WEATHERING, ROCK MASS CLASSIFICATION (SSPC), AND REMOTE SENSING WITH A LINK TO LEVEE STABILITY

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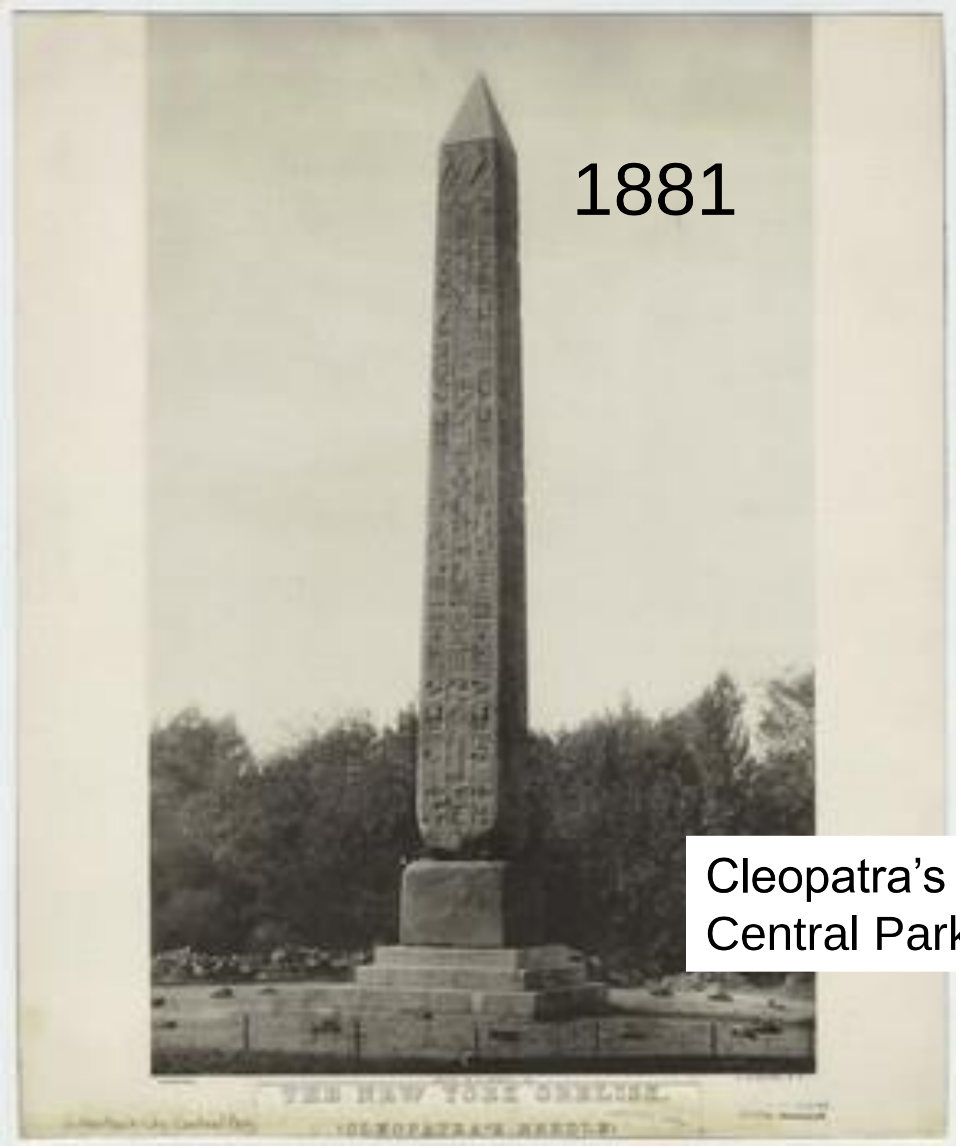
- Rock mass classification
- Slope Stability Probability Classification (SSPC)
- Remote sensing of weathering
- Remote sensing of levees for stability assessment

WEATHERING - FUTURE DEGRADATION OF SOIL AND ROCK MASSES

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)

INTACT ROCK WEATHERING



1881

2011

Cleopatra’s needle
Central Park, New York

FUTURE DEGRADATION OF A SLOPE

FUTURE DEGRADATION OF A SLOPE (2)

A simple small slope in Spain

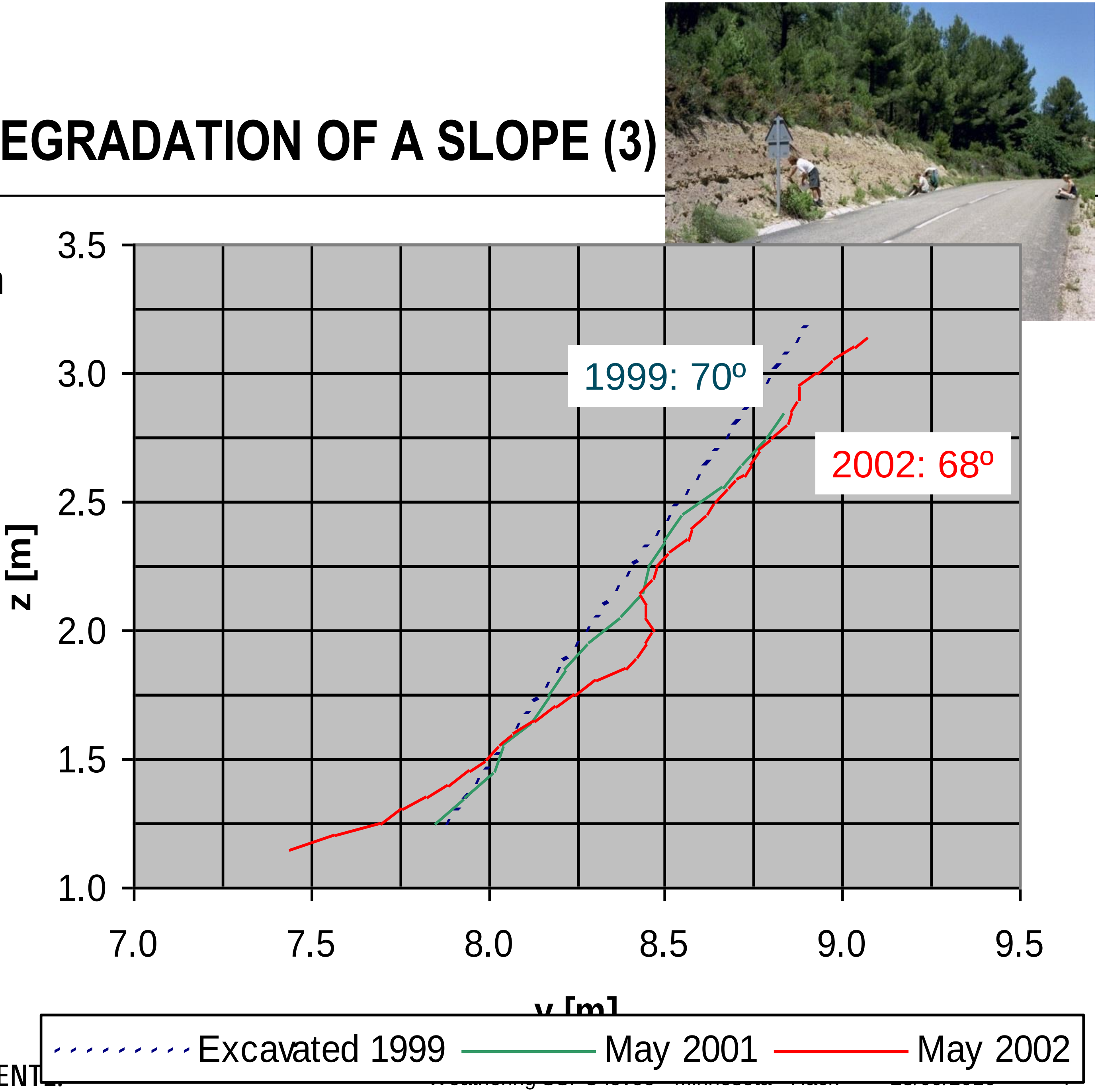
Rock mass:

