Recent
SLOPE STABILITY PROBABILITY CLASSIFICATION (SSPC)

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Slope stability

Causes and triggers for in-stability of a slope

What causes in-stability of a slope ?

- Wrong design

  (e.g. too steep, too high)
- Decrease in the future of ground mass properties

  (e.g. weathering, vegetation)
- Changes in future geometry

  (e.g. scouring, erosion, human influence – road cut)

What triggers in-stability of a slope ?

- Earthquakes (extra stress)
- Rainfall (changes the properties)

These are not causes (!) because:

- Should have been anticipated in design, or
- For long standing slopes (e.g. natural slopes): There has been an earthquake or rainfall before and then it did not collapse

What is required to analyse the stability of a slope ?

- ground mass properties
- present and future geometry
- present and future geotechnical behaviour of ground mass
- external influences such as earthquakes, rainfall, etcetera

ground mass properties

In virtually all slopes is a considerable variation

Therefore:
First divide the soil or rock mass in:

homogene “geotechnical units”

Homogene geotechnical unit?
Is that possible ?

Variation

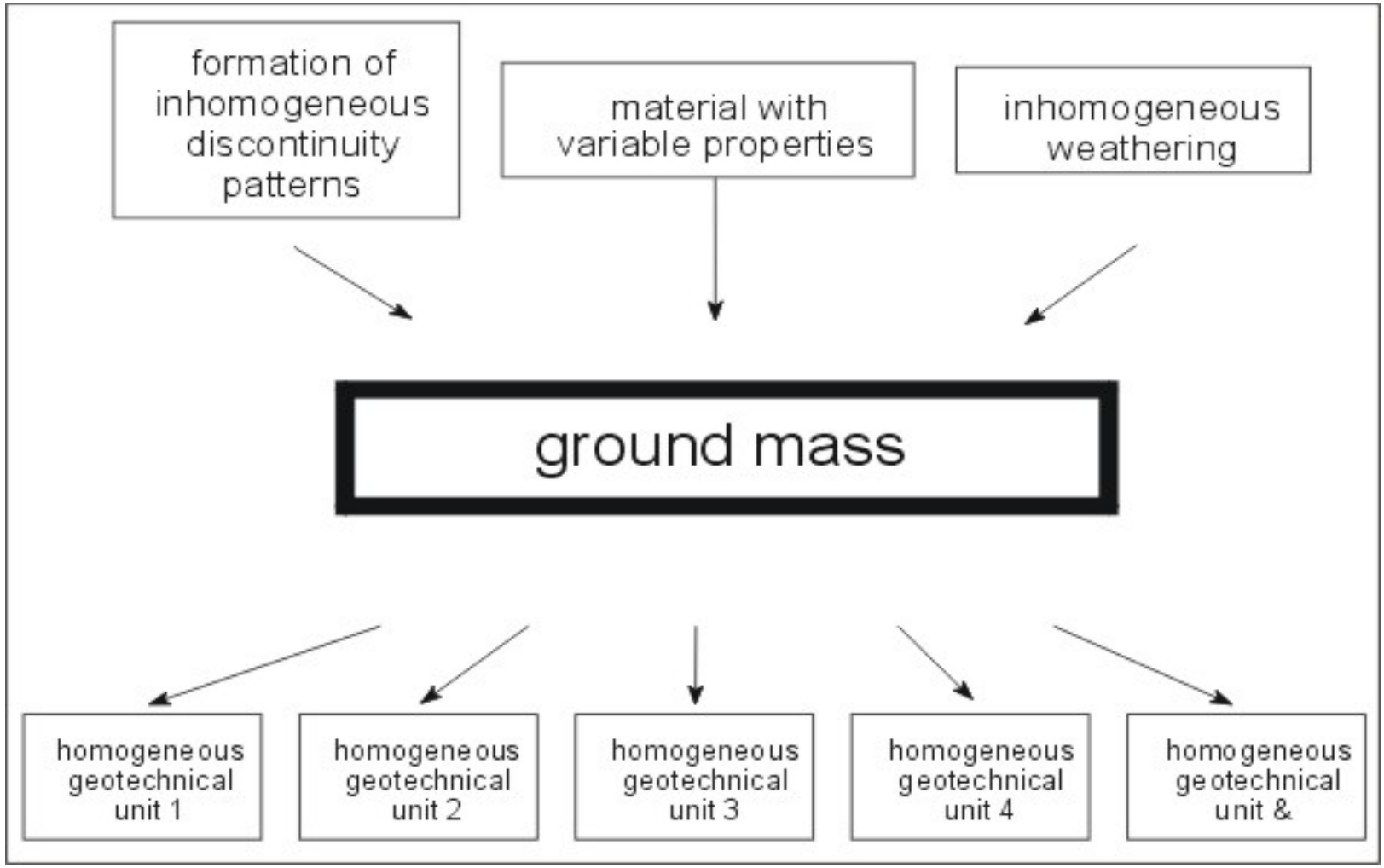
Heterogeneity of mass causes:

- variation in mass properties

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:

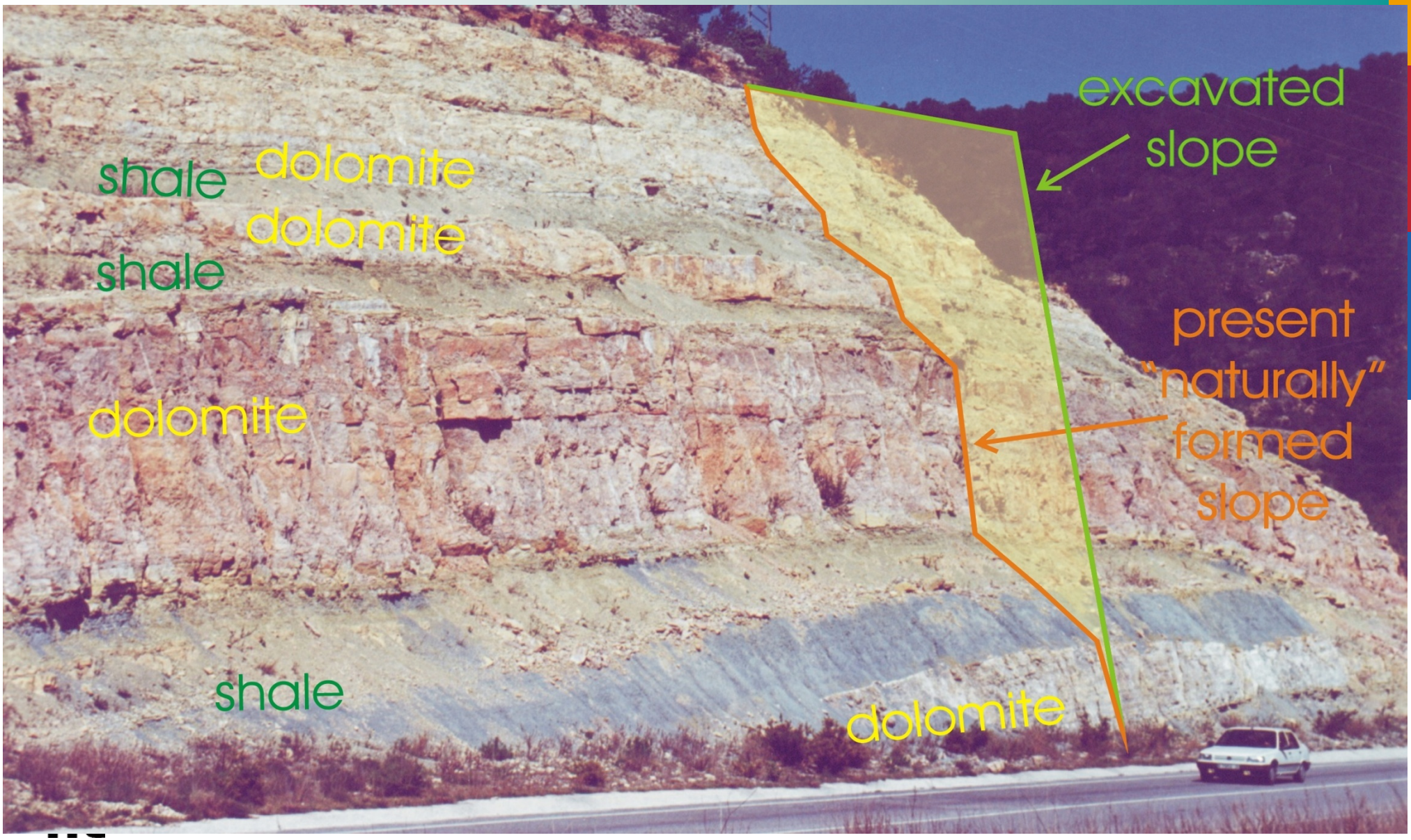
- the variations allowed within a geotechnical unit for a slope along a major highway is smaller
- the variations allowed within a geotechnical unit for a slope along a farmers road will be larger

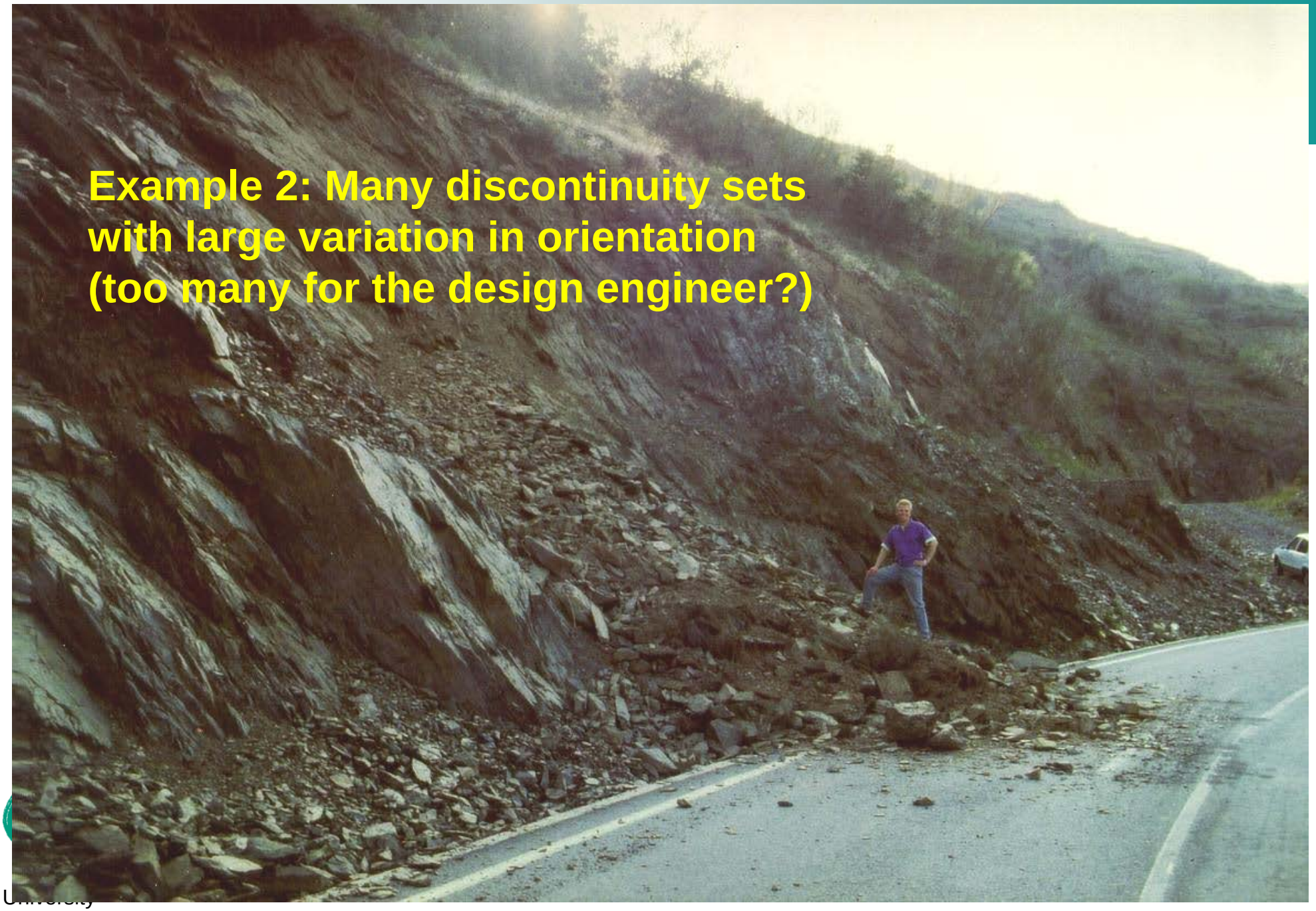
Examples

What are the implications if the units are wrongly assumed in a design?

