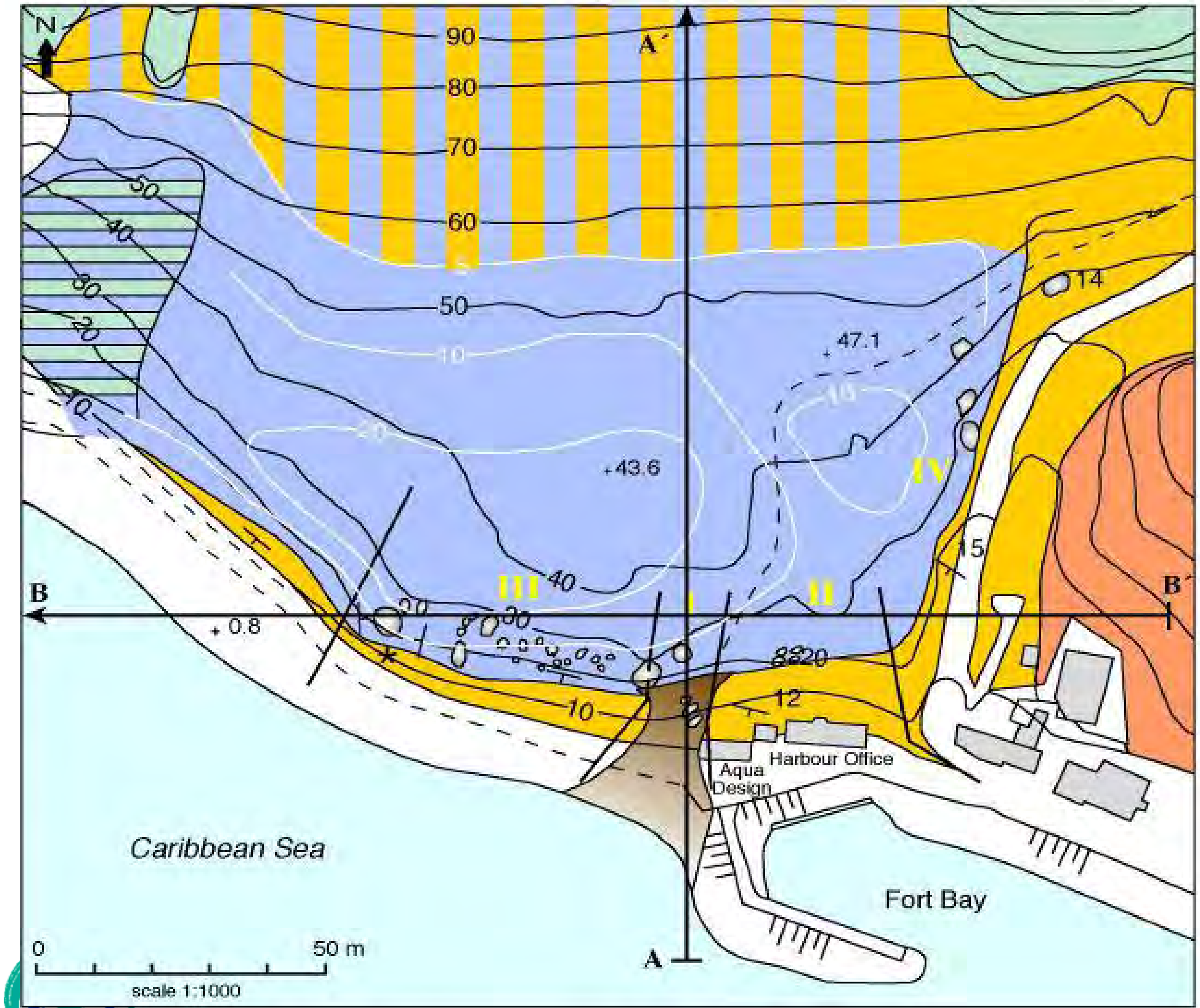
- Laboratory test: ϕ=45°
- SSPC: $\phi\approx$35°
- Stability assessed using:
  - SSPC – 55% stability probability, failure imminent ($\phi\approx$35°)

Slope Stability probability Classification (SSPC)

Saba case - Dutch Antilles

Landslide in harbour

Geotechnical zoning



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)