- Calcareous marls (calcareous clayey, silt) interbedded with very thin limestone beds

- Excavated with an excavator at a slope dip of about 70º

FUTURE DEGRADATION OF A SLOPE (3)

Reduction in slope angle due to weathering, erosion and ravelling (after Huisman, 2006)



FUTURE DEGRADATION CAUSING SLOPE SLIDING FAILURE

Another simple slope in Spain:

Rock mass:

- Limestone (partially dolomitic) (medium bedded, widely jointed)
- Excavated with blasting at a slope dip of about 90º in the 1950’s

CINDARTO SLOPE: VARIATION IN CLAY CONTENT IN INTACT ROCK CAUSES DIFFERENTIAL WEATHERING

April 1990

CINDARTO SLOPE
VARIATION IN CLAY CONTENT IN INTACT ROCK CAUSES DIFFERENTIAL WEATHERING

April 1992

mass slid

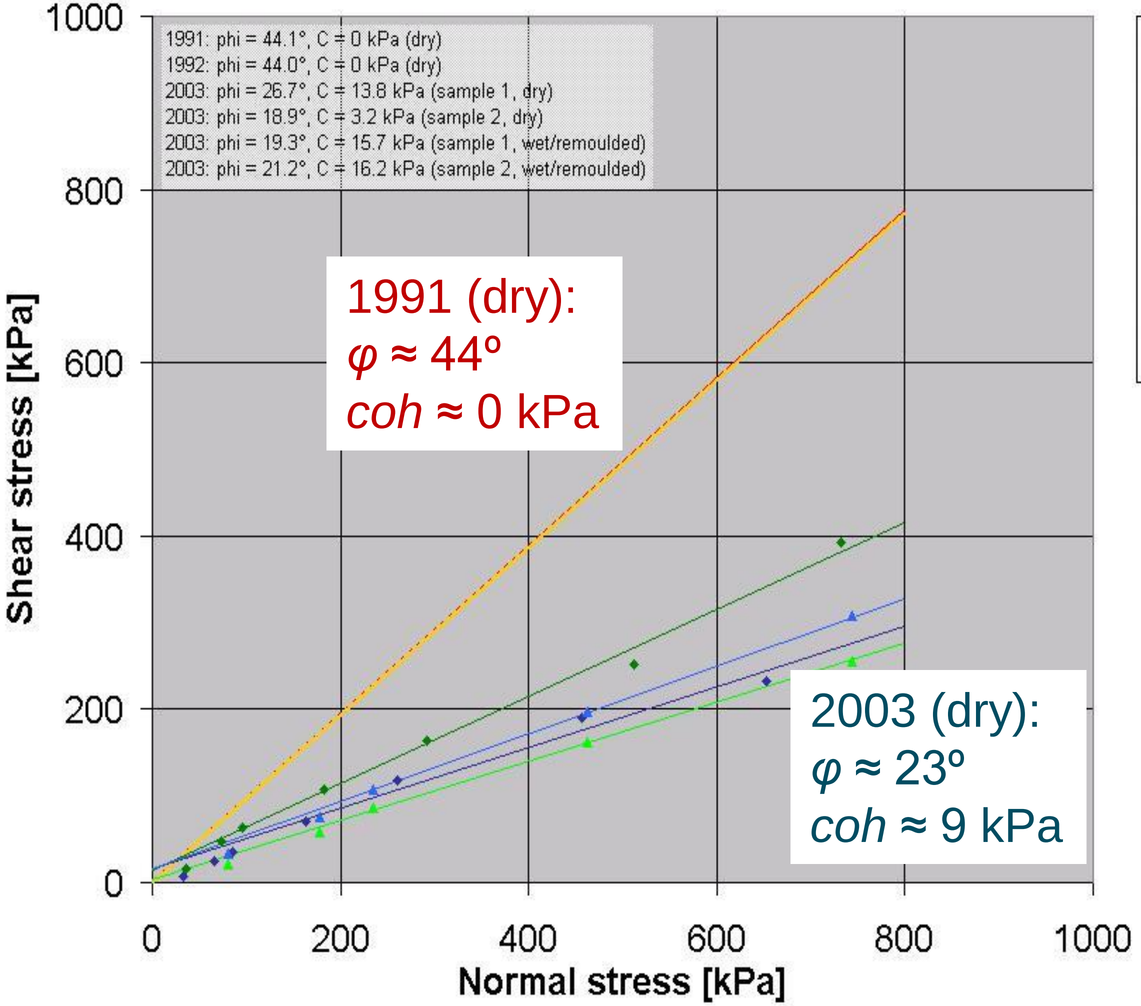
FUTURE DEGRADATION CAUSING SLOPE SLIDING FAILURE (4)

Dissolution of $CaCO_3$ at bedding plane by percolating water, caused reduction of $CaCO_3$ while clay stayed behind; hence

bedding plane got an infill of clay-rich material with a lower shear strength than the original $CaCO_3$ bedding plane

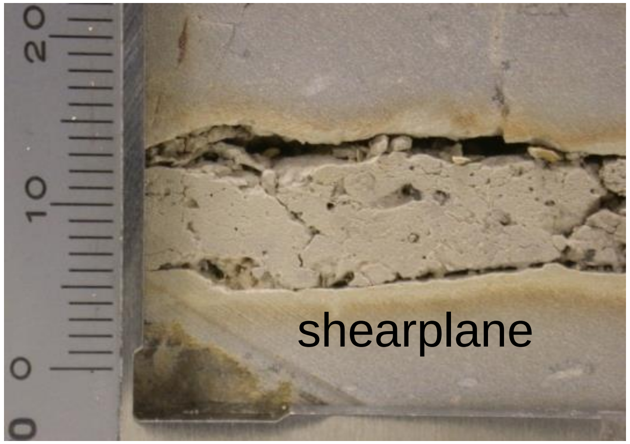
FUTURE DEGRADATION CAUSING SLOPE SLIDING FAILURE (5)