Original situation

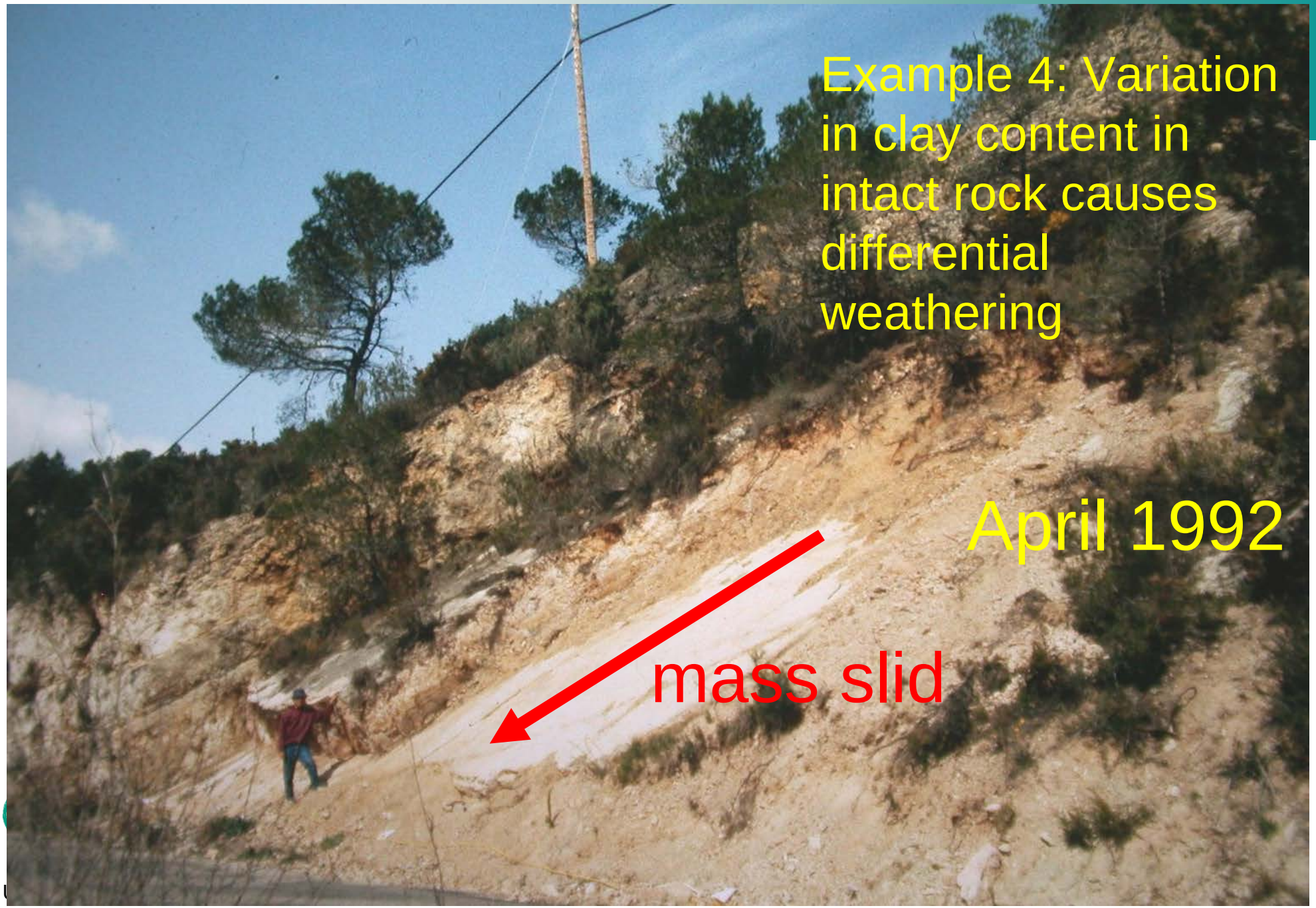
design error



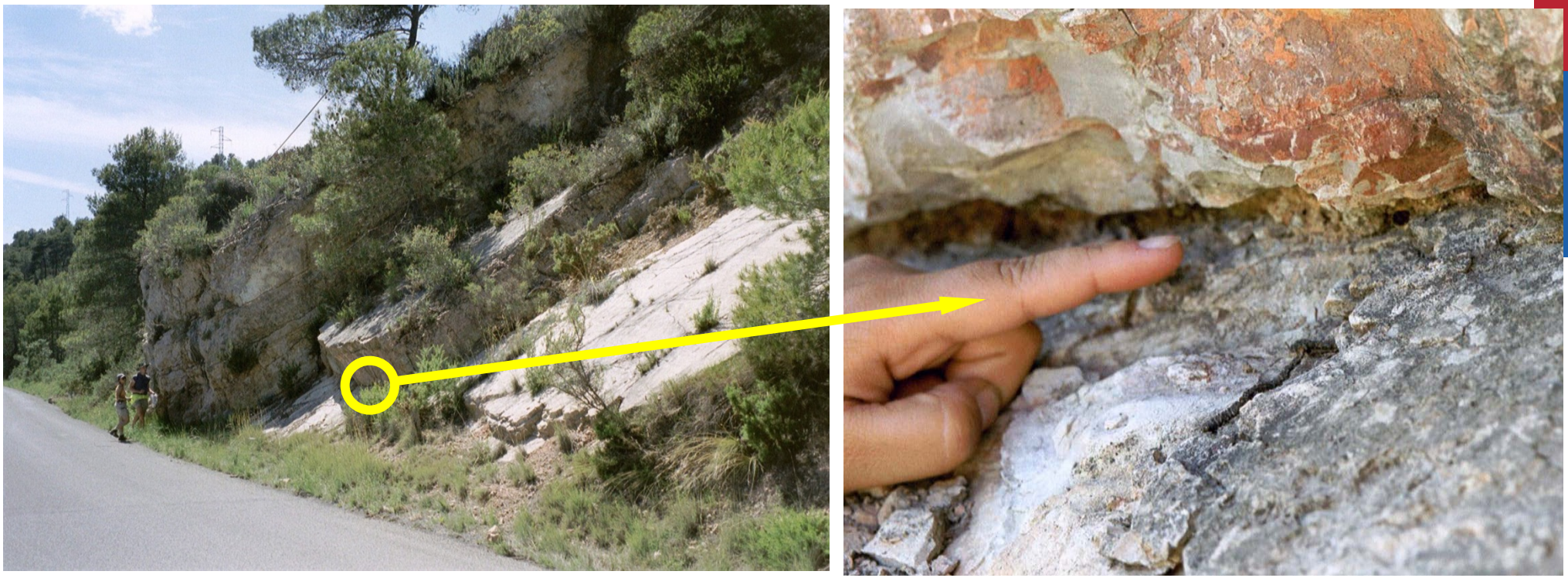

Example 2: Many discontinuity sets
with large variation in orientation
(too many for the design engineer?)

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

Example 4: Variation in clay content in intact rock causes differential weathering



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)
- Magnitude of external influences such as earthquakes, rainfall, etc. not certain

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 & 3DEC)

Analysing slope stability(2)

Extra work for deterministic numerical methods is justified if:

Quantity and quality of input data is high

E.g.:

- representative tests of discontinuity (i.e. joint) shear strength of each discontinuity family

- orientations of each discontinuity

- etcetera, etcetera.

Analysing slope stability(3)

High quality and quantity of data not only of the rock mass at the slope face but also in the slope!

Hence:

excavate the side and rebuilt (then it is exactly known)

or

many large-sized borehole samples required

Analysing slope stability(4)

High quality and quantity of data of rock mass inside the slope rock mass are virtually never available because far too expensive to obtain

Analysing slope stability(5)

Solution often used:

Use a numerical program and estimate the input parameters

Analysing slope stability(6)

How can properties be estimated:

rock mass classification

Slope 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. slope, tunnel

Classification systems:

For underground (tunnel):

- Bieniawski (RMR)
- Barton (Q)
- Laubscher (MRMR)
- etcetera

For slopes:

- Selby
- Bieniawski (RMR)
- Vecchia
- Robertson (RMR)
- Romana (SMR)
- Haines
- SSPC
- etcetera

Development of many 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 parameters from underground (read “tunnel”) systems

Development of many 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

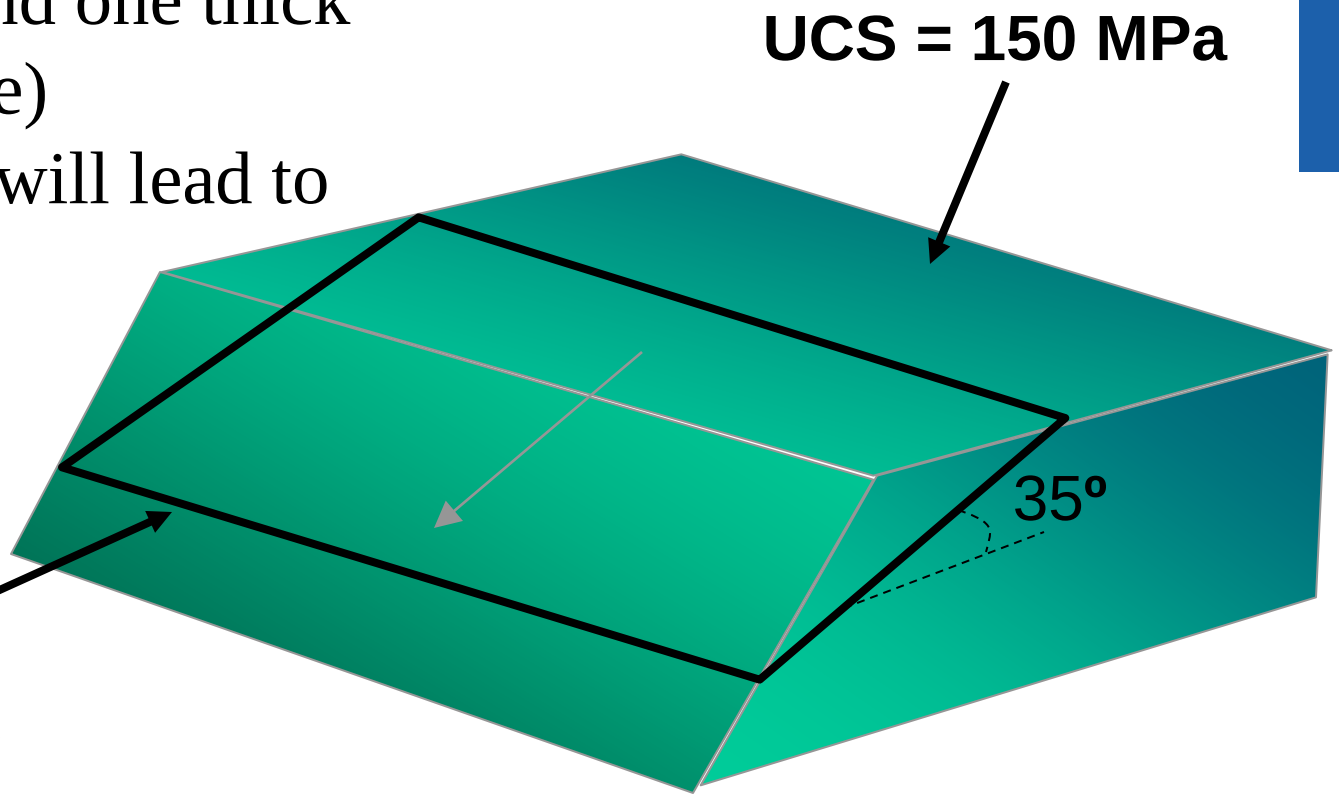
Many rock mass classification systems

- Wide variation in rating systems, methodologies, parameters, calculation methods, boundaries, 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

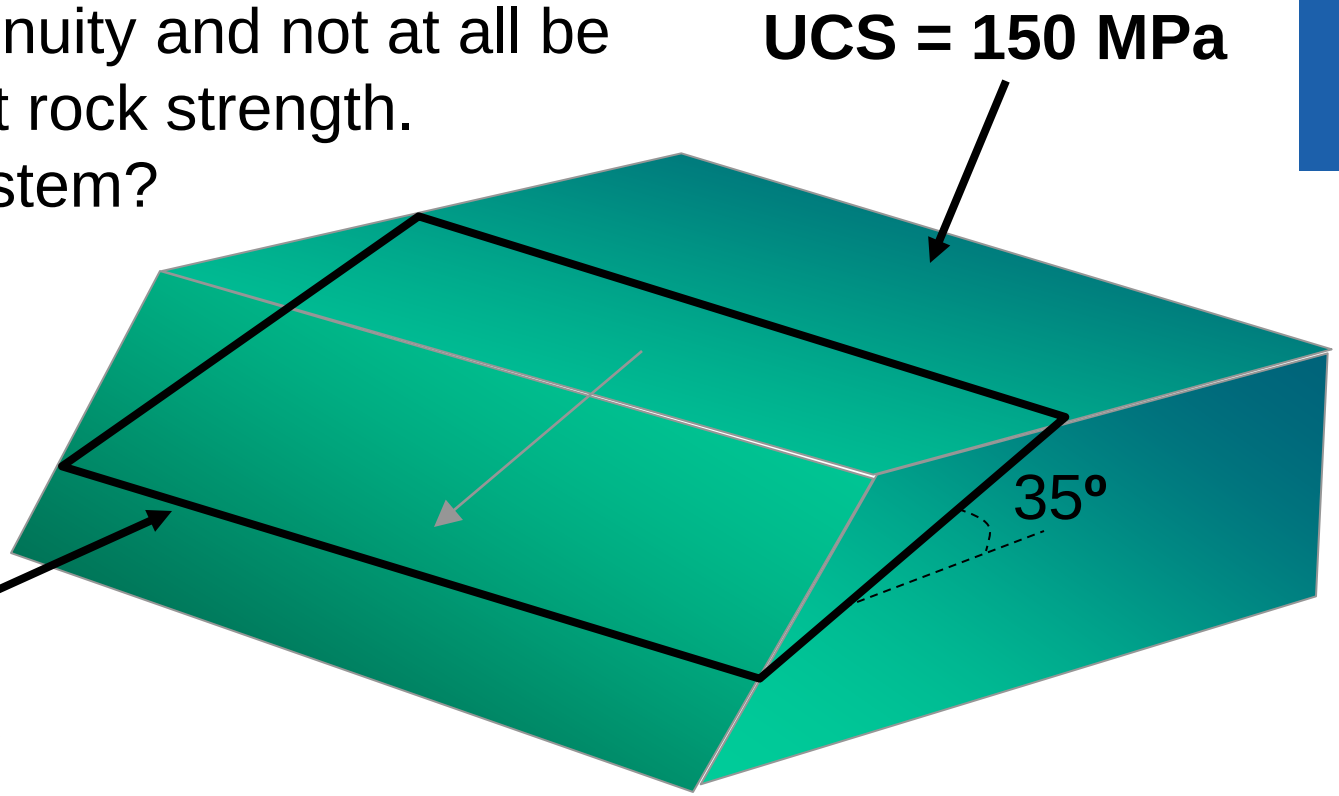
For example:

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?



No clear differentiation between "as is" and "as will be"

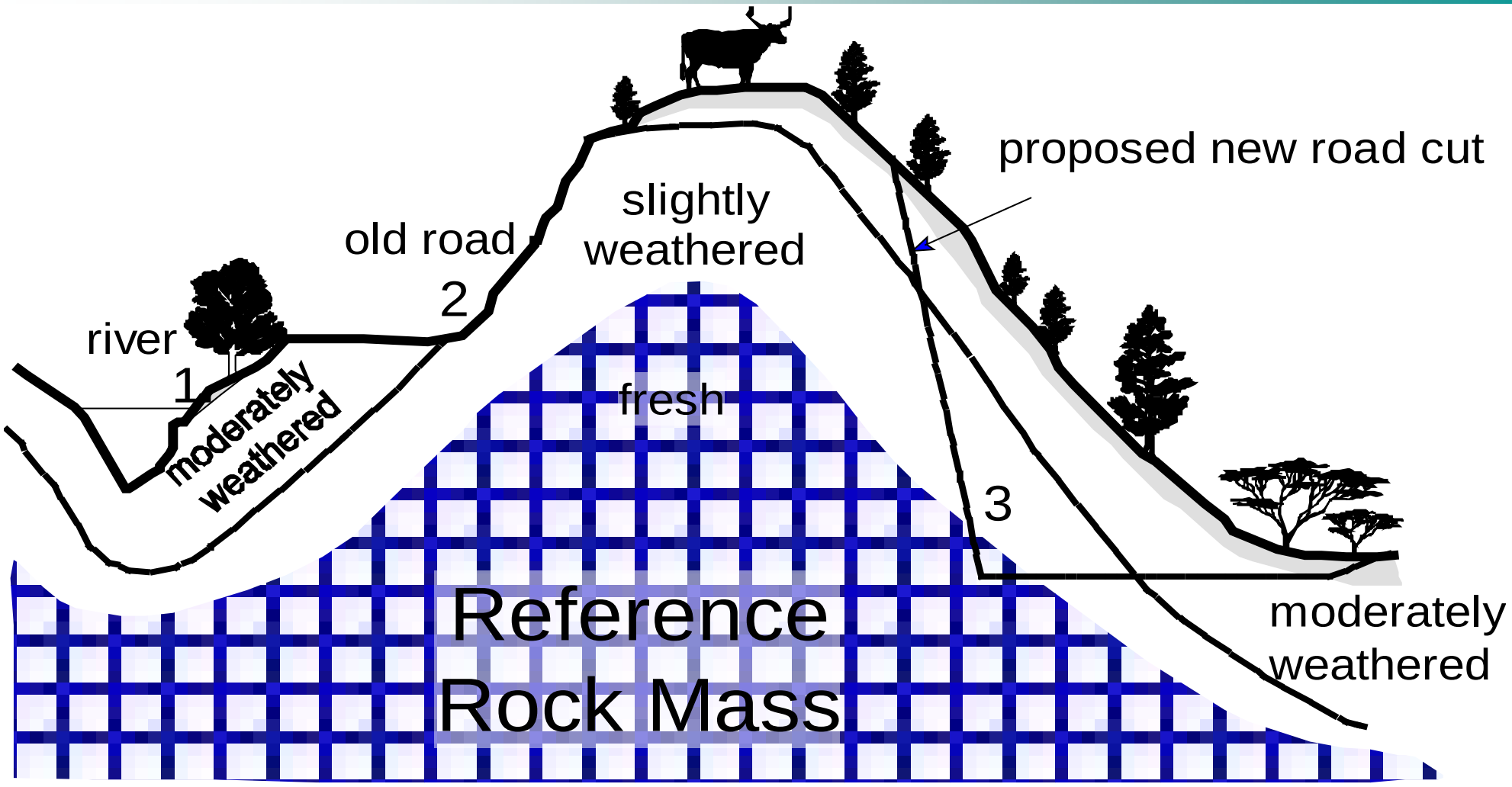
External influences as weathering and method of excavation will have influenced the site characterized but will also (and likely differently) influence the new slope in the future