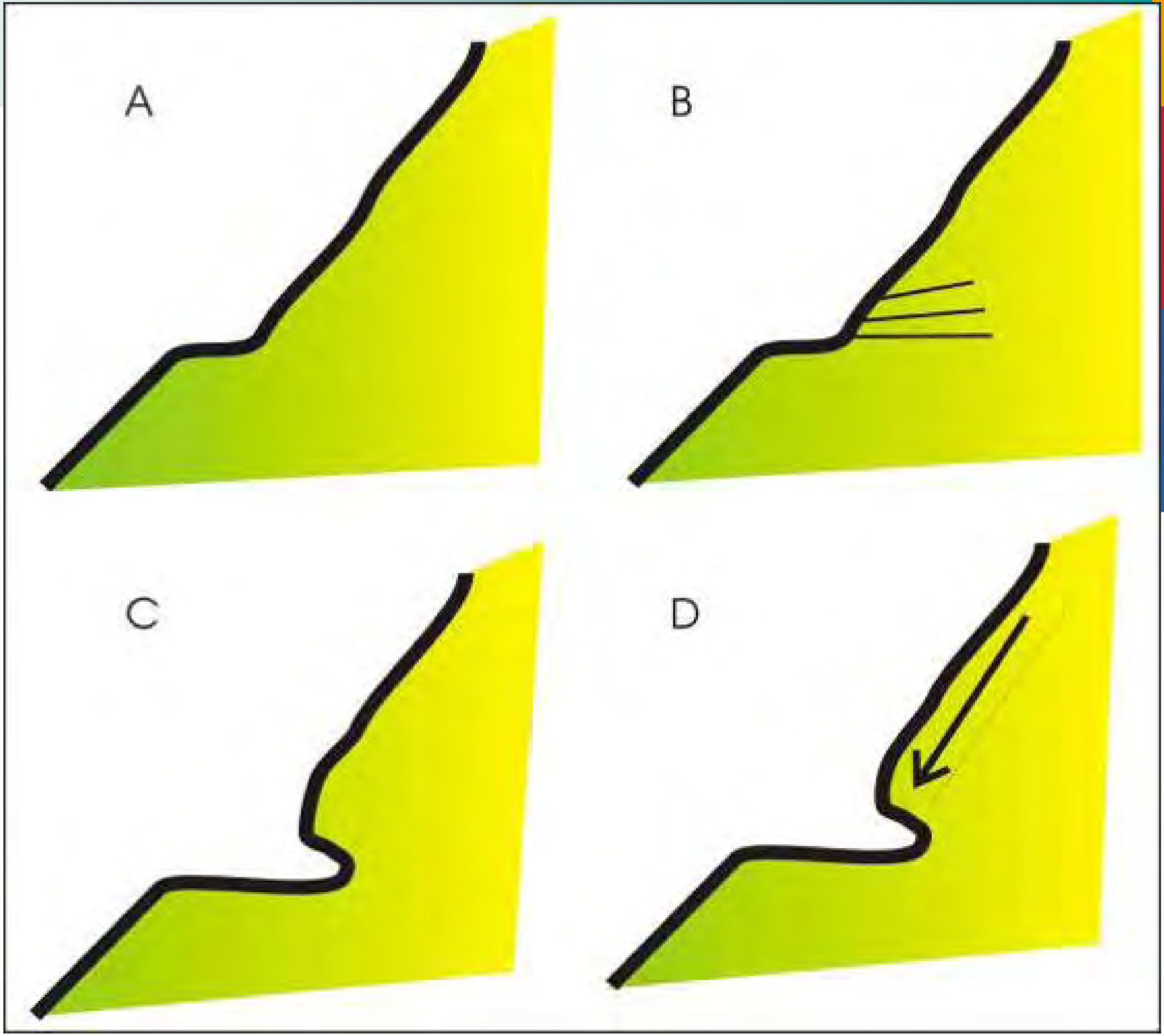
Failing slope in Manila, Philippines

Failing slope in Manila (2)

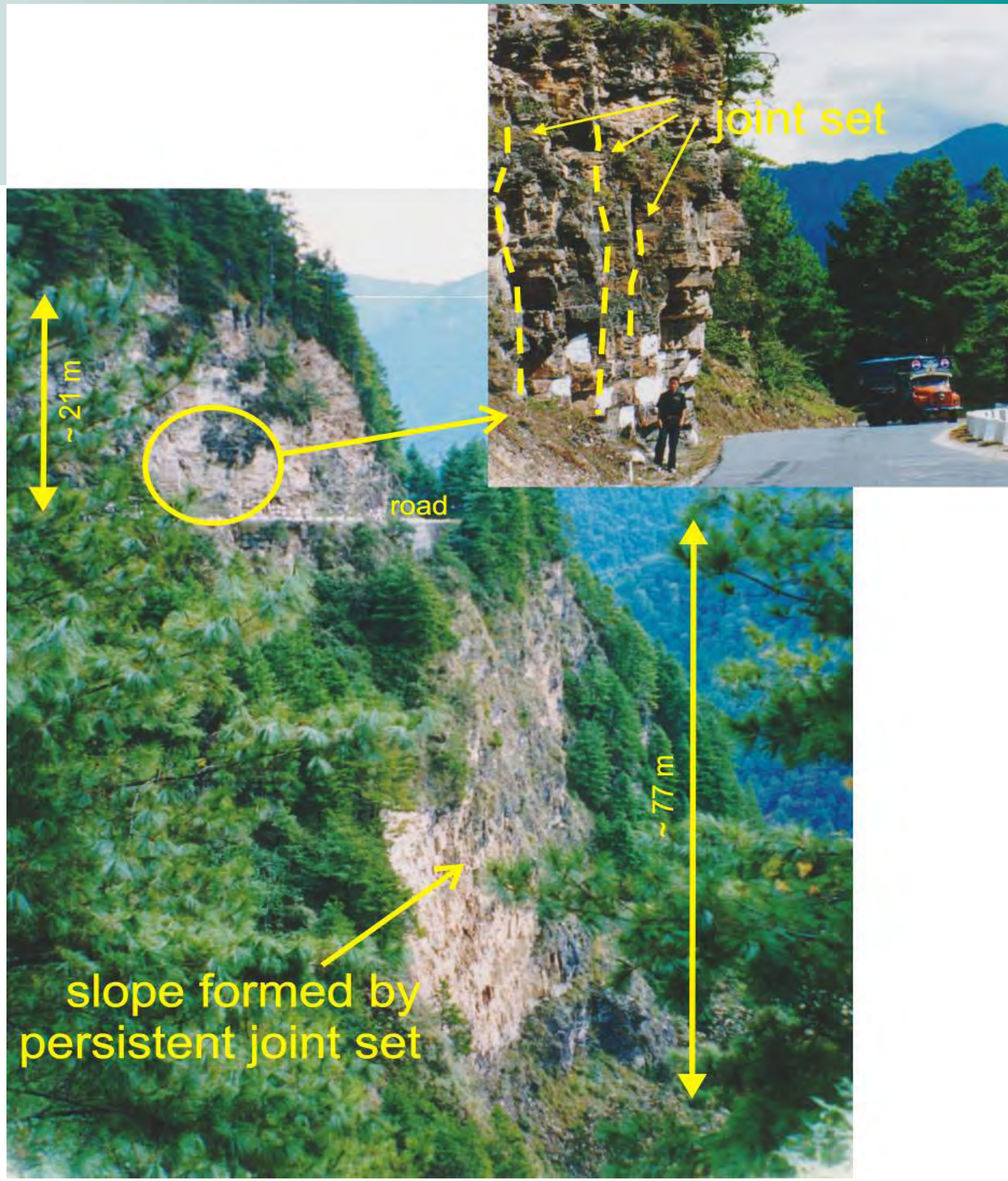
- tuff layers with near horizontal weathering horizons (about every 2-3 m)
- slope height is about 5 m
- SSPC non-orientation dependent stability about 50% for 7 m slope height
- unfavourable stress configuration due to corner