Shearbox tests Cindarto slope



1991 (dry):
φ ≈ 44º
coh ≈ 0 kPa

2003 (dry):
φ ≈ 23º
coh ≈ 9 kPa



shearplane

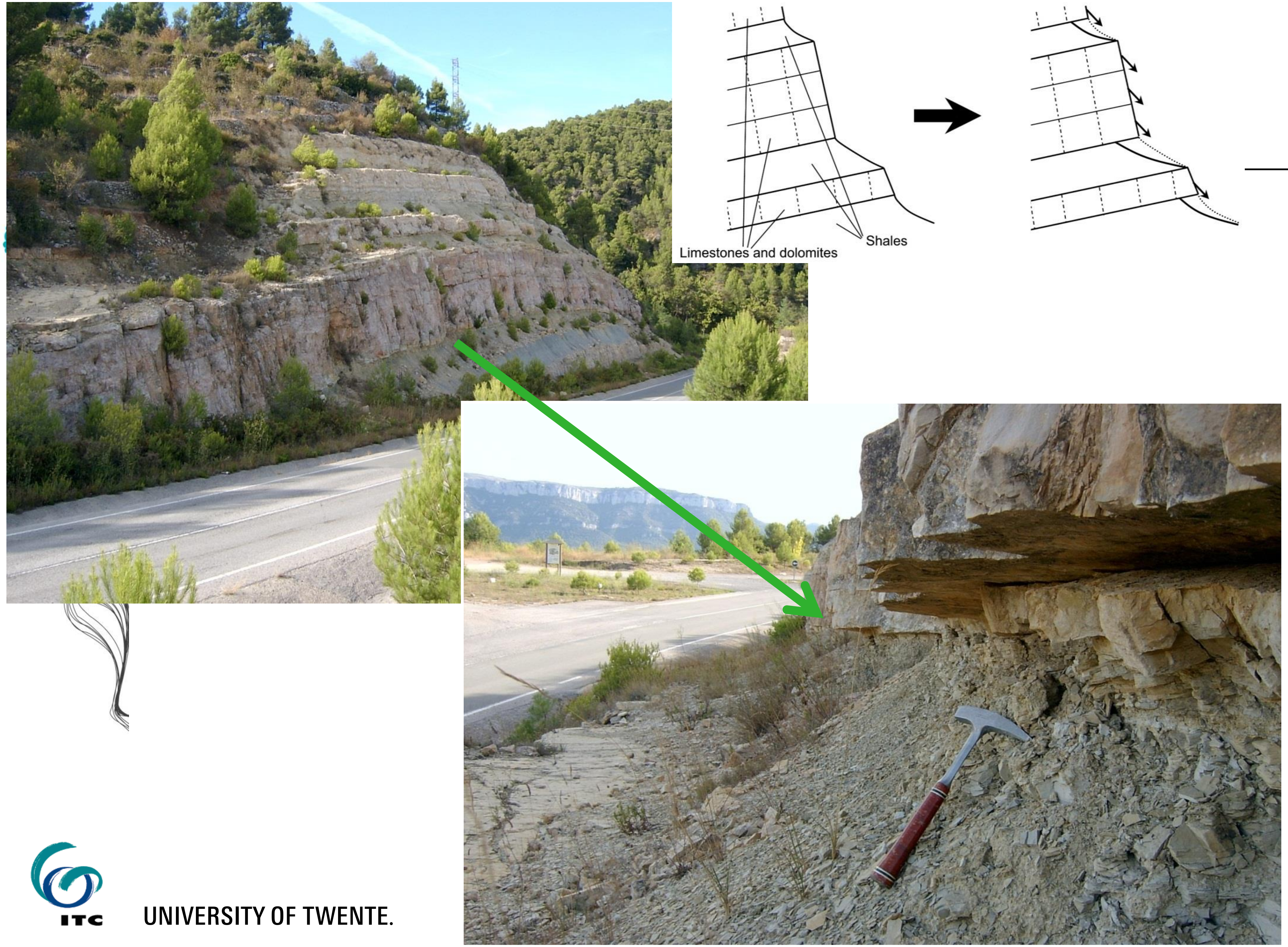
AGAIN ANOTHER SLOPE IN SPAIN

Fine-grained limestone (containing some organic material) falls apart in a couple of years from:

medium to small cubical blocky structure

to

very small flaky material


Limestones and dolomites
Shales

How to quantify the influence of weathering and the future influence?

ROCK MASS 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:

Many different classification system developed since the 60’ of the last century for various applications:

For underground (tunnels): Bieniawski (RMR), Barton (Q), Laubscher (MRMR), Geological Strength Index (GSI), etcetera

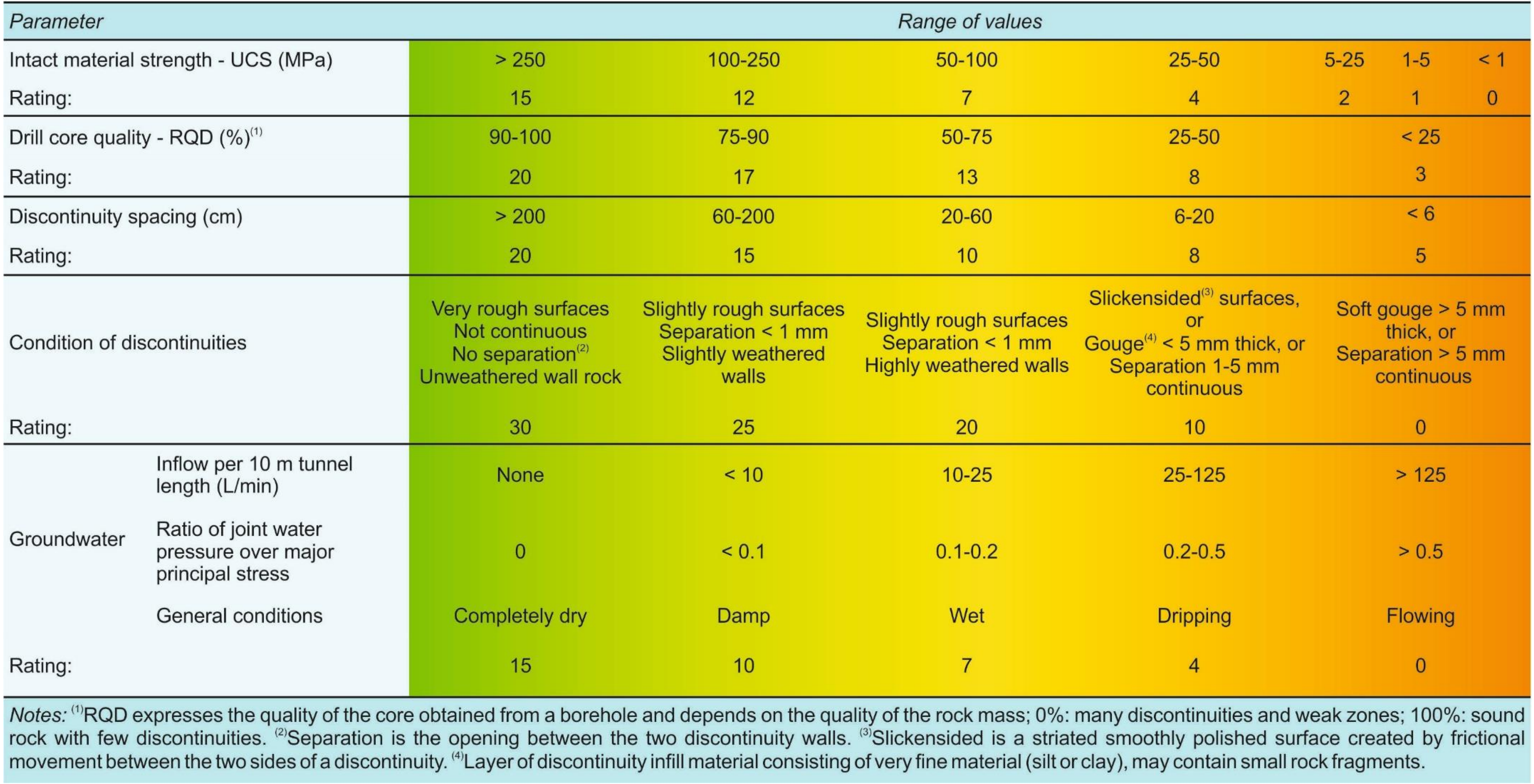
For slopes: Selby, Bieniawski (RMR), Vecchia, Robertson (RMR), Romana (SMR), Haines, SSPC, etcetera

For excavation: Singh et al. (1987)

Etc.