Slope Stability probability Classification (SSPC)

SSPC

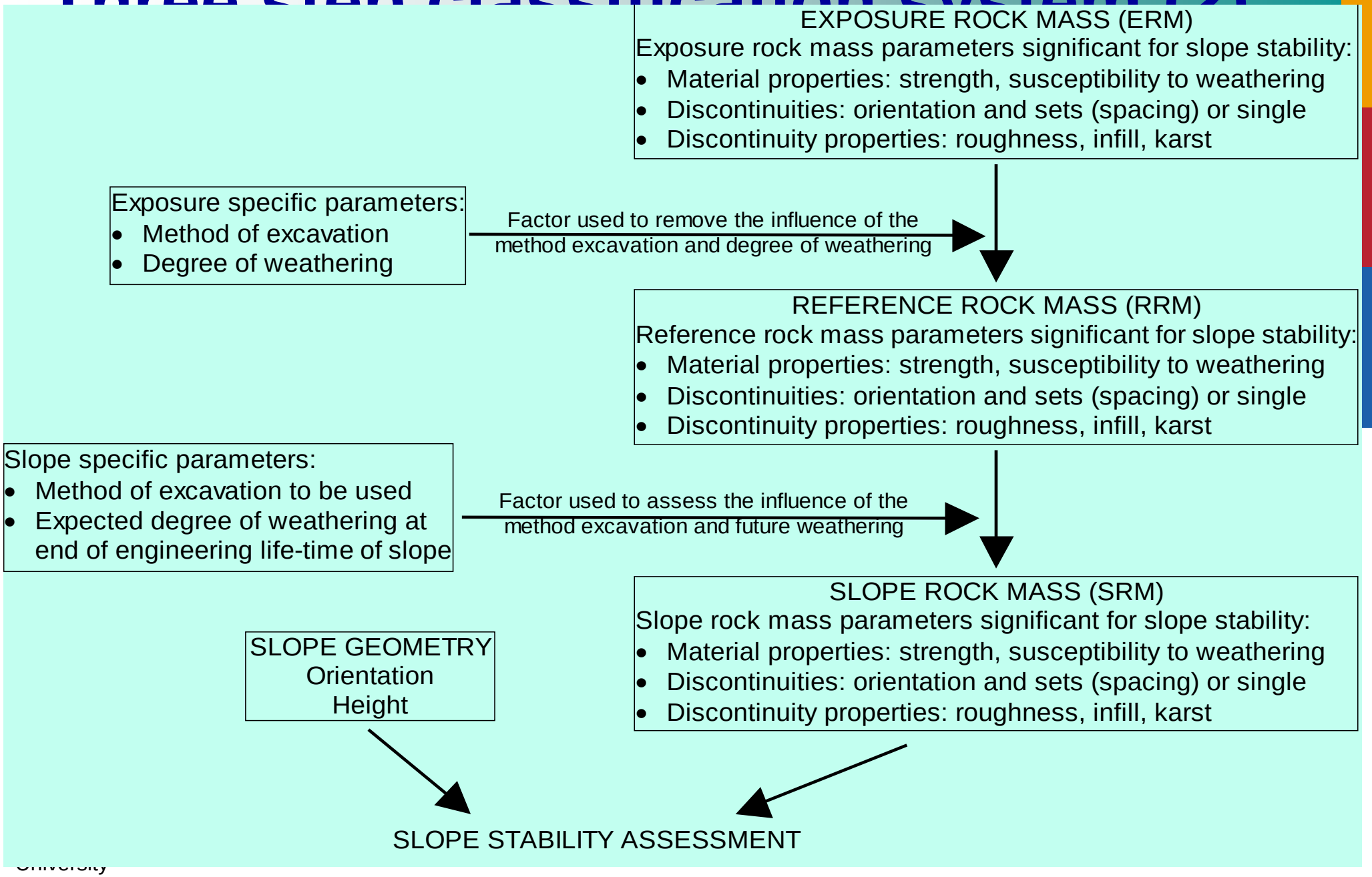
- three step classification system
- based on probabilities
- independent failure mechanism assessment

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 modern blasting, moderately weathered to fresh.

Three step classification system (2)



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

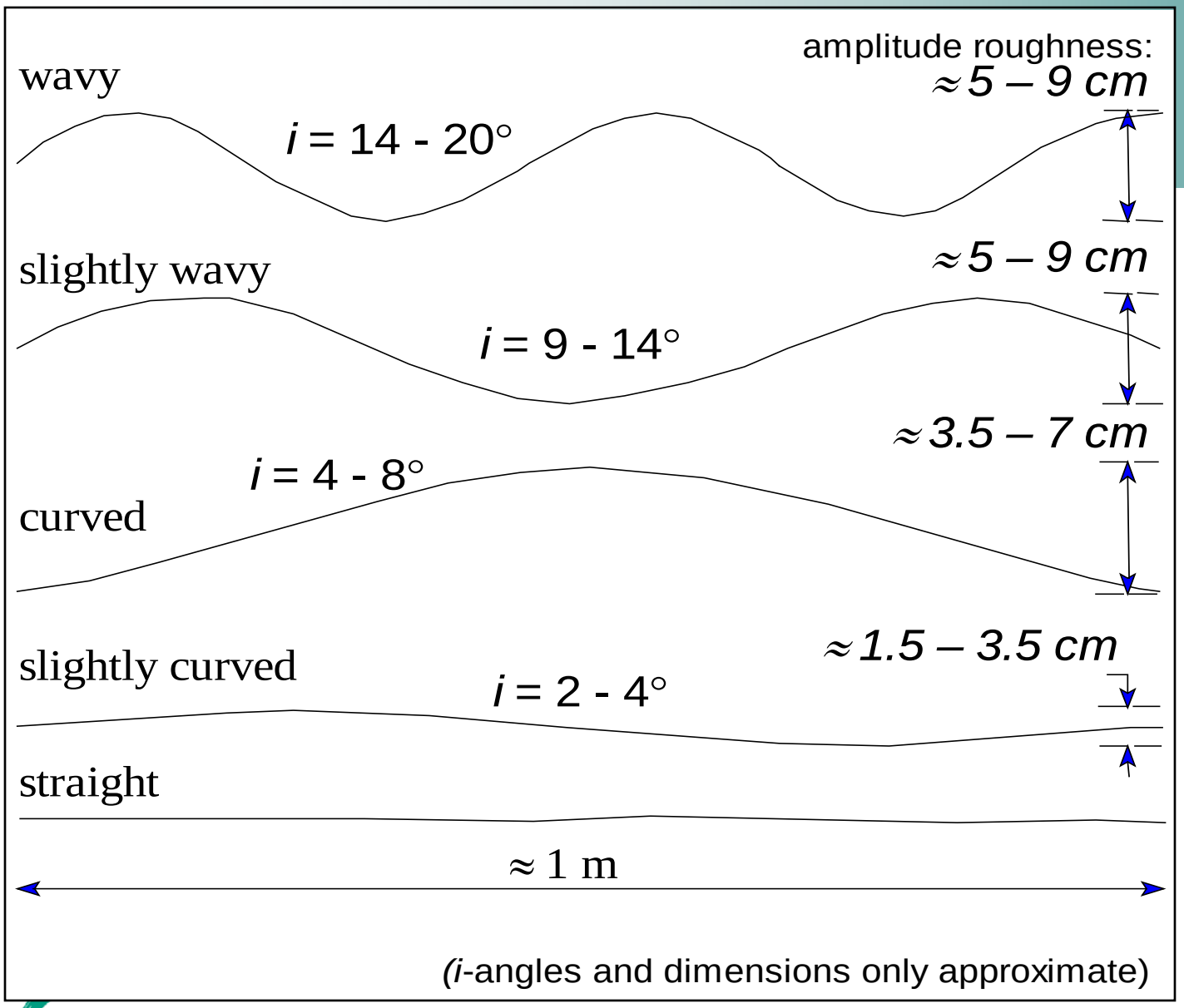
By simple means test:

hammer blows, crushing by hand, etcetera

Spacing and persistence of discontinuities

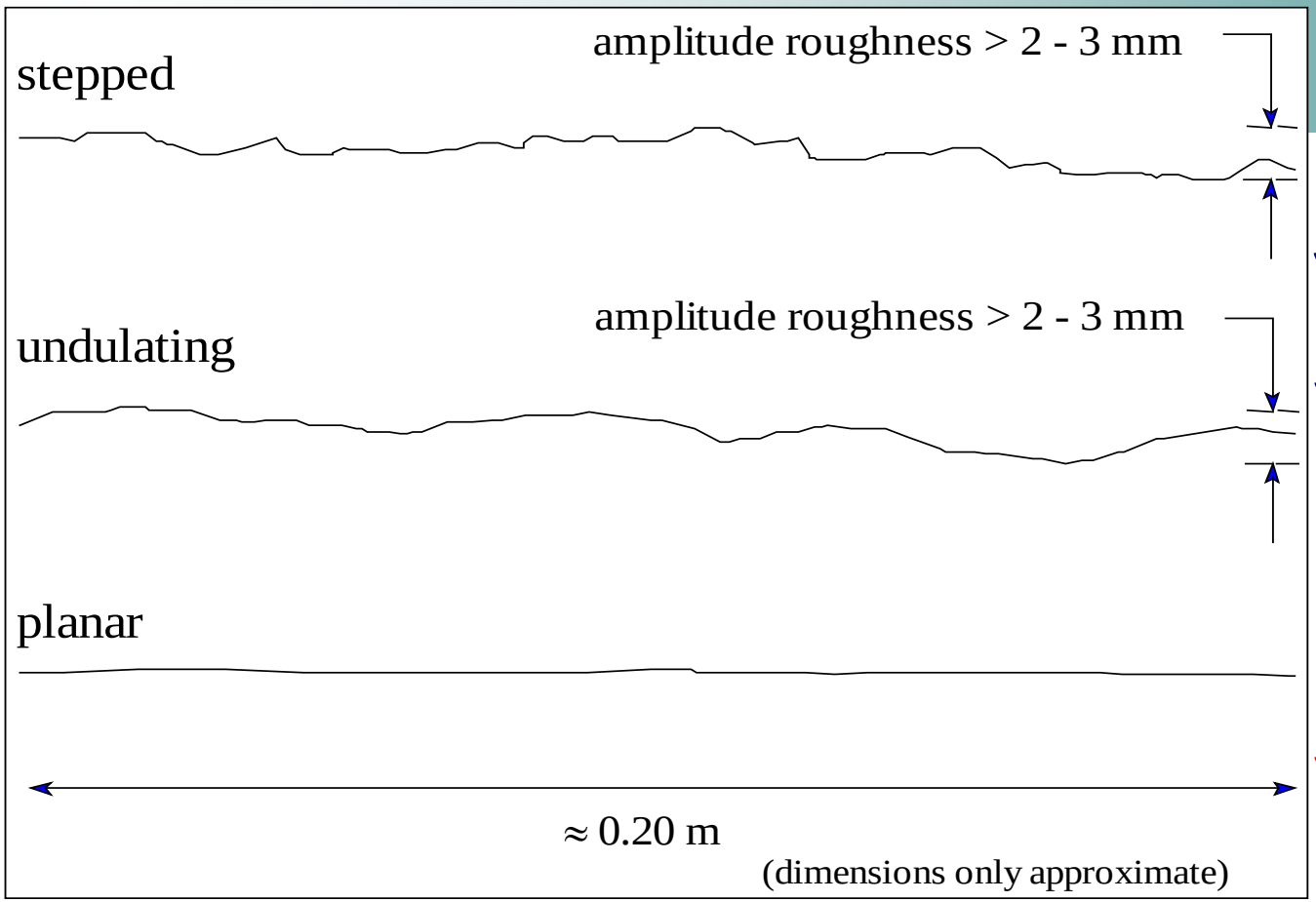
Determine block size and block form by:

- visual assessment, followed by:
- quantification (measurement) of the characteristic spacing and orientation of each set



Shear strength

roughness large scale



Shear strength

roughness

small scale

Three classes:

- rough
- smooth
- polished

Shear strength

roughness

tactile

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

Options: karst or no karst

Shear strength - condition factor

Discontinuity condition factor (*TC*) is a multiplication of the ratings for:

- small-scale roughness
- large-scale roughness
- infill
- karst

Orientation dependent stability

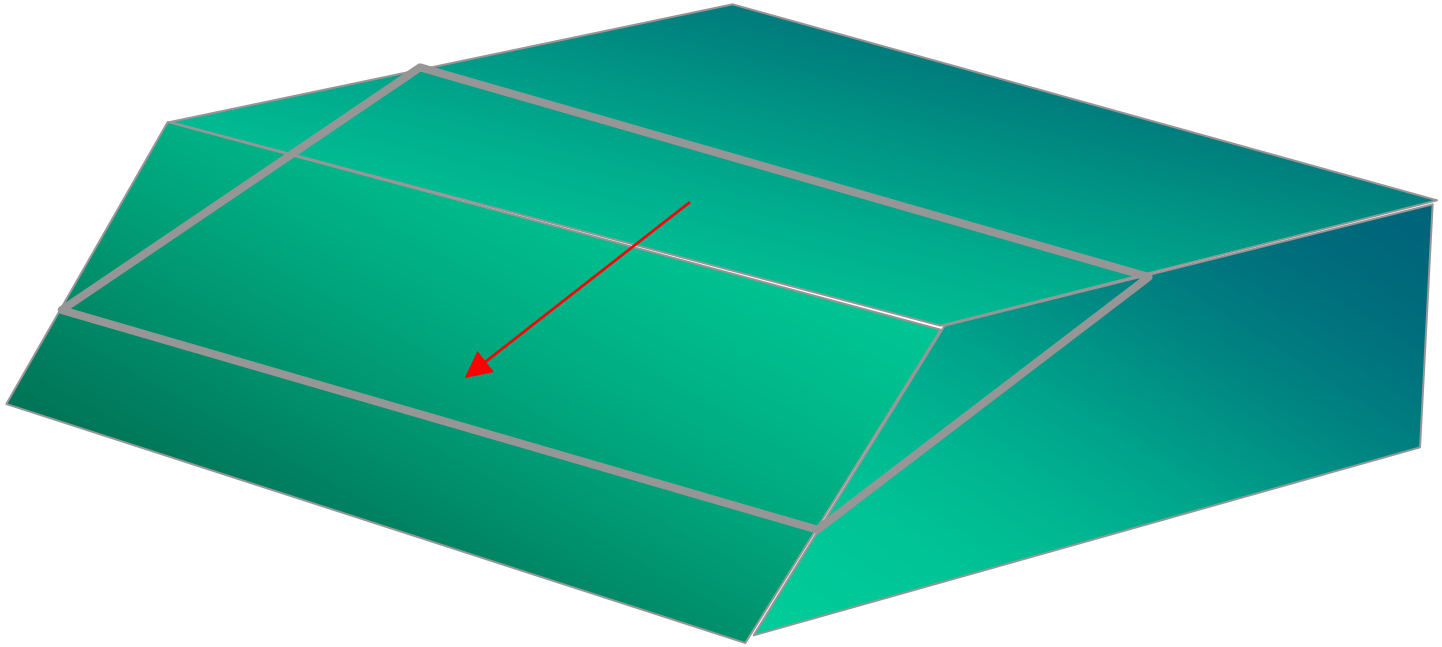
Stability depending on relation between slope and discontinuity orientation