Widening existing road in Bhutan (Himalayas)

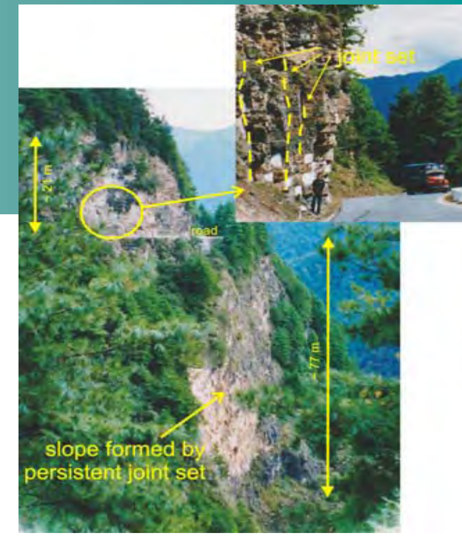
Bhutan (5) Method of excavation



Widening existing road in Bhutan (Himalayas) (2)



Widening existing road in Bhutan (Himalayas) (3)



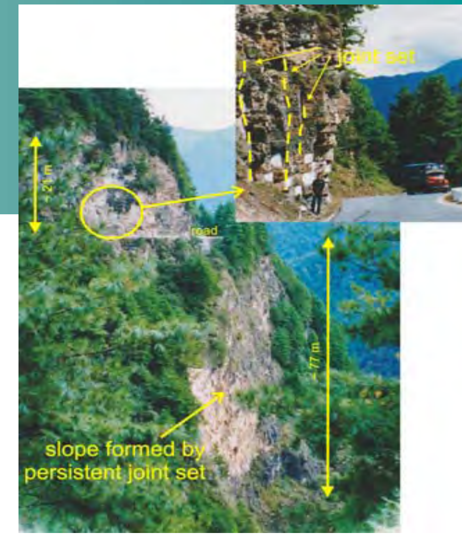
Above road level:

- Various units
- Joint systems (sub-) vertical
- Present slope about 21 m high, about 90° or overhanging (!)
- Present situation above road highly unstable (visual assessment)

Below road level:

- Inaccessible – seems stable

Widening existing road in Bhutan (Himalayas) (4)



Above road level:

- Following SSPC system about 12 – 27 m for a 75° slope (depending on unit) (orientation independent stability 85%)