EXAMPLE: ROCK MASS RATING (RMR)

- Based on a combination of five parameters
- Each parameter is expressed by a point rating



Parameter		*Range of values*				
Intact material strength - UCS (MPa)		> 250	100-250	50-100	25-50	5-25 1-5 < 1
Rating:		15	12	7	4	2 1 0
Drill core quality - RQD (%)[1]		90-100	75-90	50-75	25-50	< 25
Rating:		20	17	13	8	3
Discontinuity spacing (cm)		> 200	60-200	20-60	6-20	< 6
Rating:		20	15	10	8	5
Condition of discontinuities		Very rough surfaces Not continuous No separation[2] Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided[3] surfaces, or Gouge[4] < 5 mm thick, or Separation 1-5 mm continuous	Soft gouge > 5 mm thick, or Separation > 5 mm continuous
Rating:		30	25	20	10	0
Groundwater	Inflow per 10 m tunnel length (L/min)	None	< 10	10-25	25-125	> 125
	Ratio of joint water pressure over major principal stress	0	< 0.1	0.1-0.2	0.2-0.5	> 0.5
	General conditions	Completely dry	Damp	Wet	Dripping	Flowing
Rating:		15	10	7	4	0

Notes: [1]RQD expresses the quality of the core obtained from a borehole and depends on the quality of the rock mass; 0%: many discontinuities and weak zones; 100%: sound rock with few discontinuities. [2]Separation is the opening between the two discontinuity walls. [3]Slickensided is a striated smoothly polished surface created by frictional movement between the two sides of a discontinuity. [4]Layer of discontinuity infill material consisting of very fine material (silt or clay), may contain small rock fragments.

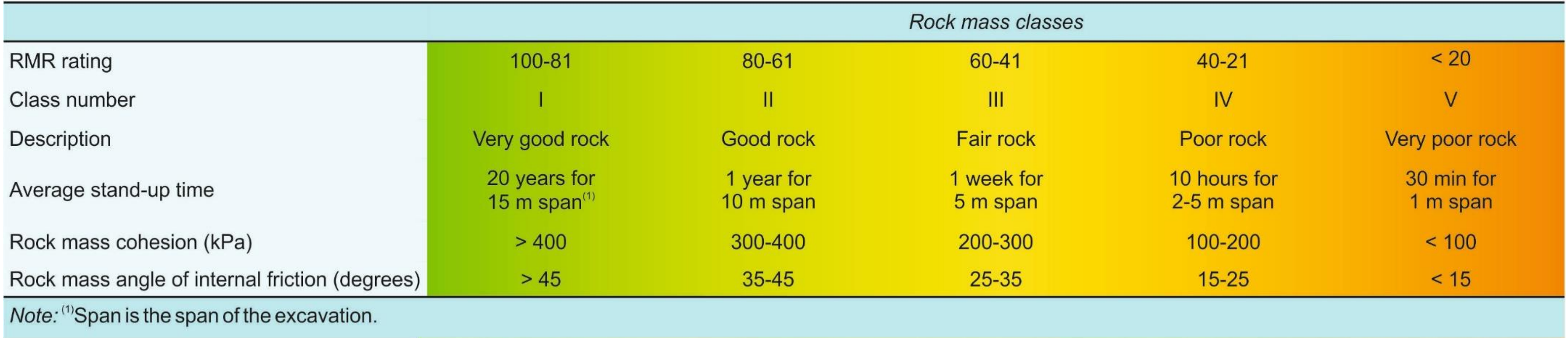
(from De Mulder et al., 2012)

RMR(2)

addition of the points results in the RMR rating

$$RMR = (IRS + RQD + spacing + condition + groundwater) + reduction\ \ factor(s)$$

reduction factors for: orientation, excavation damage, etc.



	Rock mass classes				
RMR rating	100-81	80-61	60-41	40-21	< 20
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock
Average stand-up time	20 years for 15 m span(1)	1 year for 10 m span	1 week for 5 m span	10 hours for 2-5 m span	30 min for 1 m span
Rock mass cohesion (kPa)	> 400	300-400	200-300	100-200	< 100
Rock mass angle of internal friction (degrees)	> 45	35-45	25-35	15-25	< 15

Note: (1)Span is the span of the excavation.

(from De Mulder et al., 2012)

- related (empirically) to rock mass cohesion, friction angle of the rock mass, and other rock mass properties

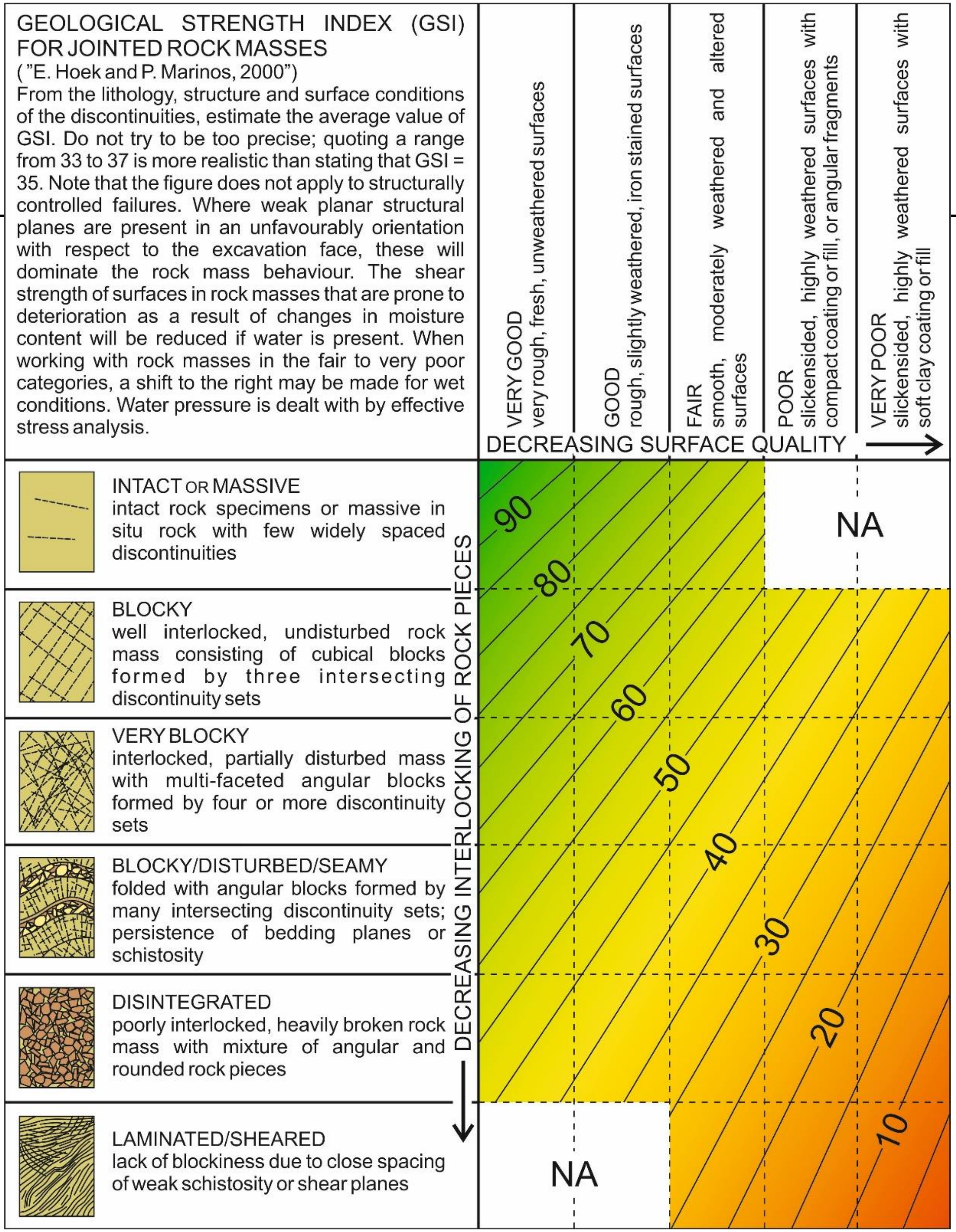
EXAMPLE: GEOLOGICAL STRENGTH INDEX (GSI)

The Geological Strength Index (GSI) is derived from a matrix describing the ‘structure’ and the ‘surface condition’ of the rock mass

GSI(2)

‘structure’ is related to the block size and the interlocking of rock blocks

‘surface condition’ is related to weathering, persistence, and condition of discontinuities.