For example:

- Plane and wedge sliding
- Toppling

Orientation dependent stability

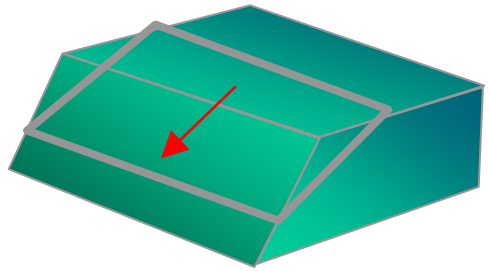
Discontinuity related shear strength failure
Plane sliding(1)



Orientation dependent stability

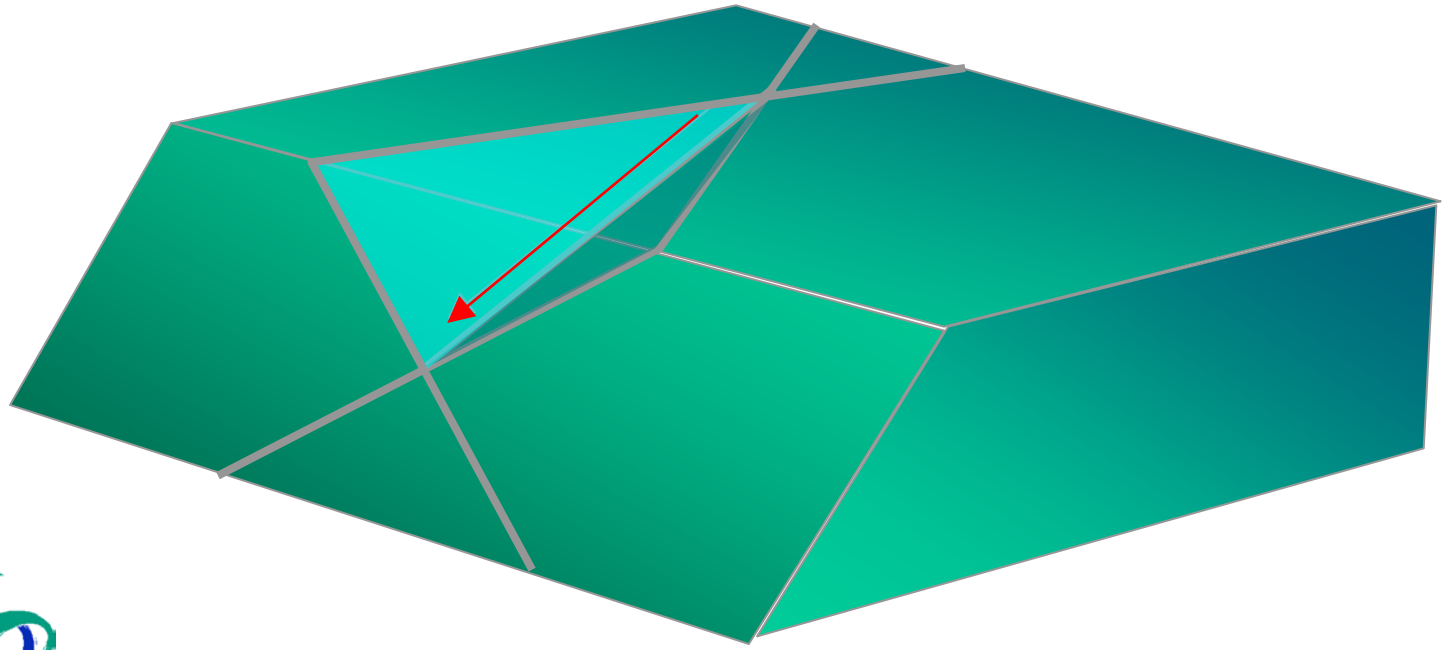
Discontinuity related shear strength failure
Plane sliding(2)

Conditions:
- discontinuity must daylight
- downward stress > shear strength along discontinuity plane



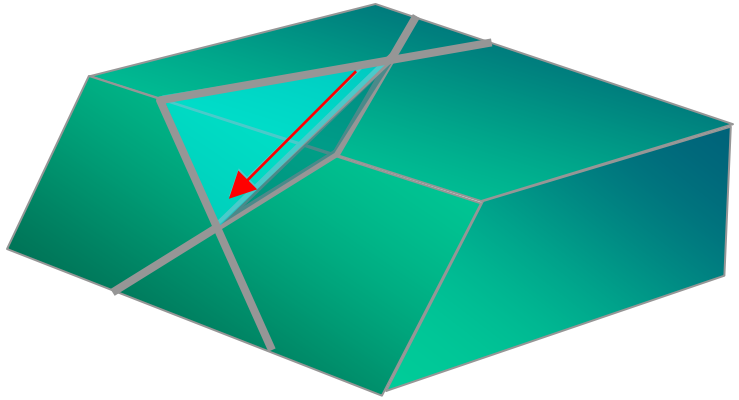
Orientation dependent stability

Discontinuity related shear strength failure
Wedge sliding



Orientation dependent stability

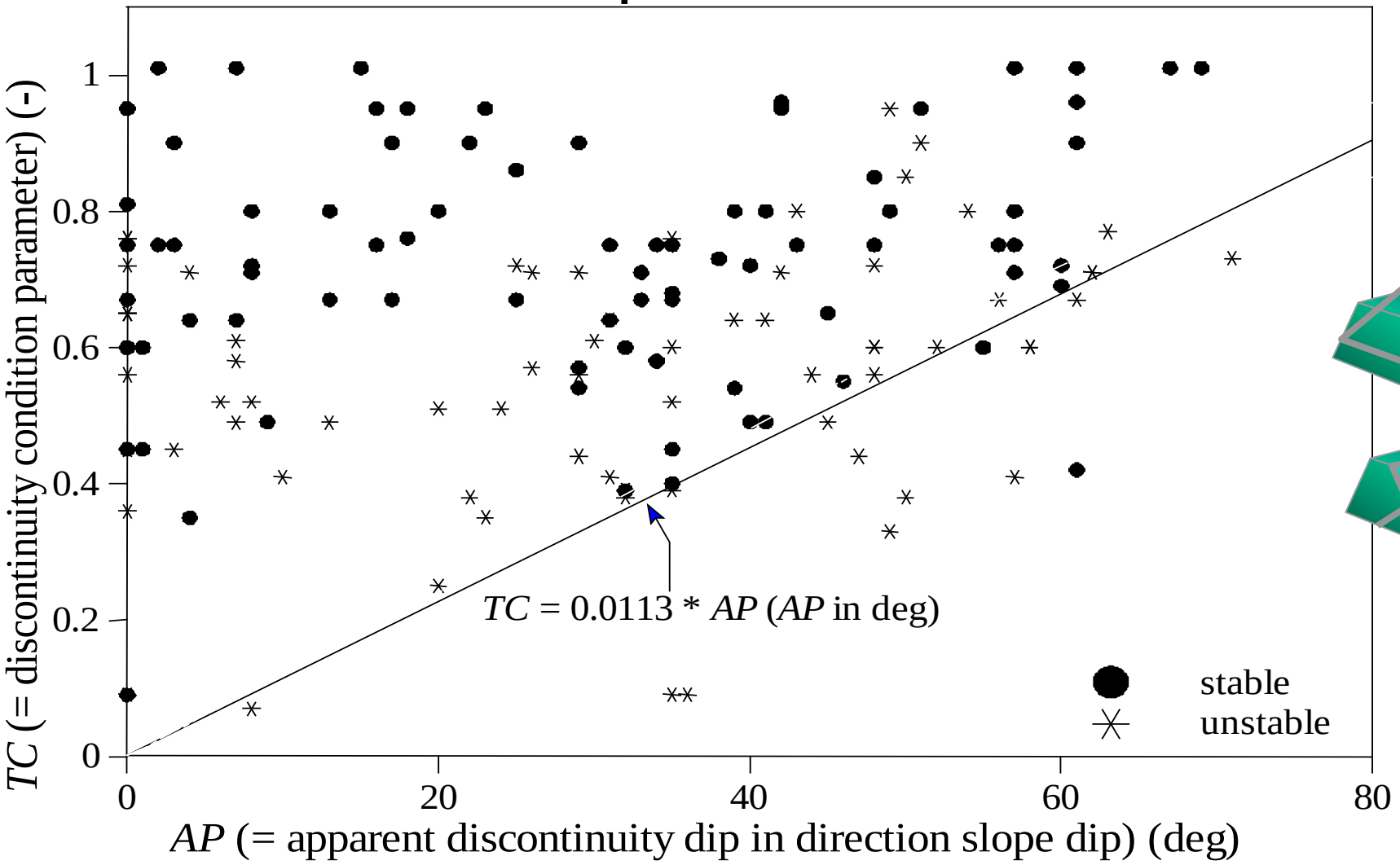
Discontinuity related shear strength failure
Wedge sliding

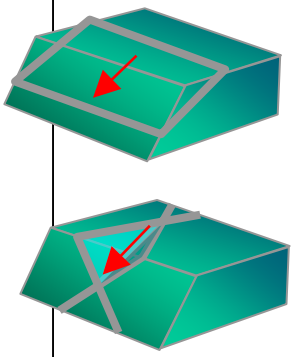


Conditions:
- intersection line must daylight
- downward stress > shear strength along discontinuity planes

Orientation dependent stability

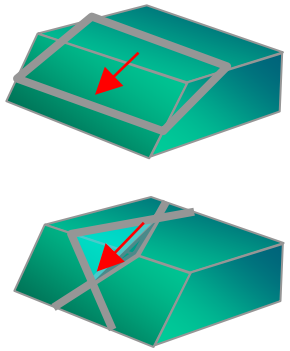
How was it developed





Orientation dependent stability

Sliding criterion

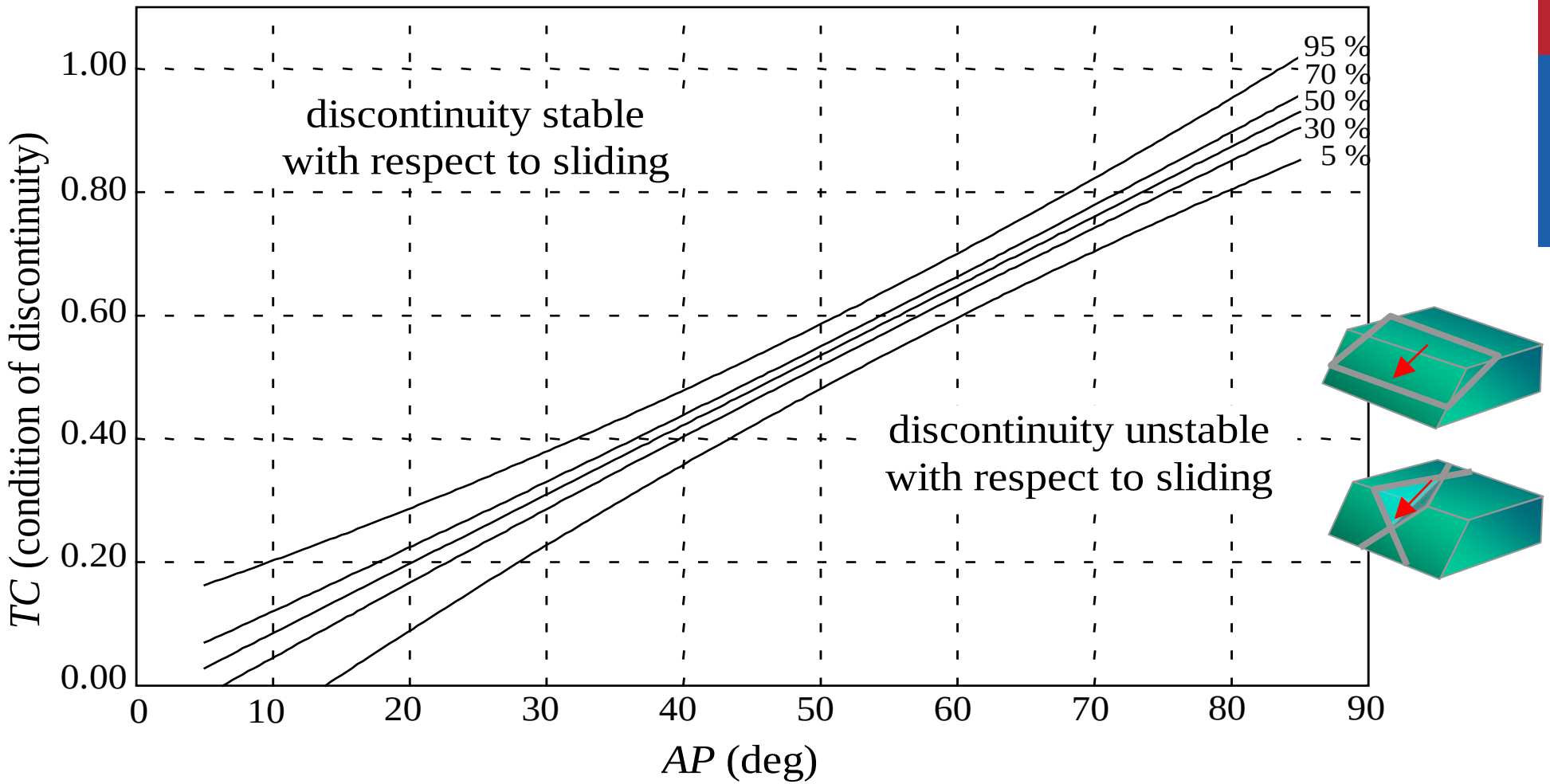


sliding occurs if :