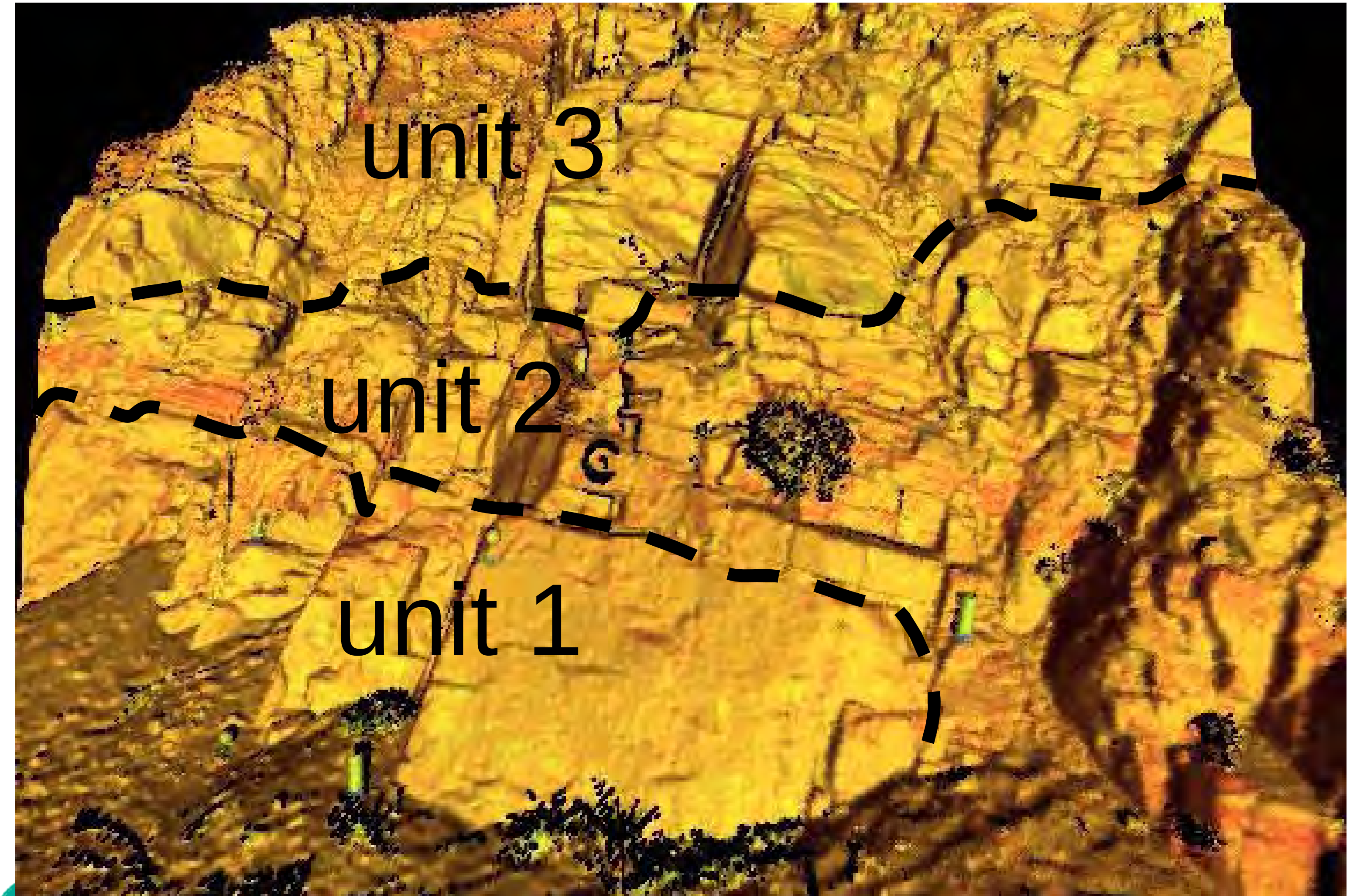
Below road level:

- Inaccessible – different unit ? – and not disturbed by excavation method

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

Heterogeneity (2)



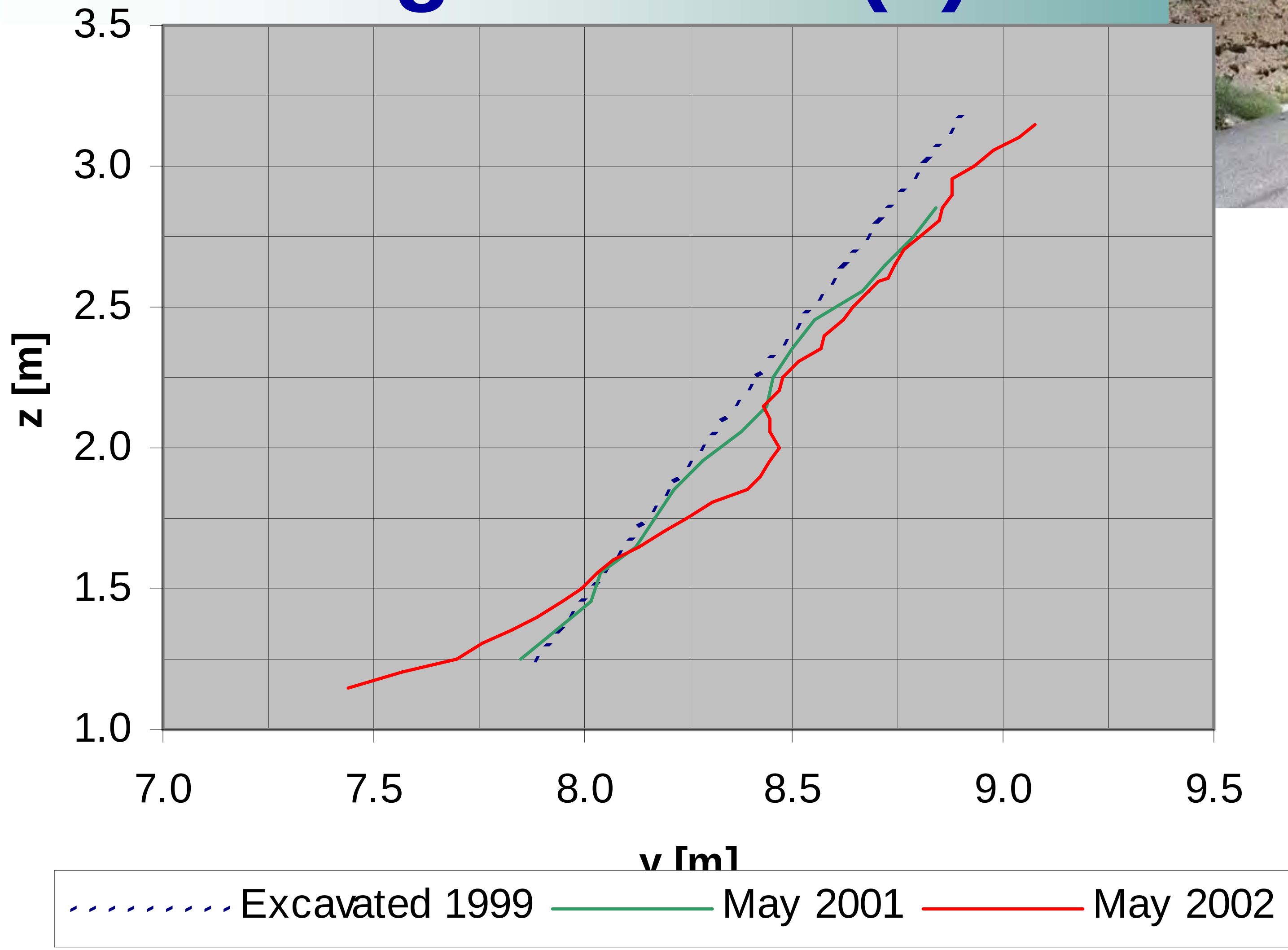
(modified after Slob et al, 2002)