GEOLOGICAL STRENGTH INDEX (GSI) FOR JOINTED ROCK MASSES
("E. Hoek and P. Marinos, 2000")

From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise; quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the figure does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourably orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rock masses that are prone to deterioration as a result of changes in moisture content will be reduced if water is present. When working with rock masses in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.

VERY GOOD very rough, fresh, unweathered surfaces

GOOD rough, slightly weathered, iron stained surfaces

FAIR smooth, moderately weathered and altered surfaces

POOR slickensided, highly weathered surfaces with compact coating or fill, or angular fragments

VERY POOR slickensided, highly weathered surfaces with soft clay coating or fill

INTACT OR MASSIVE intact rock specimens or massive in situ rock with few widely spaced discontinuities

BLOCKY well interlocked, undisturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets

VERY BLOCKY interlocked, partially disturbed mass with multi-faceted angular blocks formed by four or more discontinuity sets

BLOCKY/DISTURBED/SEAMY folded with angular blocks formed by many intersecting discontinuity sets; persistence of bedding planes or schistosity

DISINTEGRATED poorly interlocked, heavily broken rock mass with mixture of angular and rounded rock pieces

LAMINATED/SHEARED lack of blockiness due to close spacing of weak schistosity or shear planes

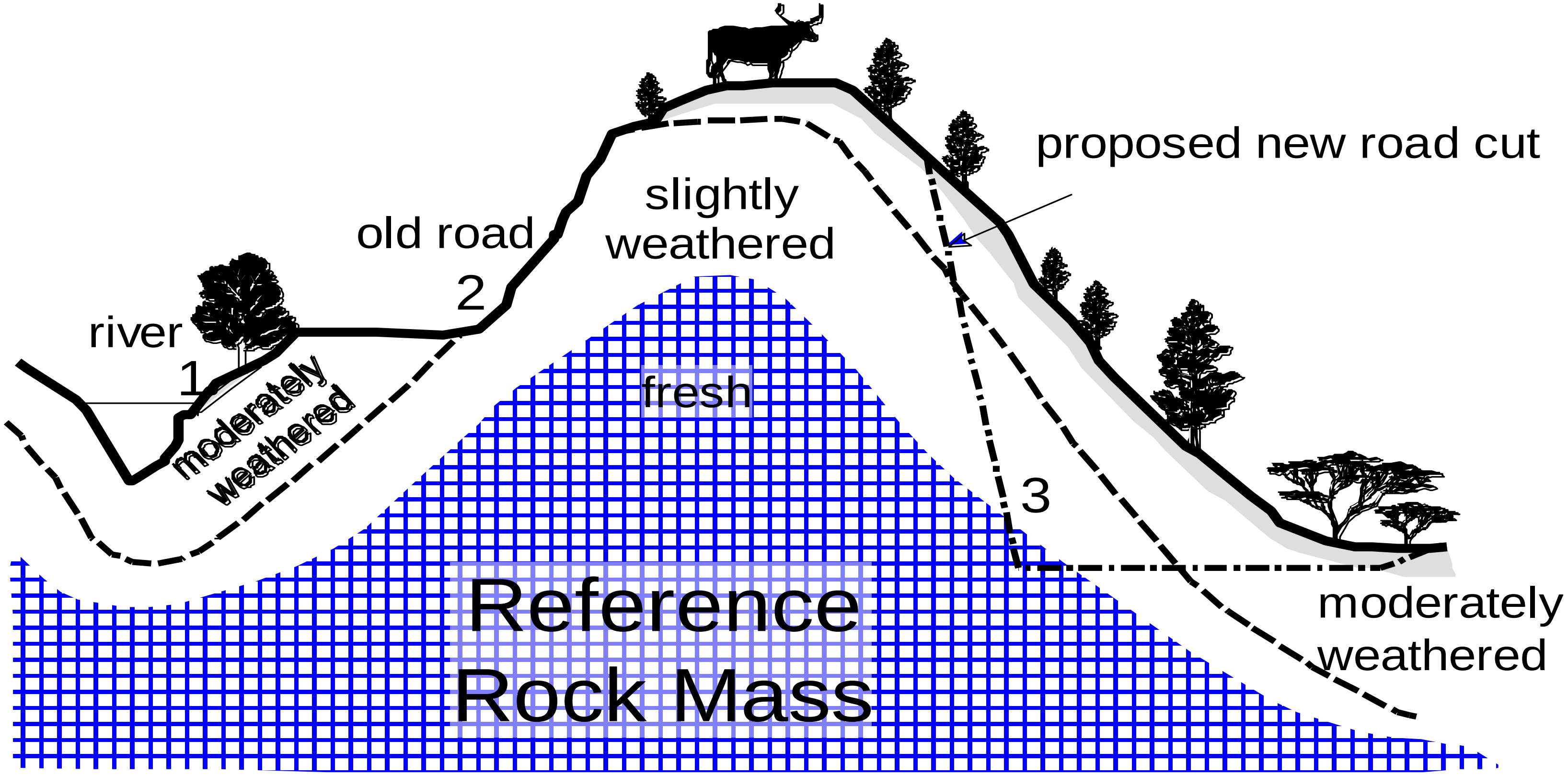
(from De Mulder et al., 2012)

SLOPE STABILITY PROBABILITY CLASSIFICATION (SSPC)

Slope Stability probability Classification (SSPC):

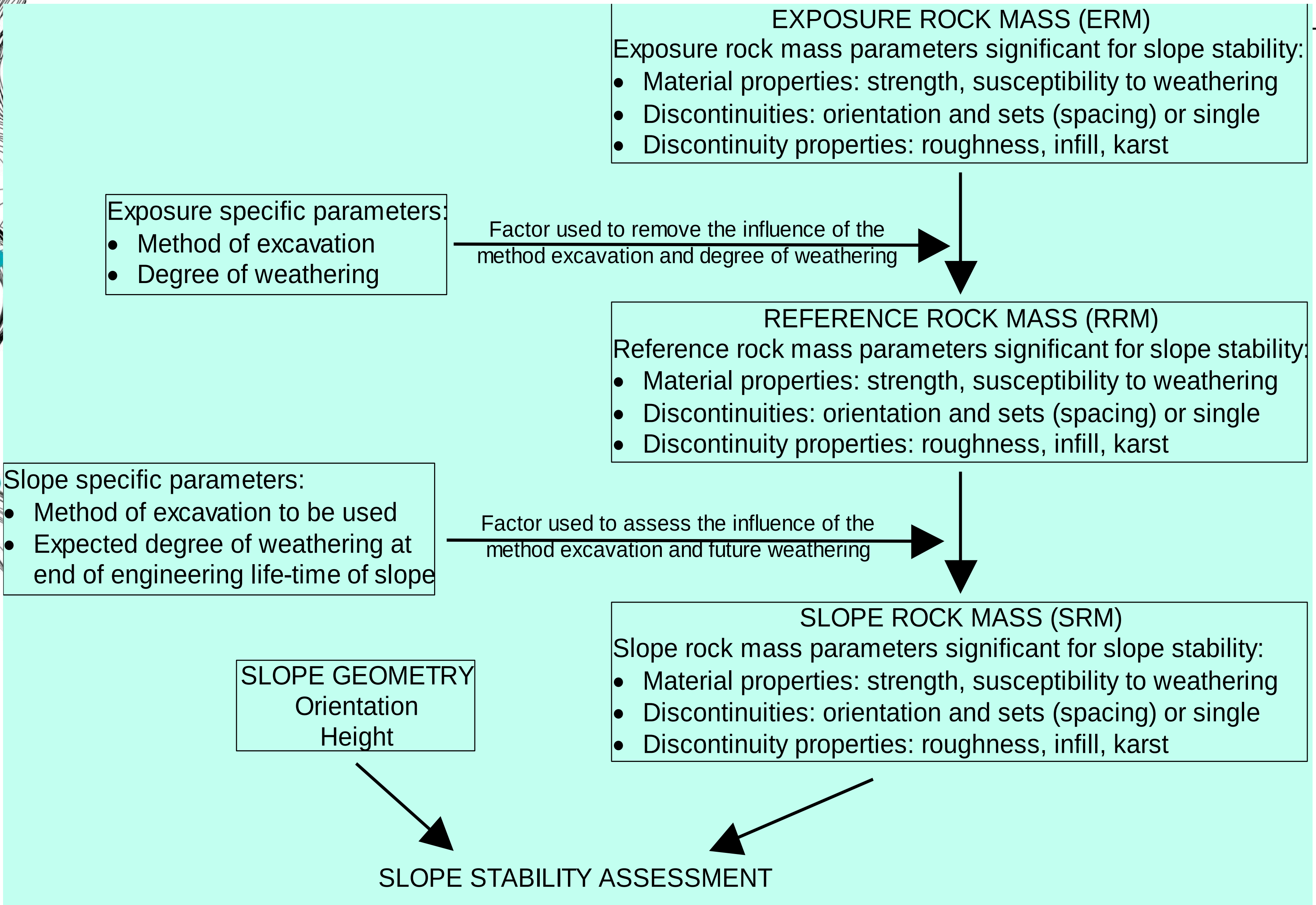
- three step classification system
- based on probabilities
- independent failure mechanism assessment