$$TC < 0.0113 * AP$$

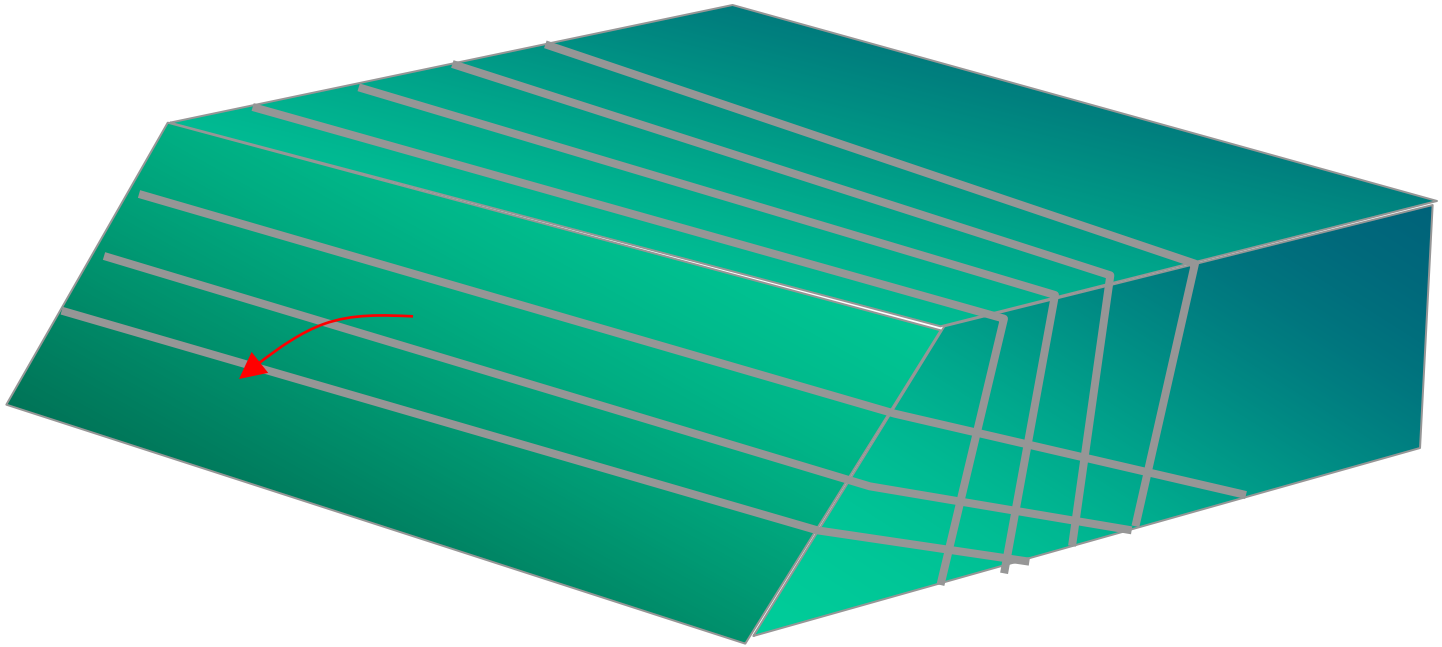
Orientation dependent stability

Sliding probability



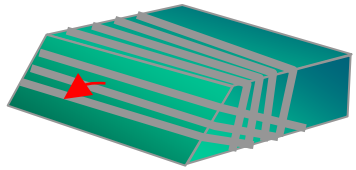
Orientation dependent stability

Discontinuity related shear strength failure
Toppling



Orientation dependent stability

Toppling criterion



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

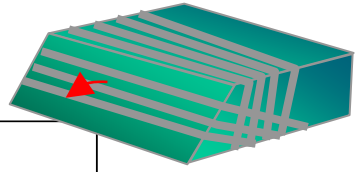
TC = discontinuity condition factor

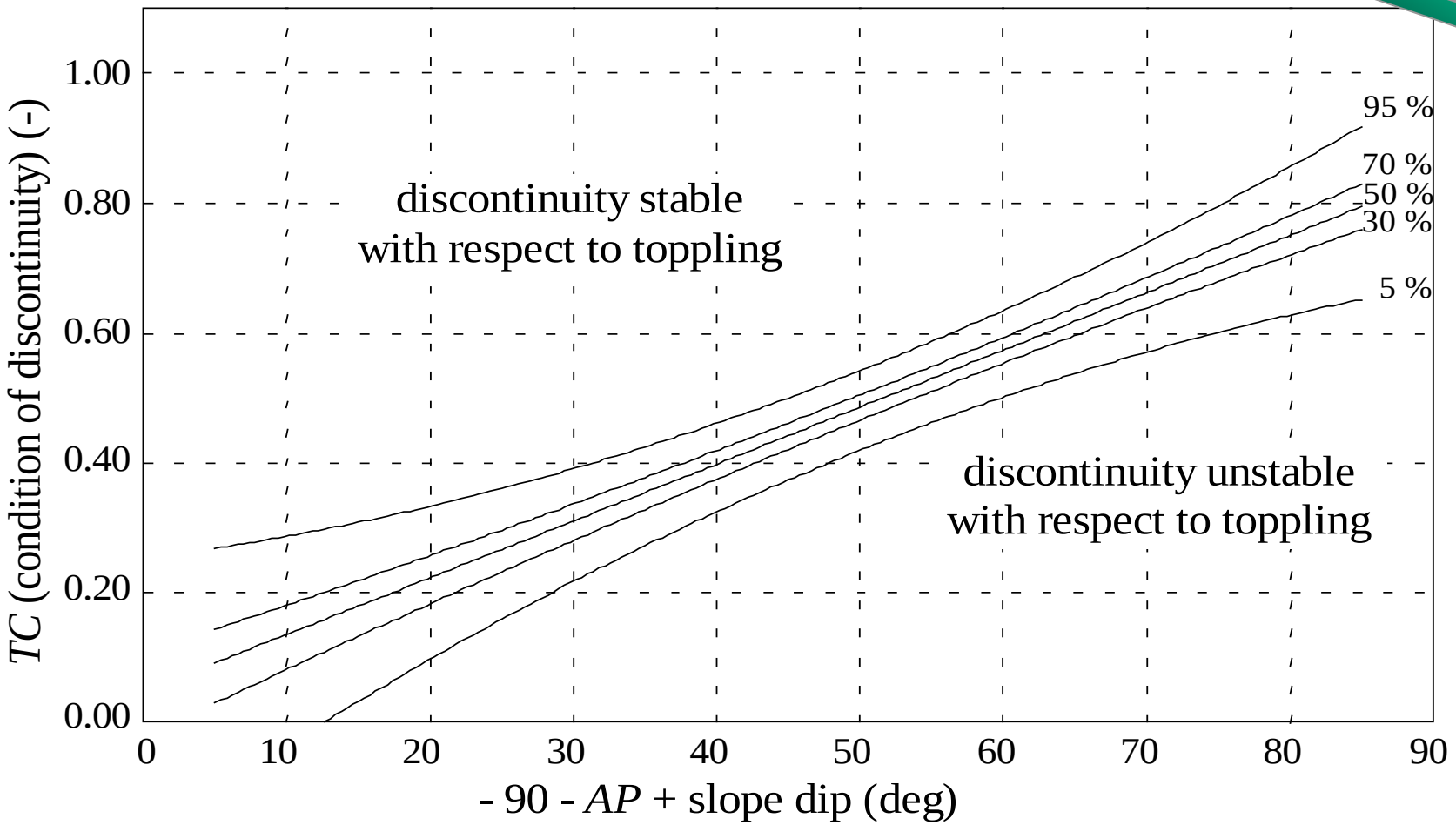
AP = apparent discontinuity dip in direction of slope dip

$DIP_{discontinuity}$ = dip of discontinuity

Orientation dependent stability

Toppling probability





Orientation independent stability

Orientation independent stability

Slope instability not dependent on the orientation of discontinuities in relation with the slope orientation

E.g. in situations:

- No discontinuities
- Too high stress for the soil or rock intact material strength (e.g. slope too high)
- So many discontinuities in so many directions that there is always a failure plane (comparable to a soil mass)

Orientation independent stability

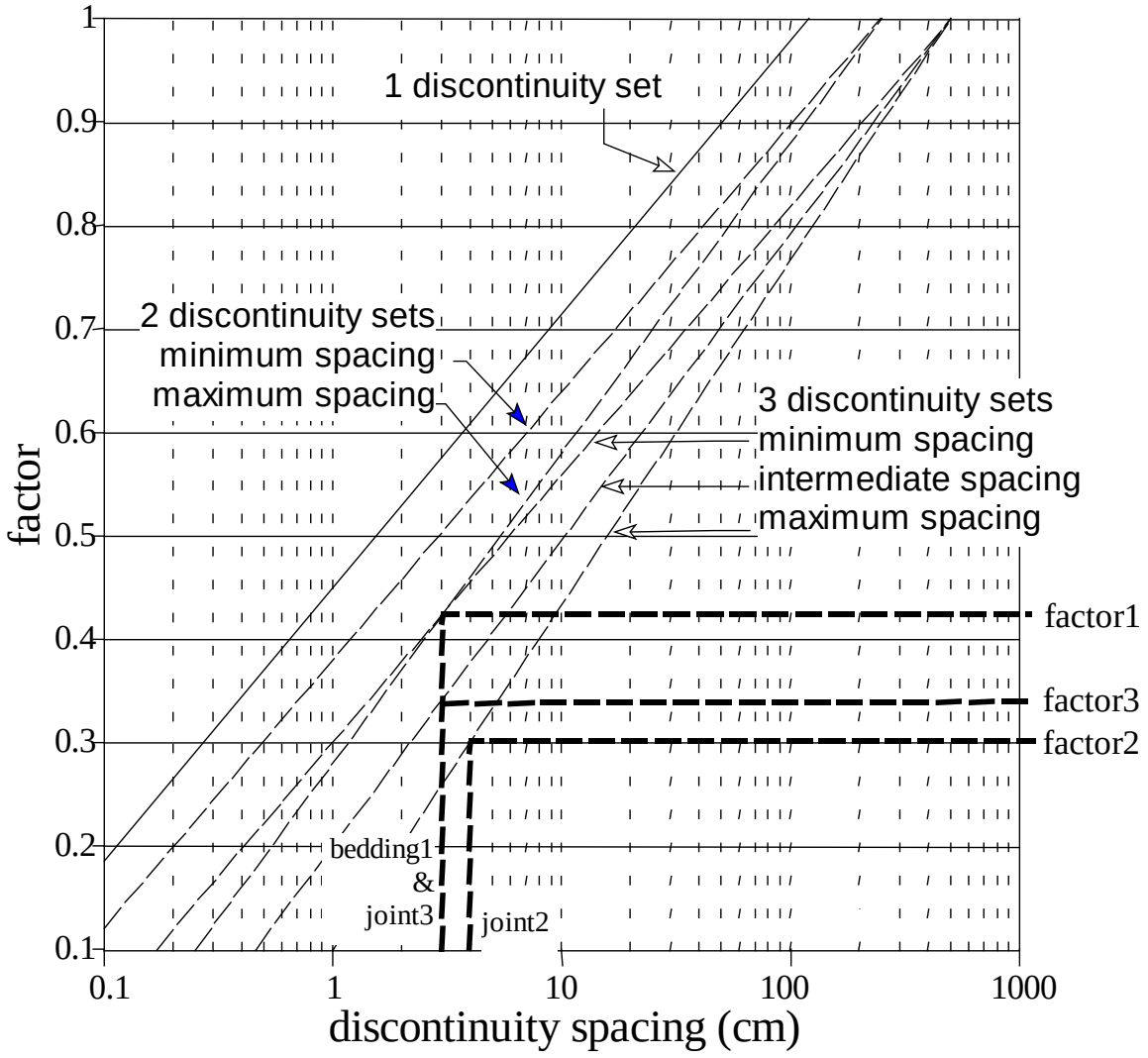
In SSPC based on:

- Intact rock strength
- Block size and form
- Condition of discontinuities

Orientation independent stability

Overall spacing of discontinuity sets

Block size and form relations from Taylor



Orientation independent stability

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 discontinuity sets 1, 2, 3

Orientation independent stability

Shear plane failure following Mohr-Coulomb for rock mass

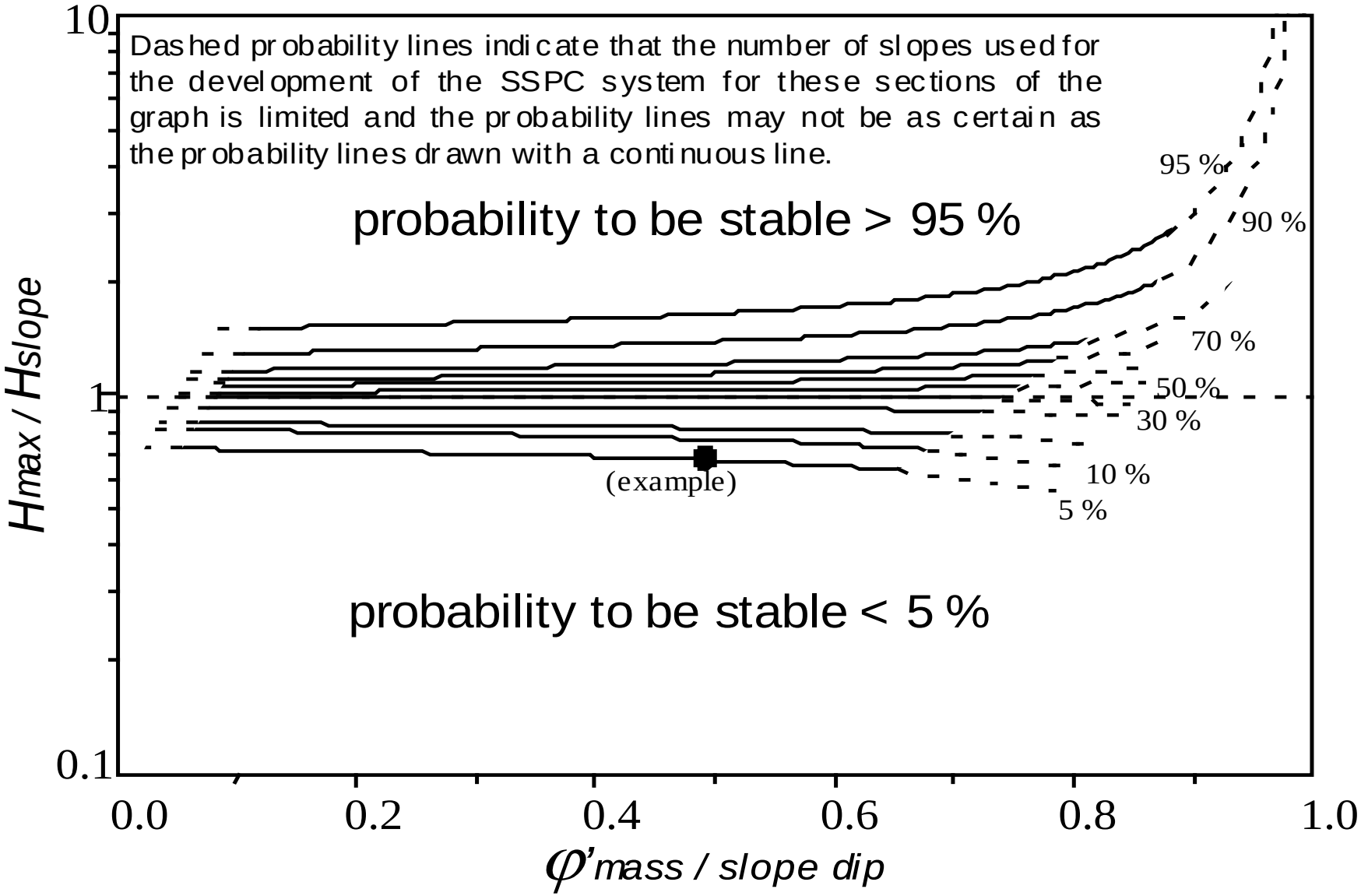
$$\text{If the } dip_{slope} \leq \varphi'_{mass}:$$