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)

Future degradation (3)



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

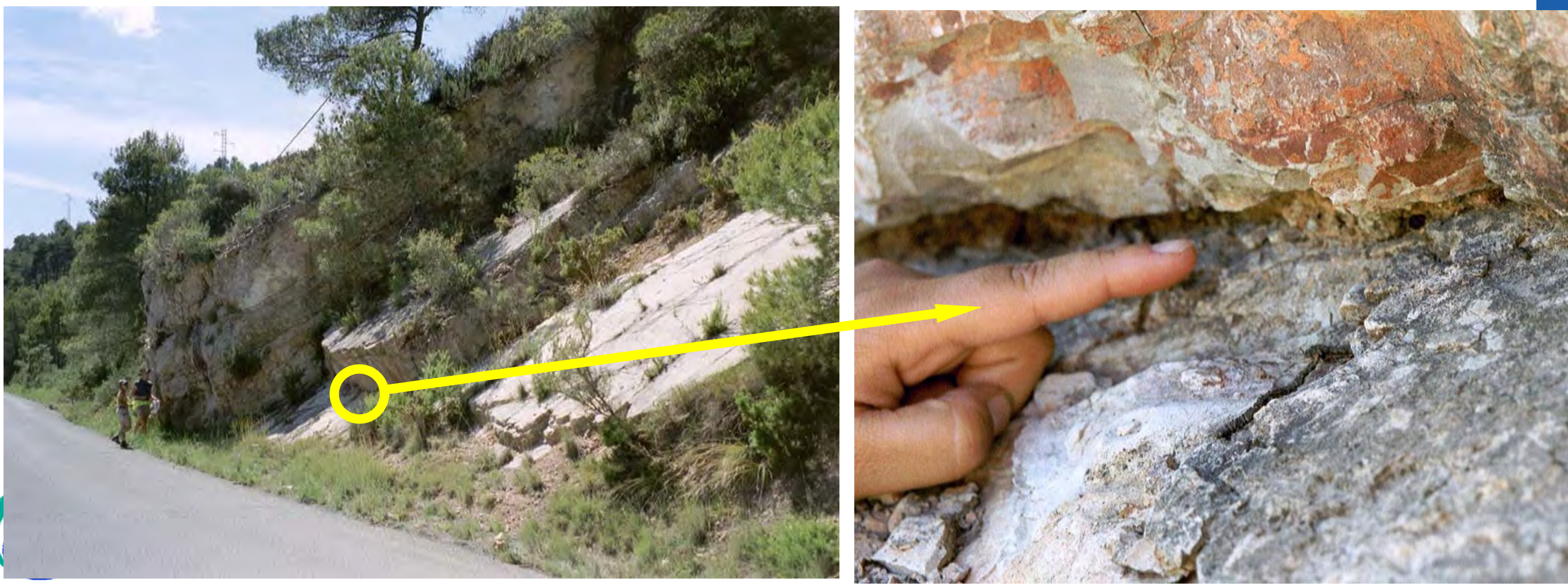
Degradation processes

Main processes involved in degradation:

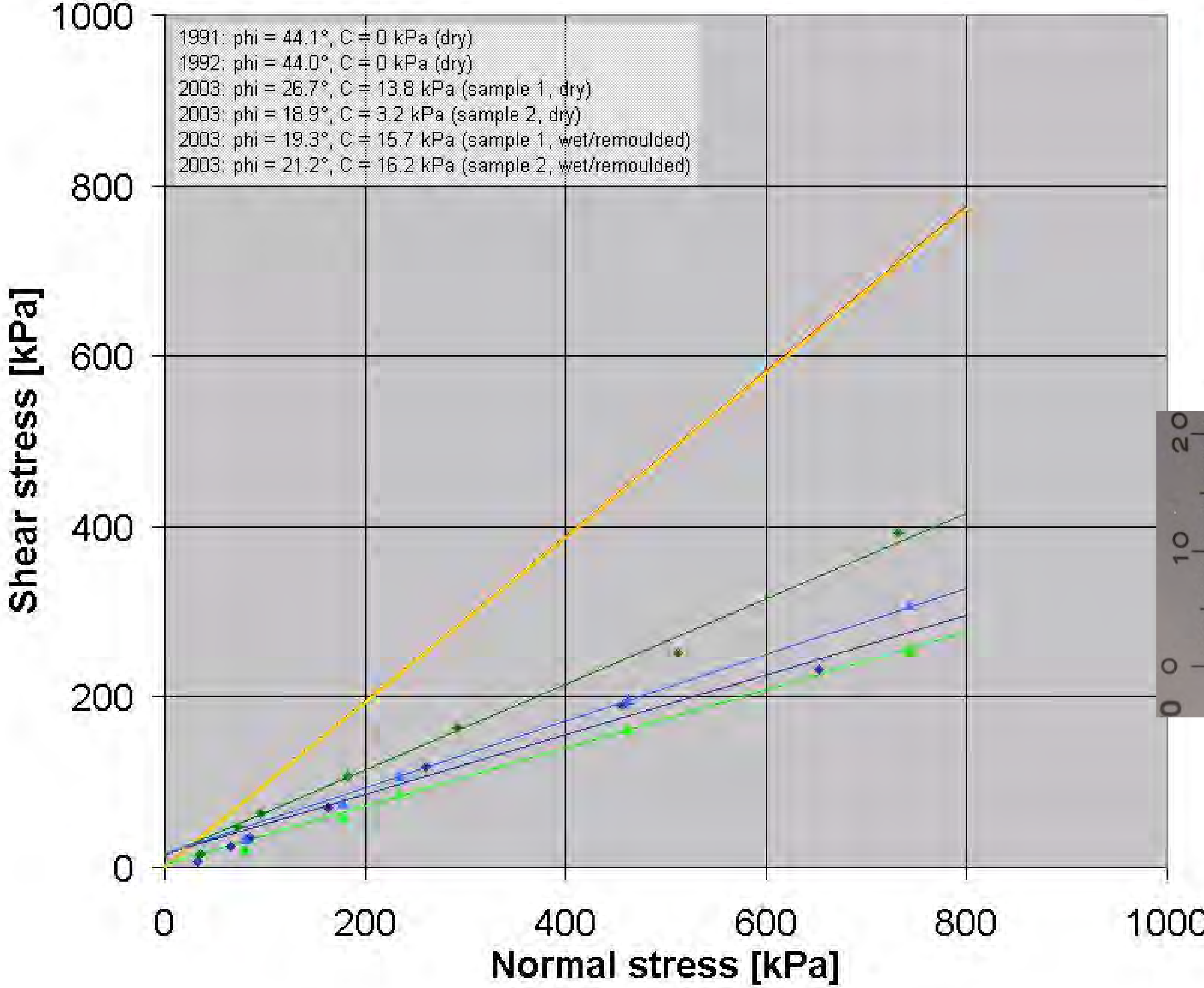
- Loss of structure due to stress release
- **Weathering** (In-situ change by inside or outside influences)
- **Erosion** (Material transport with no chemical or structural changes)

Significance in engineering

- When rock masses degrade in time, slopes and other works that are stable at present may become unstable



Shearbox tests Cindarto slope



Erosion

- Essentially: migration of solid or dissolved material
- Weathering occurs usually before and possibly during erosion
- Transporting agents:
  - Water
  - Gravity
  - Ice
  - Wind
  - Man!