SSPC - 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



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

SSPC

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

- Degree of weathering
- Method of excavation

SSPC

Rock mass Parameters:

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

SSPC

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

SSPC

Intact rock strength (IRS)

By simple means test:

hammer blows, crushing by hand, etcetera

SSPC

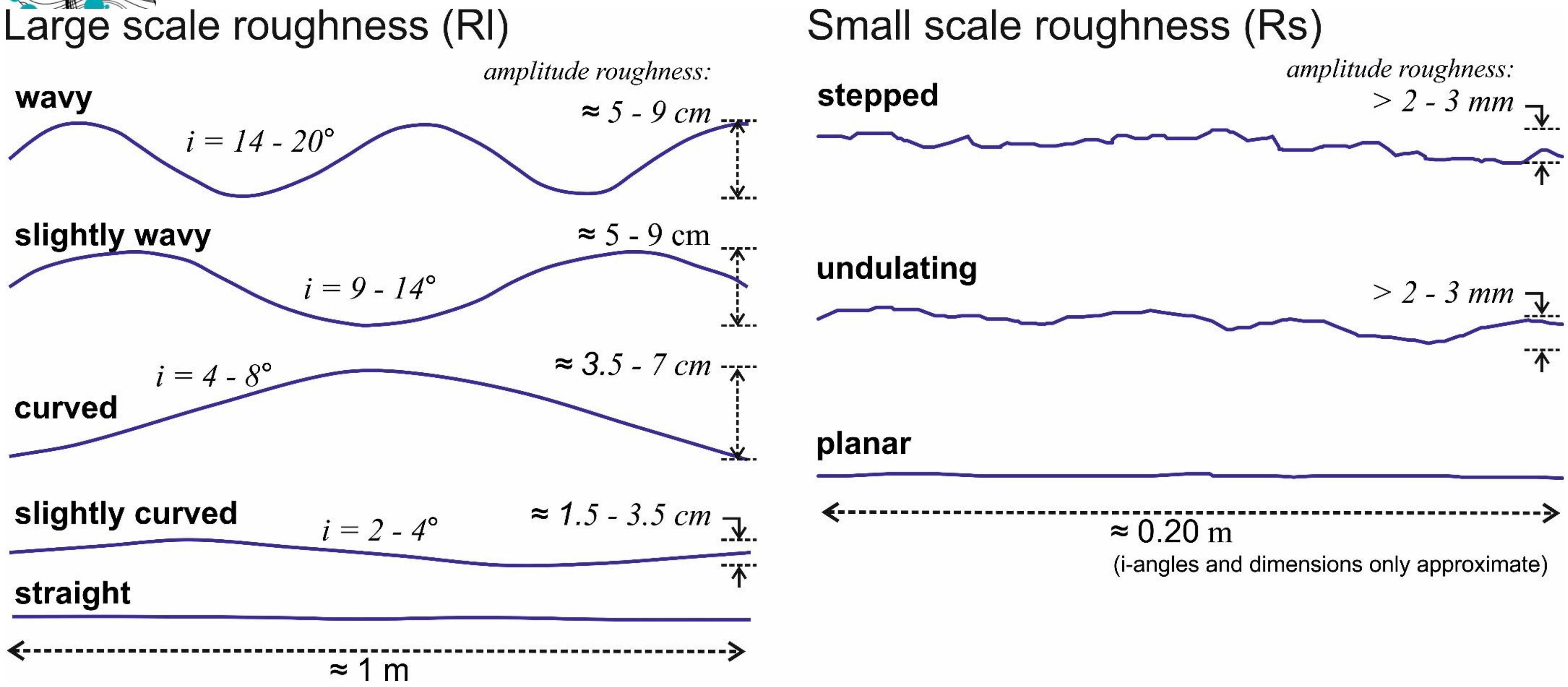
Spacing and persistence of discontinuities:

Determine block size and block form by:

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

SSPC

Shear strength – roughness



SSPC

Infill (In):

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

Discontinuity Condition (TC) factors:

CONDITION OF DISCONTINUITY			factor
Roughness large scale (Rl) (visual area > 0.2 x 0.2 and < 1 x 1 m2)	wavy		1.00
	slightly wavy		0.95
	curved		0.85
	slightly curved		0.80
	straight		0.75
Roughness small scale (Rs) (tactile and visual on an area of 20 x 20 cm2)	rough stepped/irregular		0.95
	smooth stepped		0.90
	polished stepped		0.85
	rough undulating		0.80
	smooth undulating		0.75
	polished undulating		0.70
	rough planar		0.65
	smooth planar		0.60
	polished planar		0.55
Infill material (Im)	cemented/cemented infill		1.07
	no infill - surface staining		1.00
	non softening & sheared material, e.g. free of clay, talc, etc.	coarse	0.95
		medium	0.90
		fine	0.85
	soft sheared material, e.g. clay, talc, etc.	coarse	0.75
		medium	0.65
		fine	0.55
	gouge < irregularities		0.42
	gouge > irregularities		0.17
	flowing material		0.05
Karst (Ka)	none		1.00
	karst		0.92

SSPC - SHEAR STRENGTH - CONDITION FACTOR

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

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

SLIDING CRITERION

Condition of Discontinuity (TC) is related to friction along plane by:

$$\varphi_{sliding\ angle} = \frac{Rl*Rs*Im*Ka}{0.0113}$$

SLIDING CRITERION (EXAMPLE)

Bedding dip angle ≈ 35.5º

bedding plane	description	factor
large scale	straight	0.75
small scale & tactile	rough stepped	0.95
infill	fine soft sheared	0.55
karst	none	1.00

$$\varphi_{sliding\ angle} = \frac{Rl * Rs * \mathrm{Im} * Ka}{0.0113} = \frac{0.75*0.95*0.55*1.00}{0.0113} = 35 \text{ degrees}$$