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

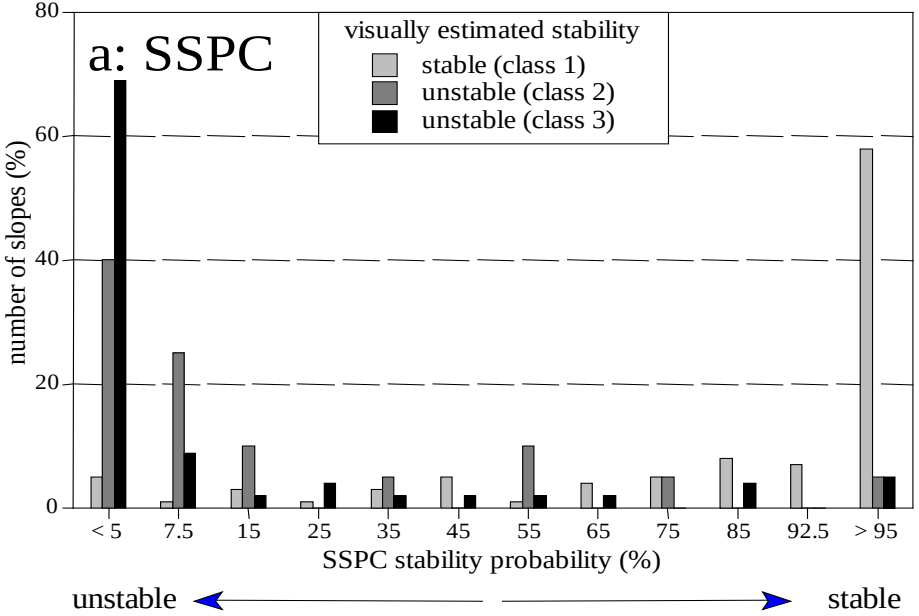
$$\text{else}$$

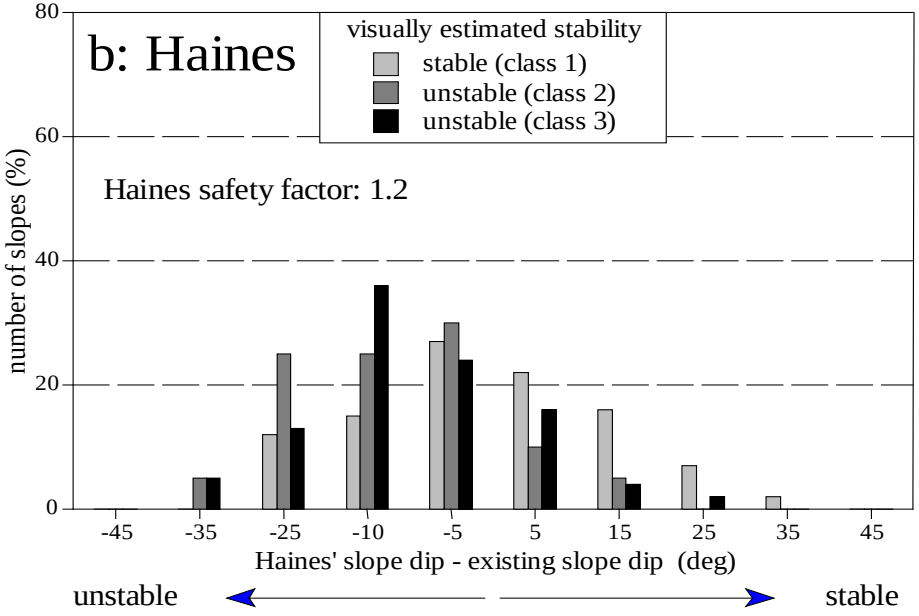
$$H_{max} = 1.6 * 10^{-4} * coh'_{mass} * \frac{\sin\left(dip_{slope}\right) * \cos\left(\varphi'_{mass}\right)}{1 - \cos\left(dip_{slope} - \varphi'_{mass}\right)}$$

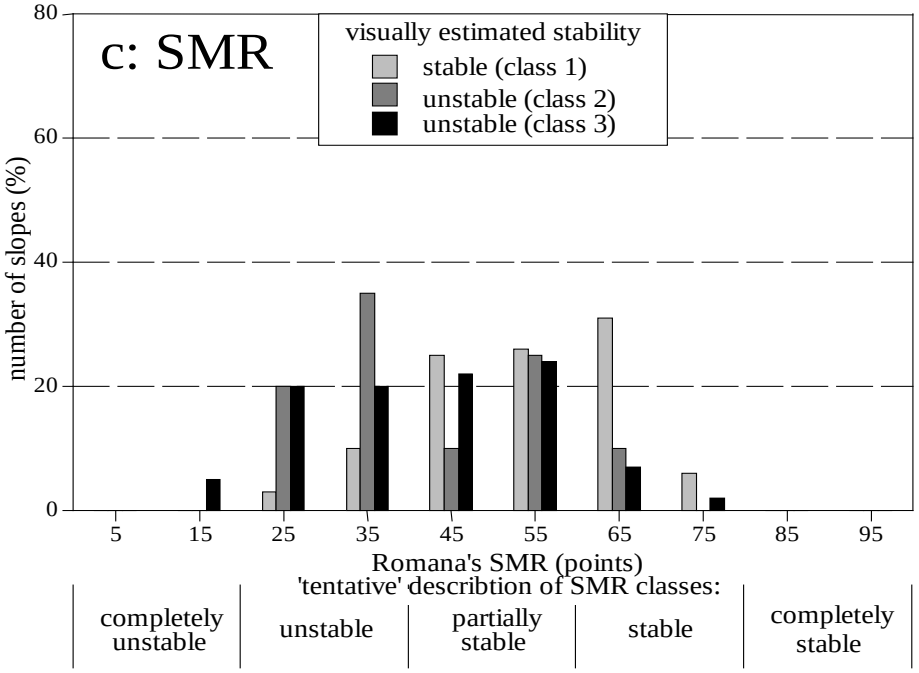
Probability orientation independent failure



Comparison between SSPC and other classification systems







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

Examples

Poorly blasted slope

Poorly blasted slope

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

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

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

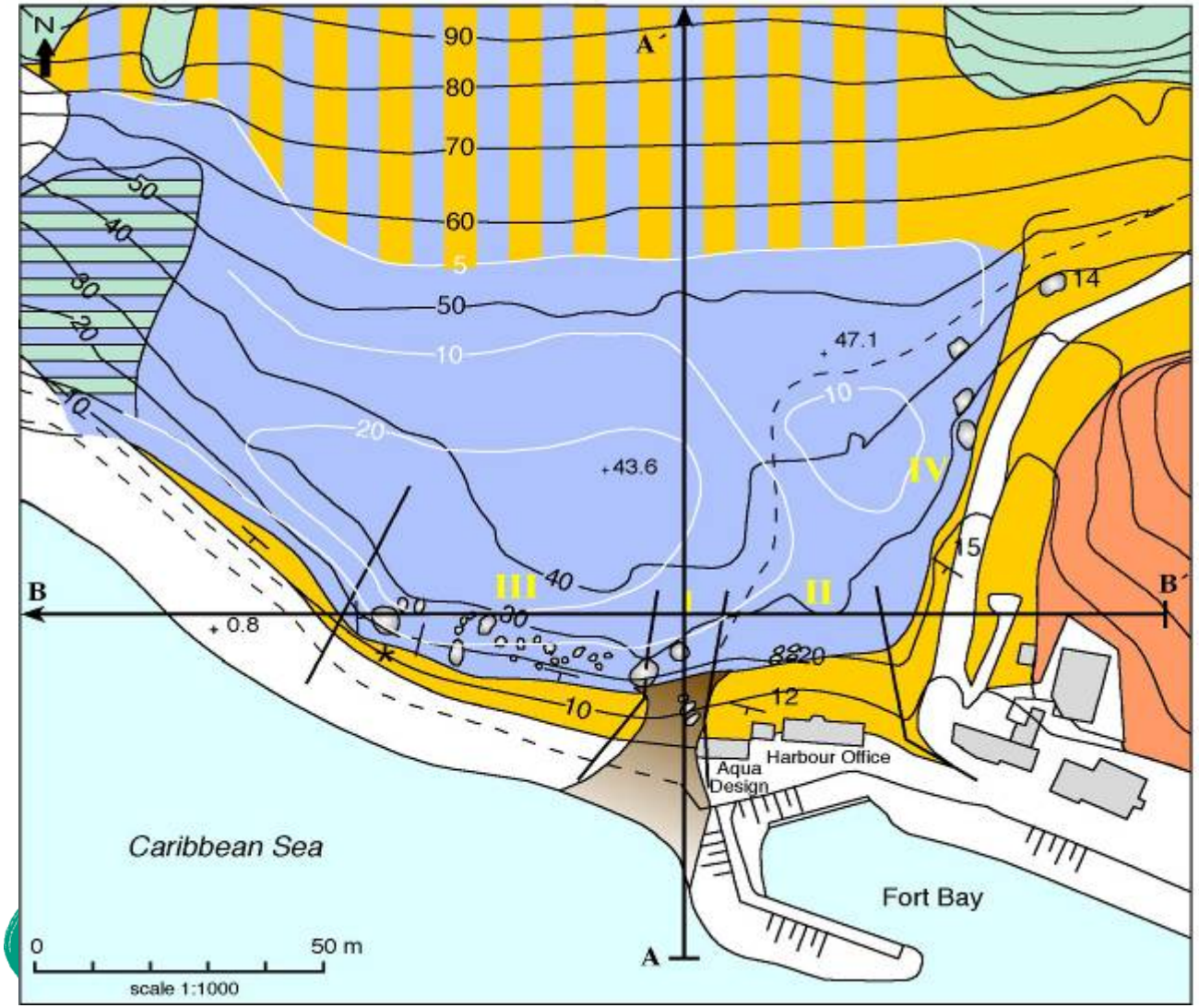
In 2005: Slope dip about 52°

Slope Stability probability Classification (SSPC)

Saba case - Dutch Antilles

Landslide in harbour

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)