Quantify weathering: SSPC

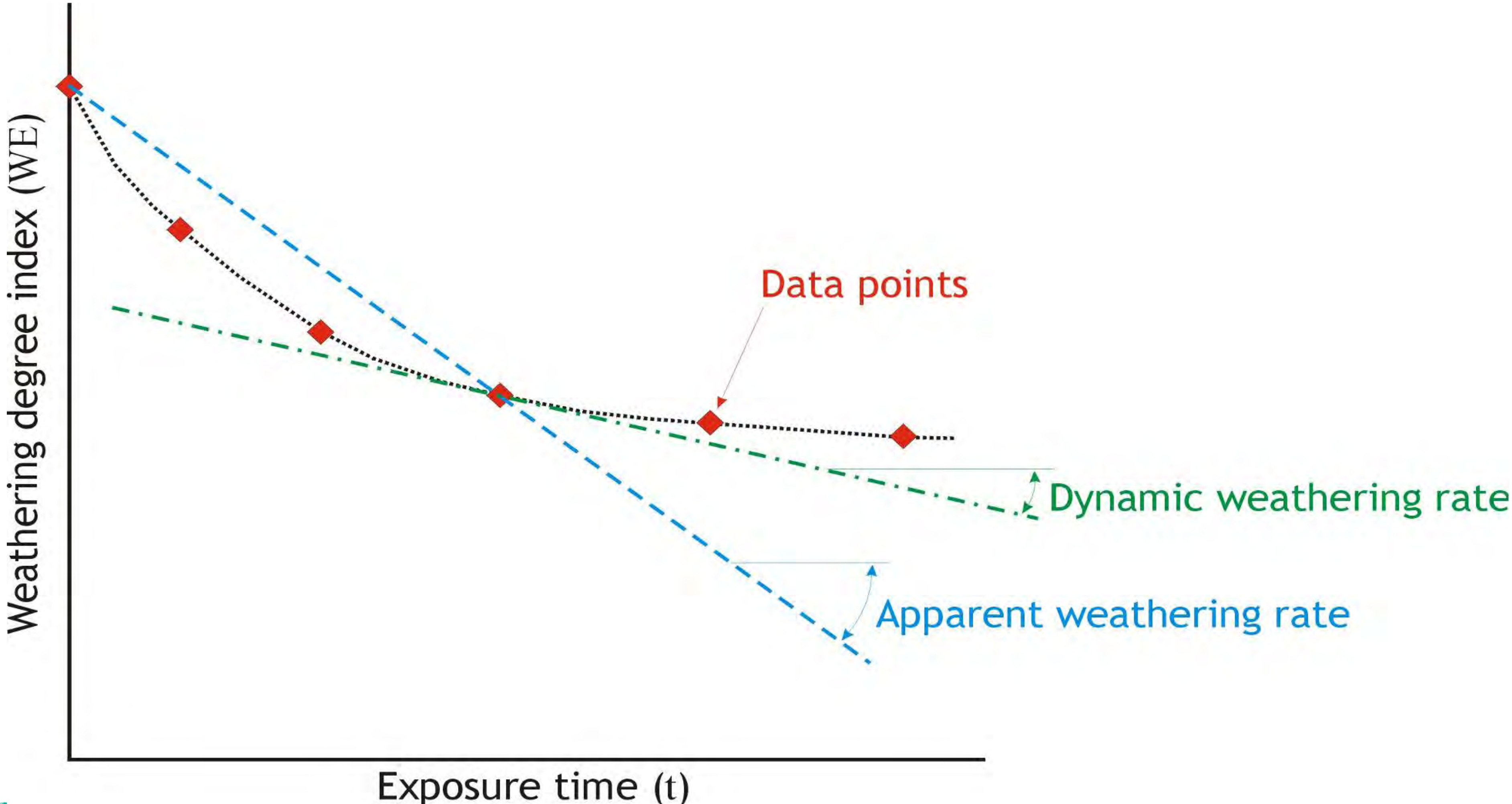
Degree of weathering in slope (BS5930, 1981)	WE [-] (SSPC)
Unweathered	1.00
Slightly weathered	0.95
Moderately weathered	0.90
Highly weathered	0.62
Completely weathered	0.35

ITC

Weathering in time

- The susceptibility to weathering is a concept that is frequently addressed by “the” weathering rate of a rock material or mass.
- Weathering rates may be expected to decrease with time, as the state of the rock mass becomes more and more in equilibrium with its surroundings.