SSPC’S ROCK MASS PROPERTIES

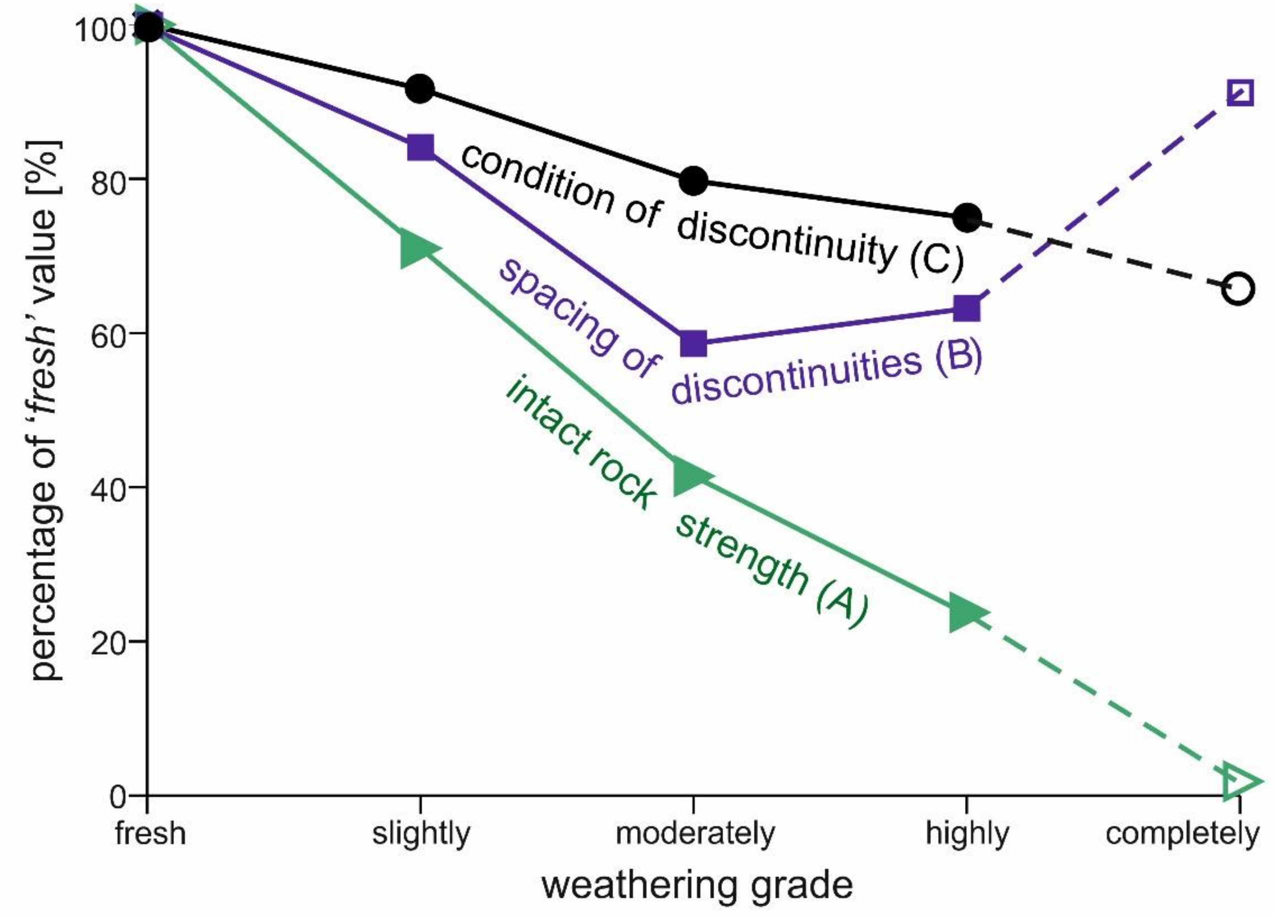
Rock mass properties derived from SSPC system:

- Condition of discontinuity (“sliding angle”)

- Rock mass angle of internal friction
- Rock mass cohesion

Quantification of weathering influence

IMPACT OF WEATHERING



Notes: Data of various sources and rock masses; averaged after normalization with values for fresh equal 100 %. Standard deviation around 15 to 23 % (points) for slightly through highly weathered; data for completely weathered are few and average not reliable. *Fresh, slightly*, etc. refer to rock mass weathering following ISO 14689-1;2003. '*Spacing of discontinuities*' based on rock block size and form following Taylor (1980) in Hack et al. (2003) or on discontinuity spacing. '*Condition of discontinuity*' (determining the shear strength) following sliding criterion (Hack et al. 2003) or friction and cohesion properties for discontinuities. Data: A: 1, 5, 6, 7 & 10; B: 2, 3, 4 & 5; C: 5, 8 & 9. (1) Begonha & Sequeira Braga (2002) (2) Ehlen (1999) (3) Ehlen (2002) (4) GCO (1990) (5) Hack & Price (1997) (6) Marques et al. (2010) (7) Pickles (2005) (8) Reissmüller (1997) (9) Snee (2008) (10) Tugrul (2004).

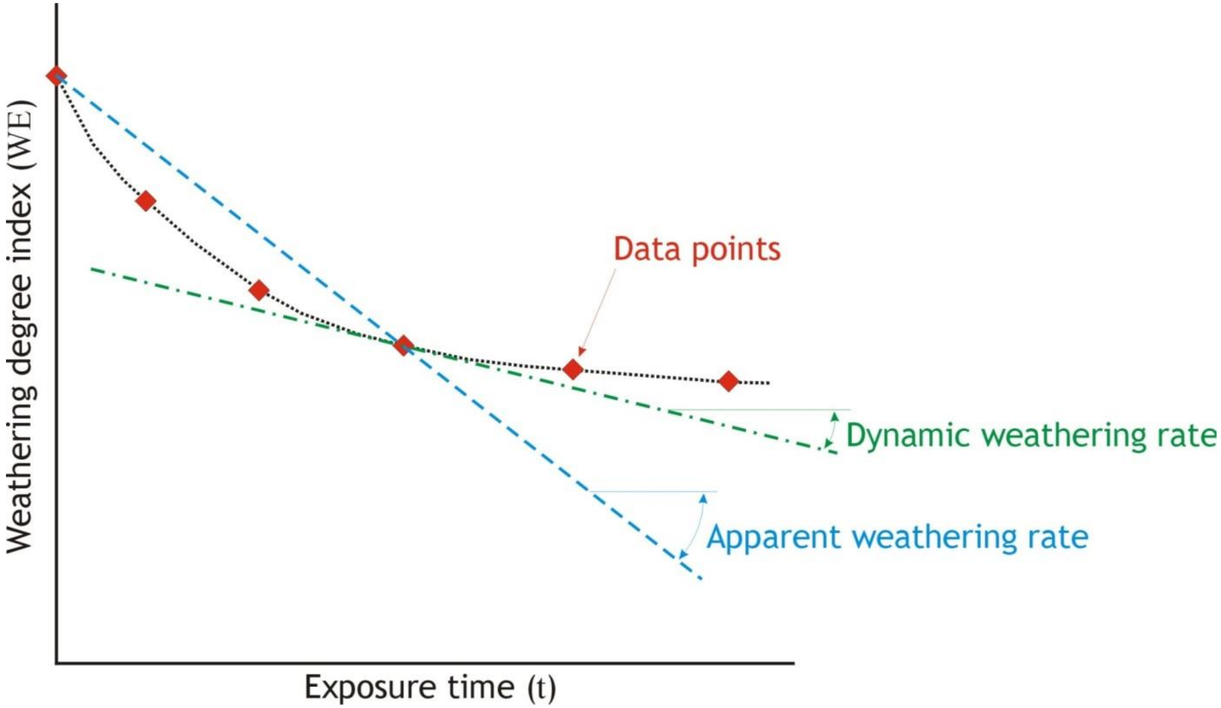
From: De Mulder, E.J.F., Hack, H.R.G.K., Van Ree, C.C.D.F., 2012.
Sustainable Development and Management of the Shallow Subsurface.
The Geological Society, London. ISBN: 978-1-86239-343-1. p. 192.