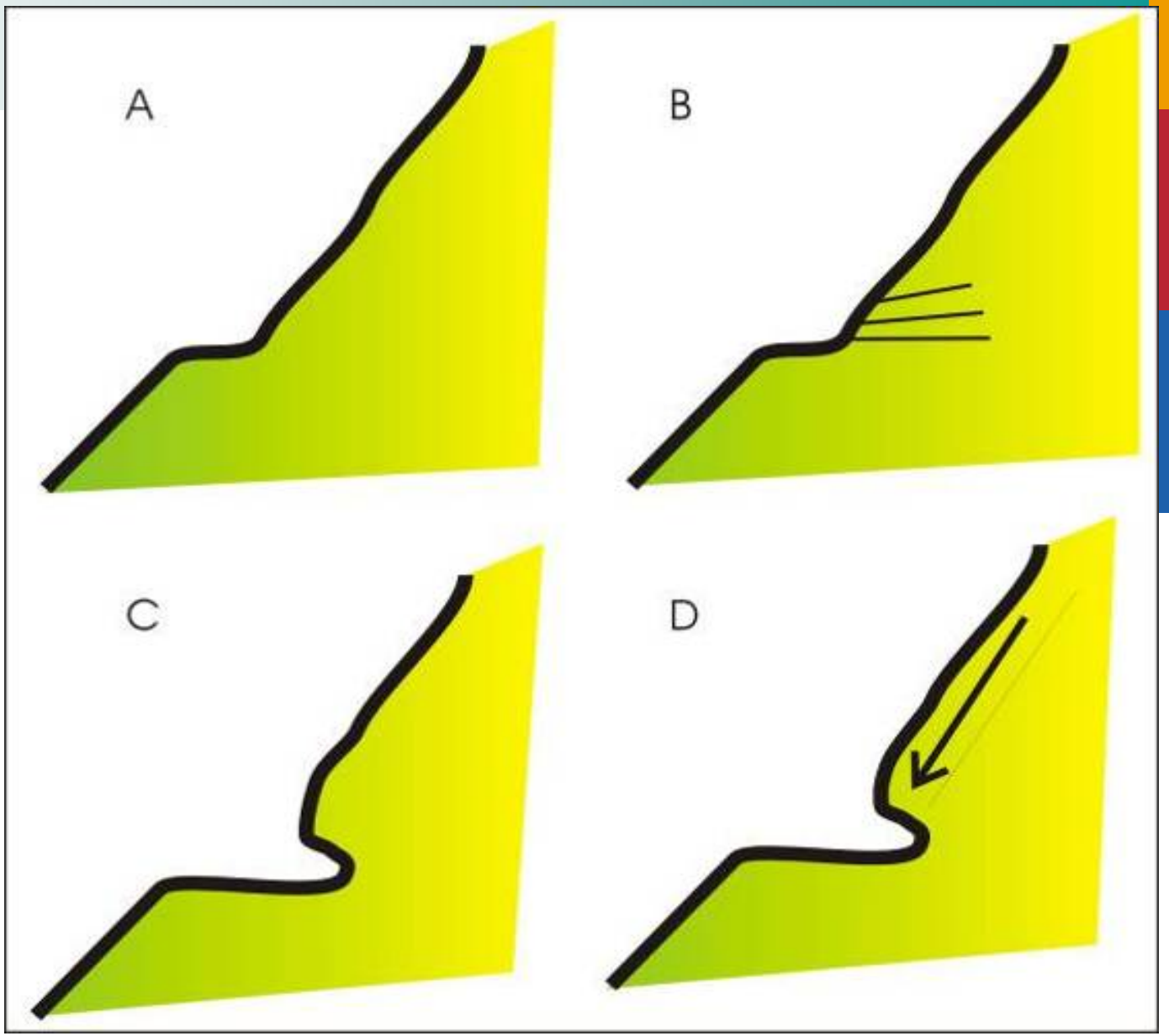
Failing slope in Manila, Philippines

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 Method of excavation



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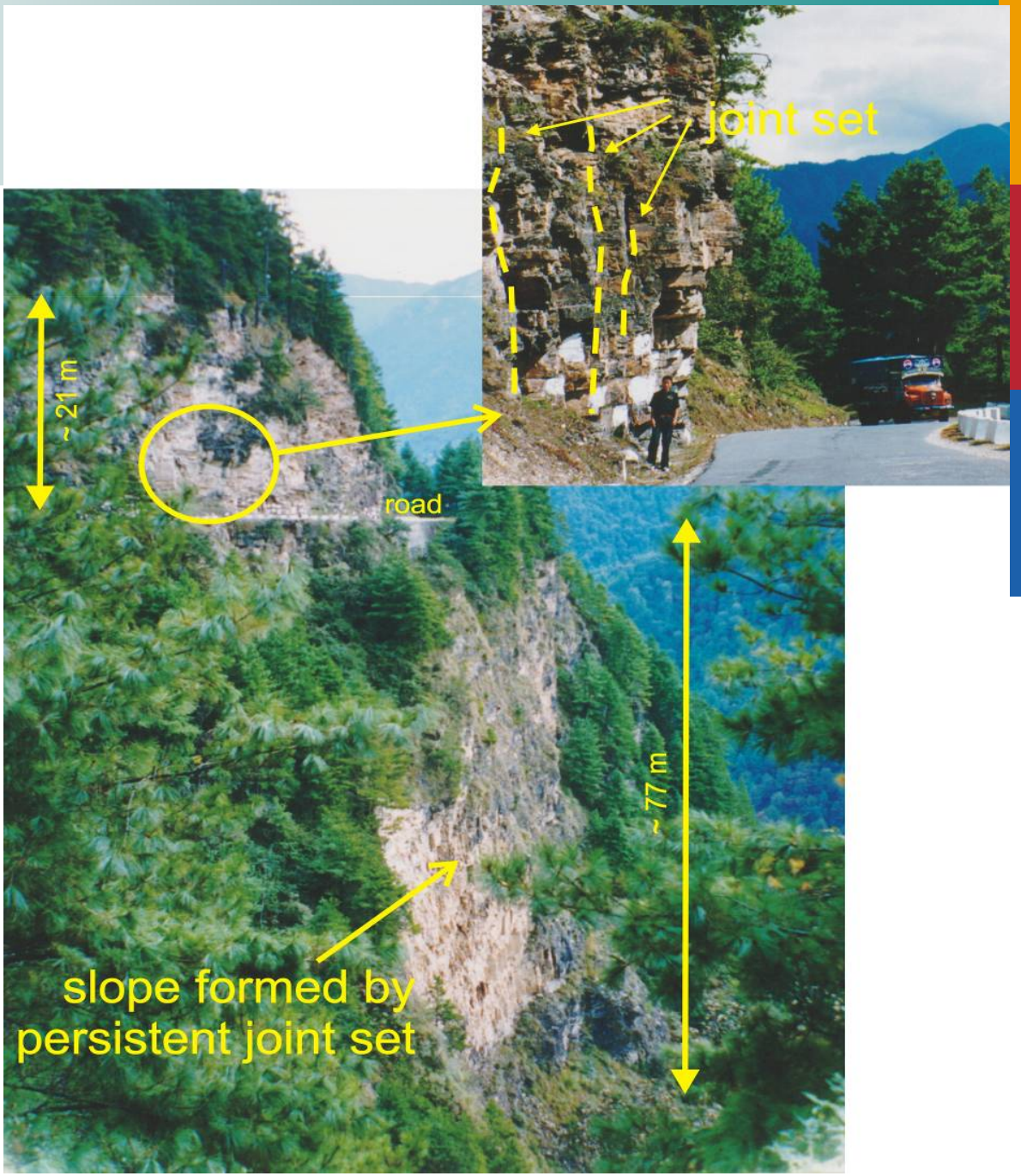

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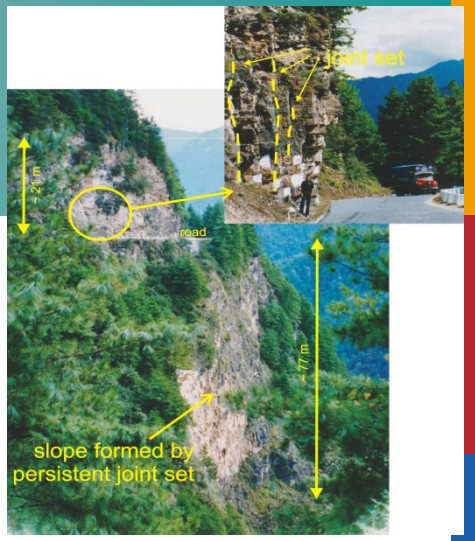


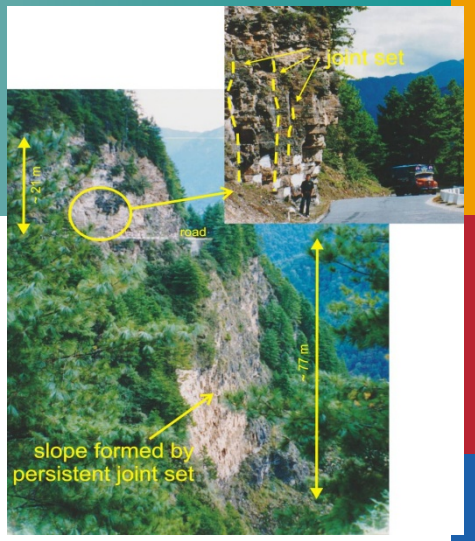
Above road level:

- 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)



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

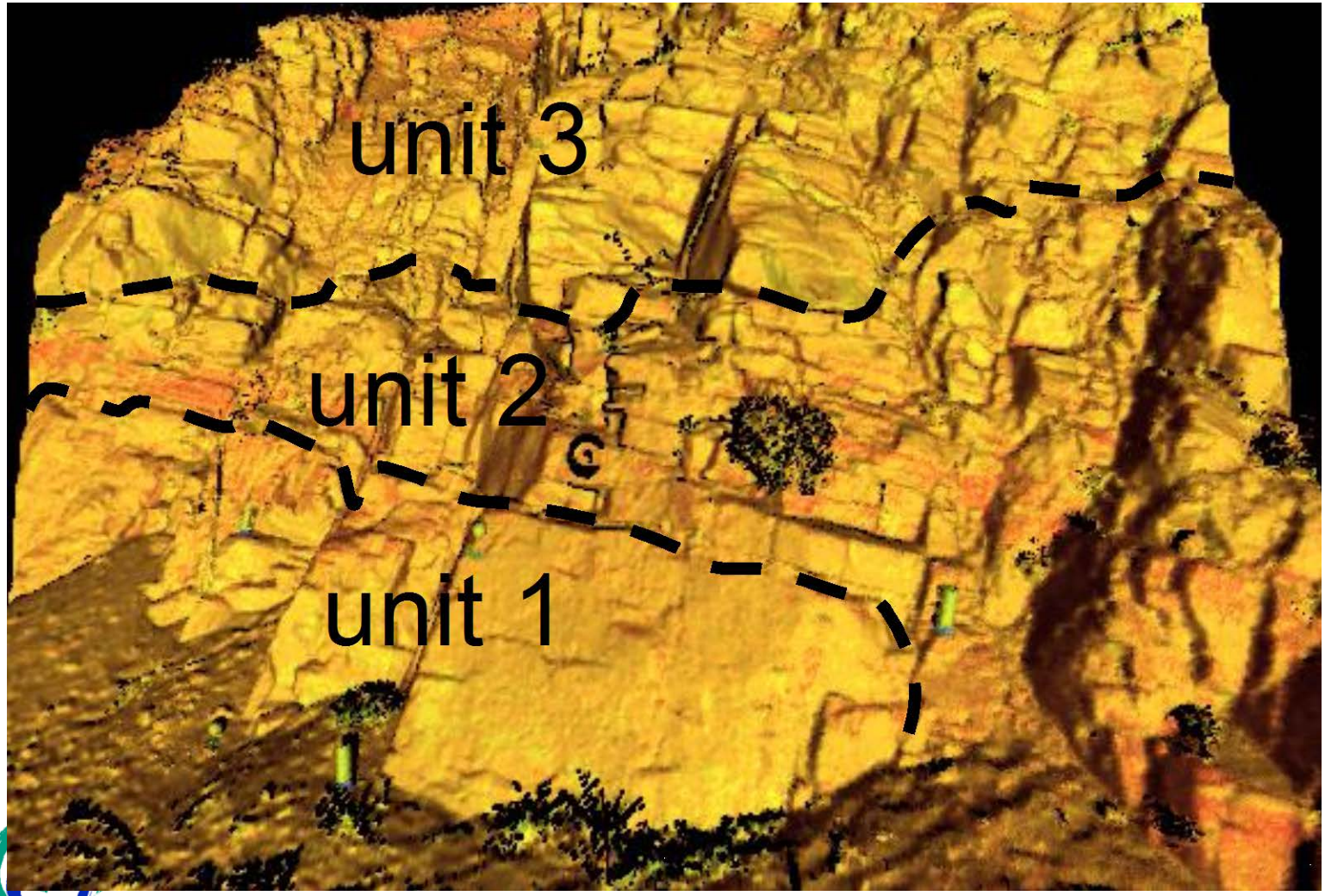
SSPC extensions:

measuring discontinuities
&
future decay of slope material

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)



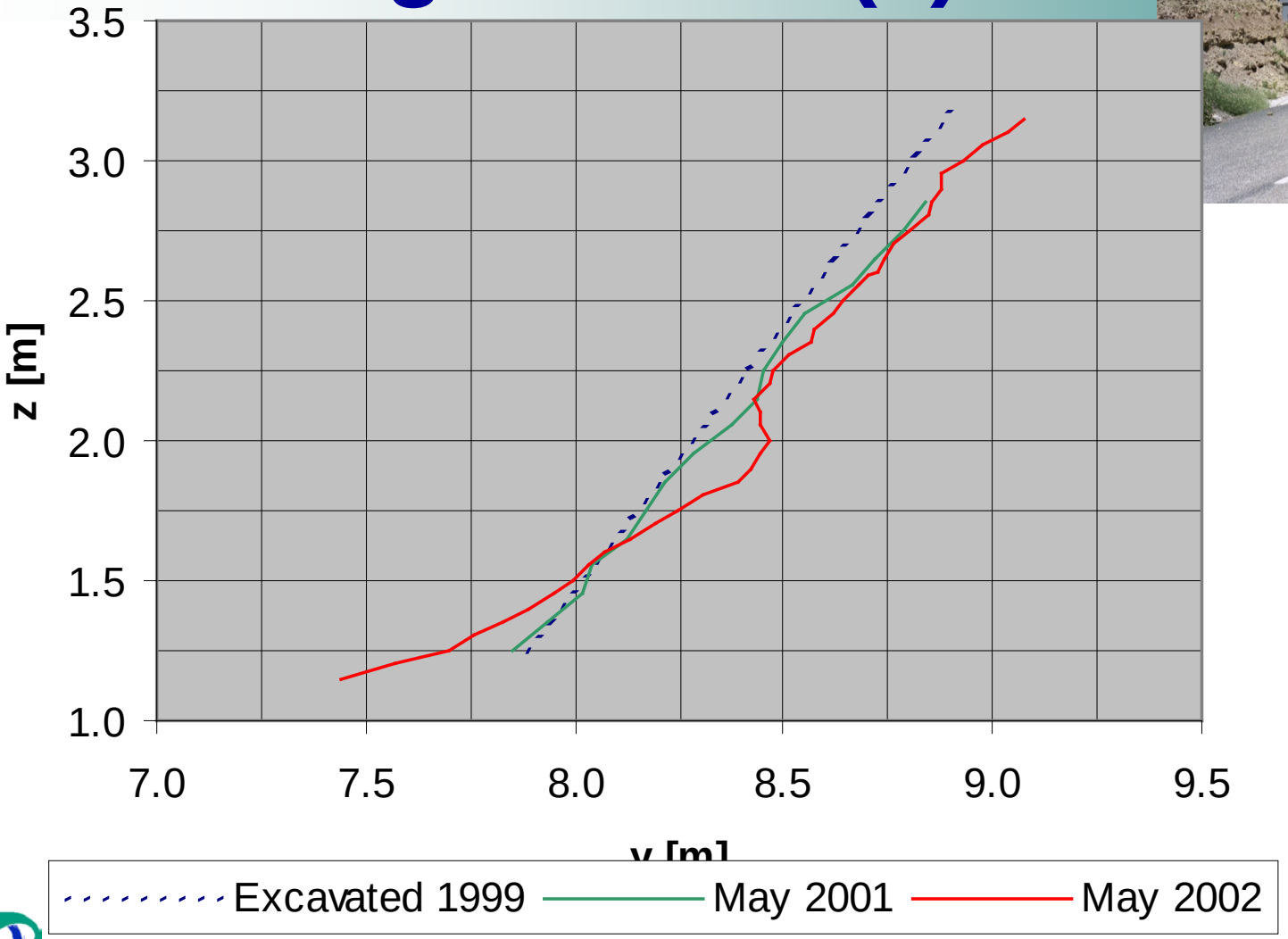
(modified after Slob et al, 2002)

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)

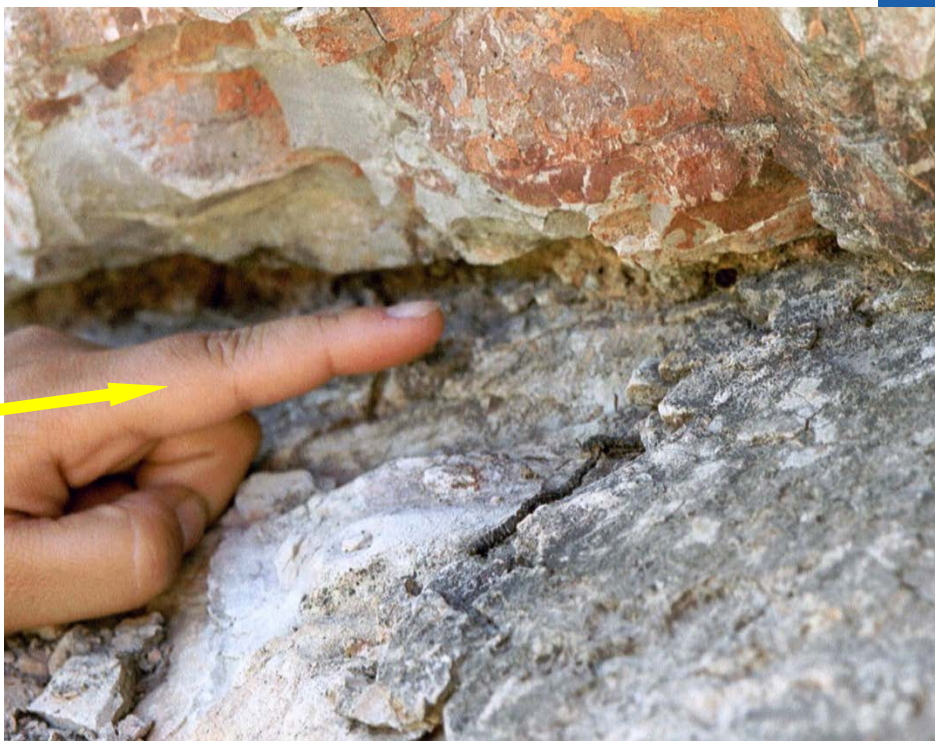
Degradation processes

Main processes involved in degradation:

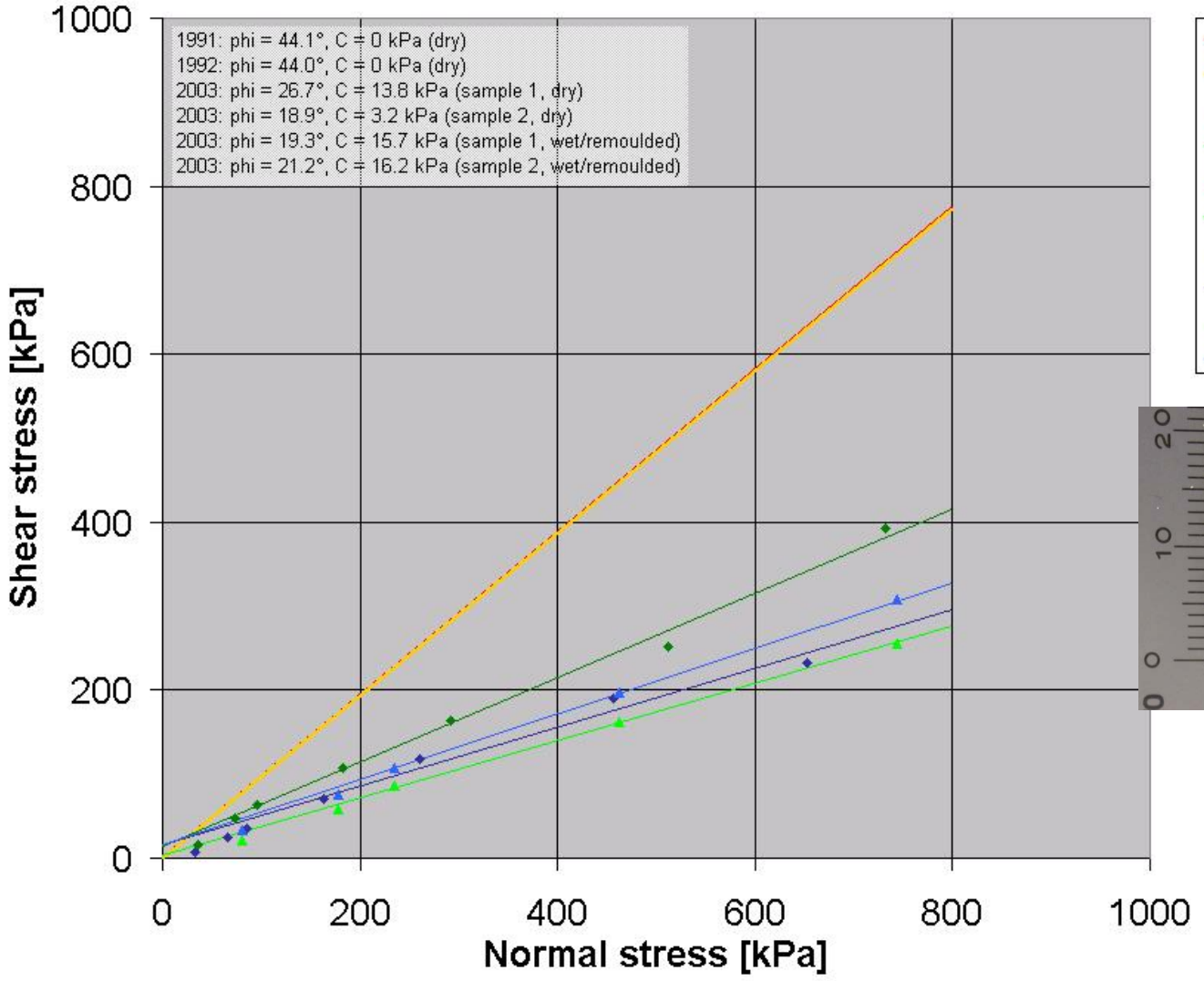
- Loss of structure due to stress release
- **Weathering** (In-situ change by inside or outside influences)
- **Erosion** (Material transport with no chemical or structural changes)

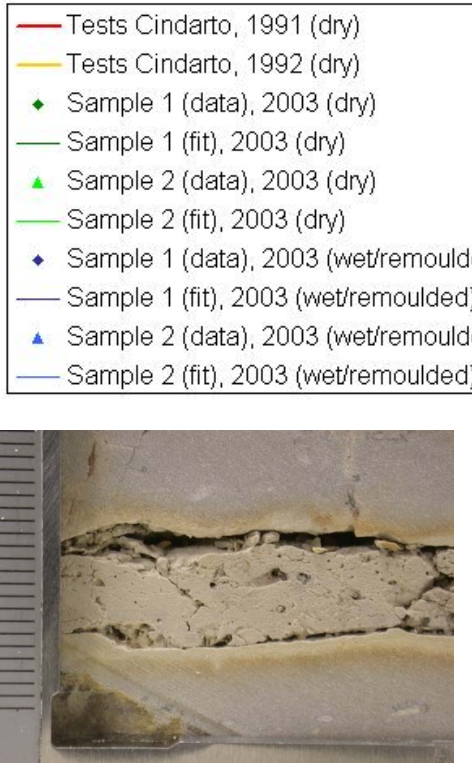
Significance in engineering

- 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!

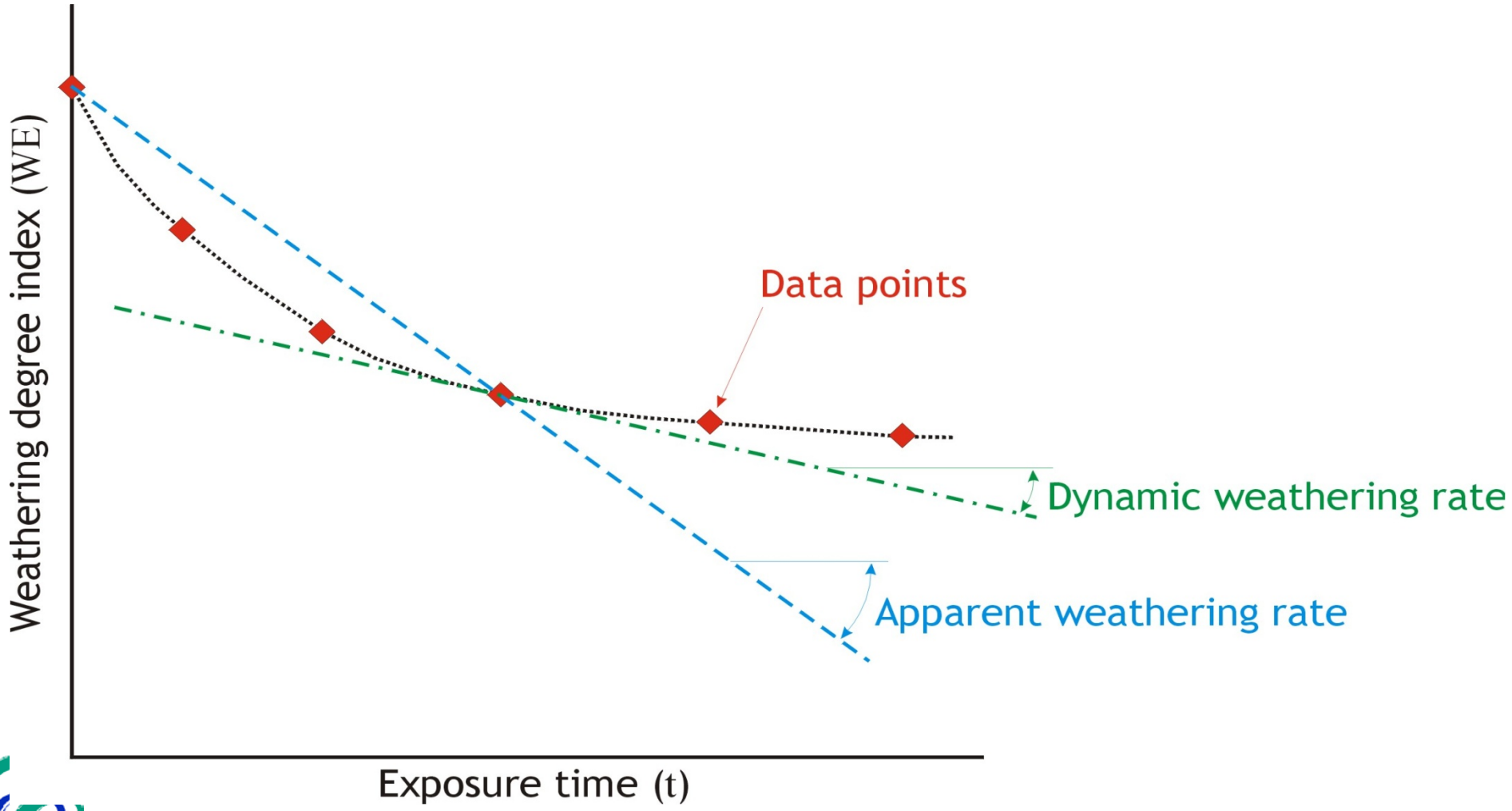
Quantify weathering: SSPC

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

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

Weathering rates

- **Material:**
  Gypsum layers
  Gypsum cemented siltstone layers

Middle Muschelkalk near Vandellos (Spain)

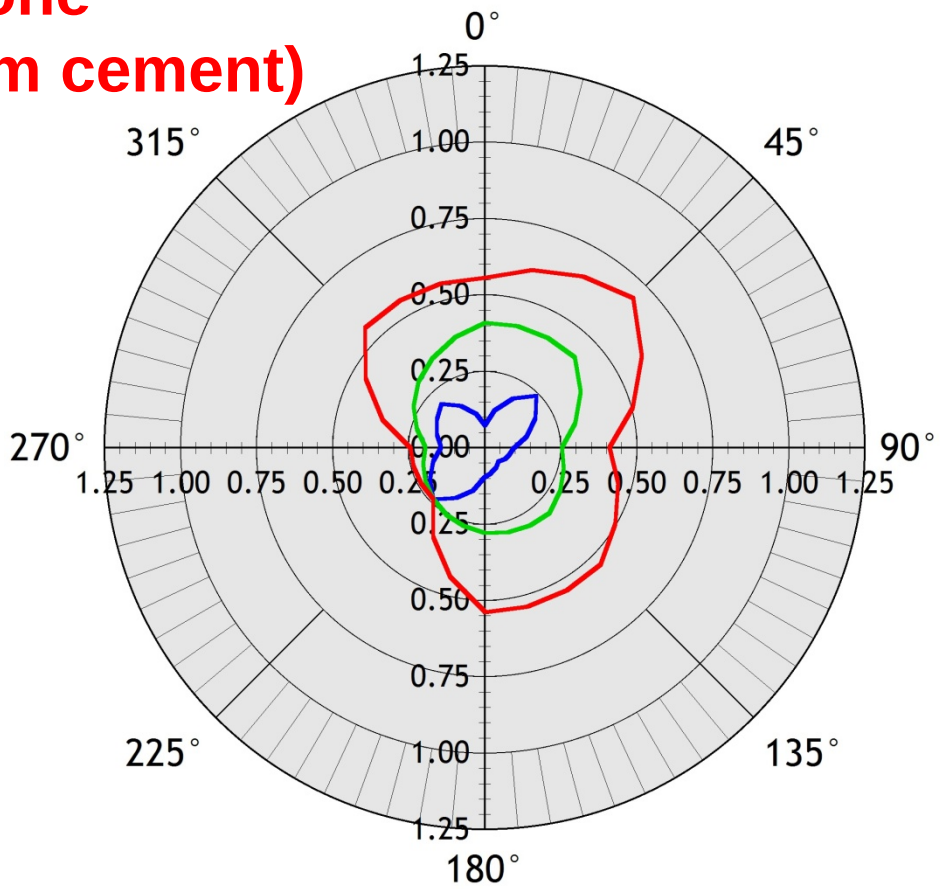
Weathering rates

- **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

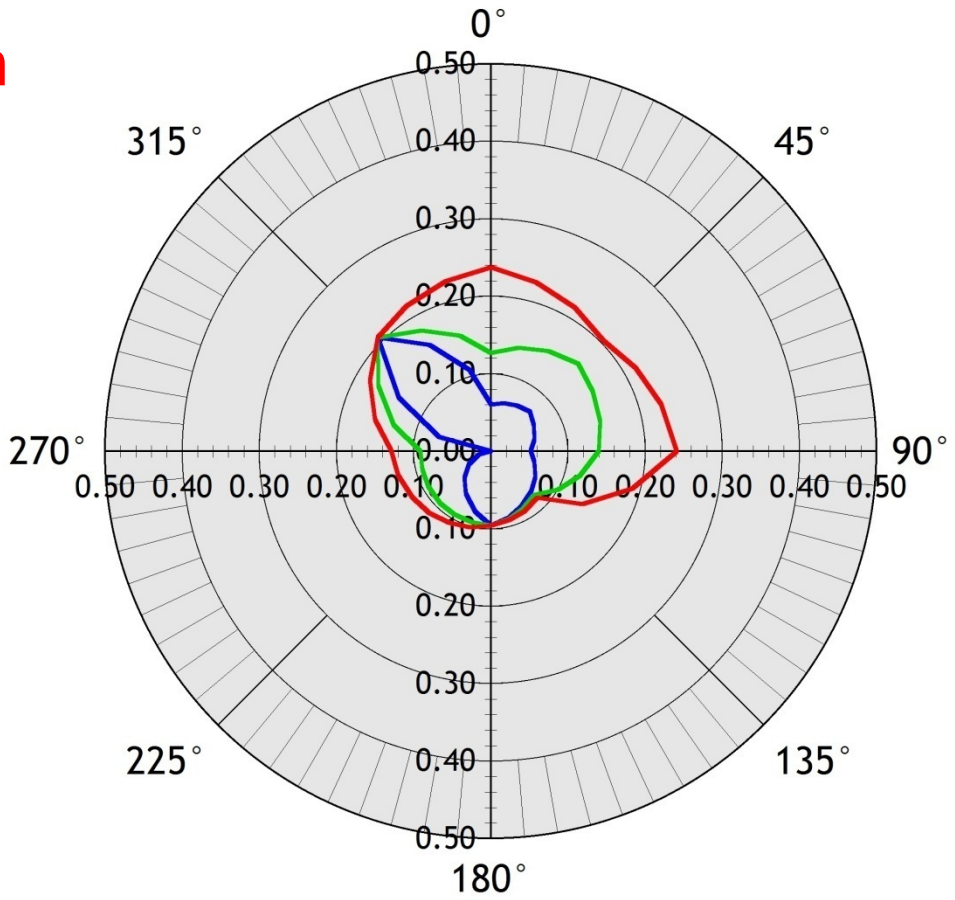
siltstone (with gypsum cement)



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

Weathering intensity rate

gypsum



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

SSPC system in combination with degradation forecasts gives:

- reasonable design for slope stability
- with minimum of work and
- in a short time

Kota Kinabalu, Malaysia

Kota Kinabalu, Malaysia

Side road: 5 years old

slightly weathered

SSPC

stability:

Sandstone:

stable

Shale:

unstable

Kota Kinabalu, Malaysia

Main road: 10 years old

moderately weathered

SSPC

stability:

Sandstone:

stable

Shale:

ravelling

Kota Kinabalu, Malaysia

SSPC friction & cohesion:

	friction (deg)	cohesion (kPa)
shale		
slightly (5 years)	4	2.4
moderately (10 years)	2	1.1
sandstone		
slightly (5 years)	20	10.0
moderately (10 years)	11	6.3

Kota Kinabalu, Malaysia

Expected stability when sandstone highly weathered:

Main road: (30 deg slope dip; 6 m high)

10% (i.e. instable)

Side road: (45 deg slope dip; 8 m high)

< 5 % (i.e. instable)

WHEN ??????

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