Weathering rates



Weathering rates

$$WE(t) = WE_{init} - R_{WE}^{app} \log(1+t)$$

WE(t) = degree of weathering at time *t*

WE_{init} = *(initial) degree of weathering at time t = 0*

R^{app}_{WE} = *weathering intensity rate*

WE as function of time, initial weathering and the weathering intensity rate

ITC

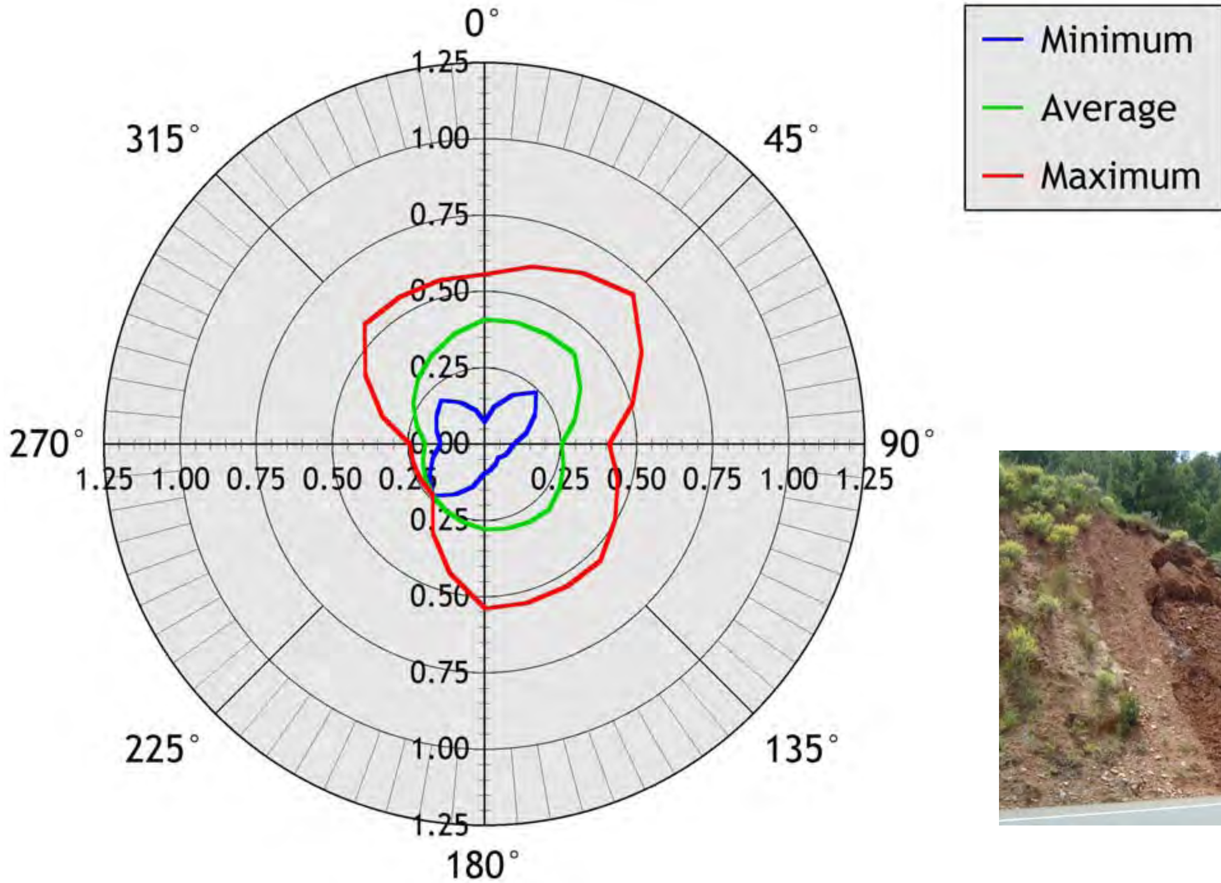
Weathering rates

Weathering rates

- Balance between weathering and erosion (or generally) decay, and exposure orientation dependent features, such as: sunlight, wind, and rain.

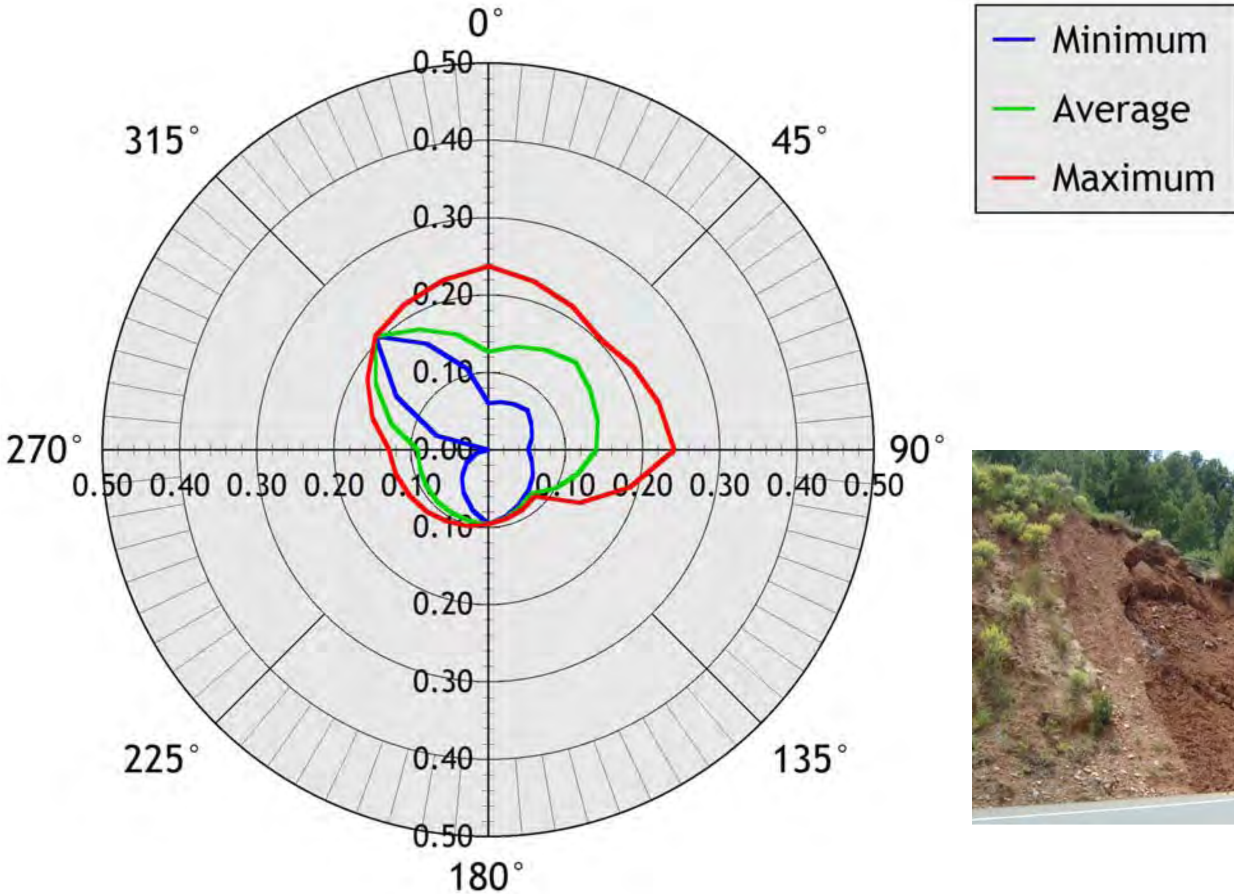
Middle Muschelkalk near Vandellos (Spain)

Weathering intensity rate



Weathering intensity rates *R(appWE)* for Middle Muschelkalk, siltstone, versus slope dip-direction (after Huisman)

Weathering intensity rate



Weathering intensity rates *R(appWE)* for Middle Muschelkalk, gypsum, versus slope dip-direction (after Huisman)

Weathering intensity rate

SSPC system with applying weathering intensity rate:

- original slope cut about 50º (1998)
- in 15 years decrease to 35º

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
- classification systems for earthquake areas
- influence of snow and ice
- submersed marine slopes ?