But if possible to assess the influence quantitatively than also the relation with time if the time of exposure is known

TIME RELATION - WEATHERING

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.



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

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)

SSPC system with applying weathering intensity rate:

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

KOTA KINABALU, MALAYSIA

(after Tating, Hack, & Jetten, 2011)

KOTA KINABALU

Side road (dip 45°, 5 years old)

sandstone: slightly weathered

SSPC

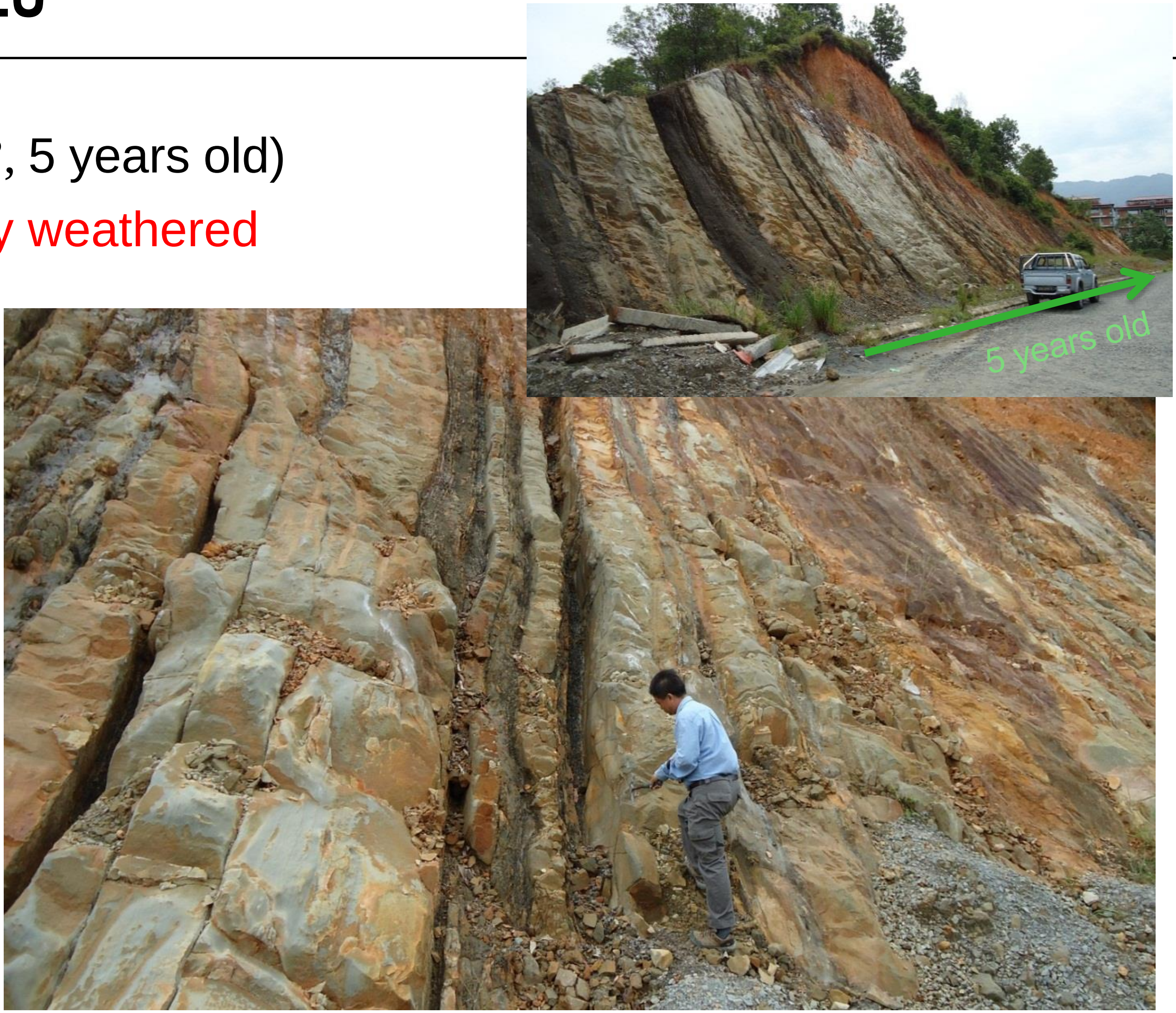
stability:

Sandstone:

stable (92%)

Shale:

unstable (< 5%)



KOTA KINABALU

Main road (dip 30°, 10 years old):

sandstone: moderately weathered

SSPC

stability:

Sandstone:

stable (95%)

Shale:

ravelling (<5%)

KOTA KINABALU

	time [years]	dip [degrees]	SSPC		visual
unit			RM friction	RM cohesion	
			[degrees]	[kPa]	
shale					
Slightly weathered	5	45	4	2.4	unstable
Moderately weathered	10	30	2	1.1	unstable
sandstone					
Slightly weathered	5	45	20	10.0	stable
Moderately weathered	10	30	11	6.3	stable

SSPC

SSPC system in combination with degradation forecasts gives:

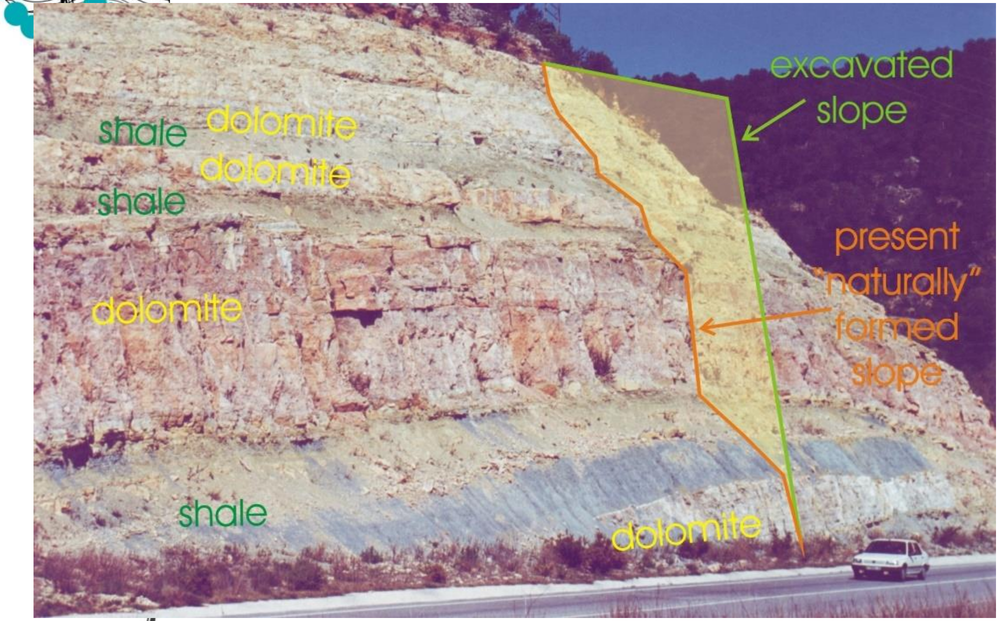
- reasonable design for slope stability
- with minimum of work and
- in a short time
- (likely a reasonable tool to forecast susceptibility to weathering)

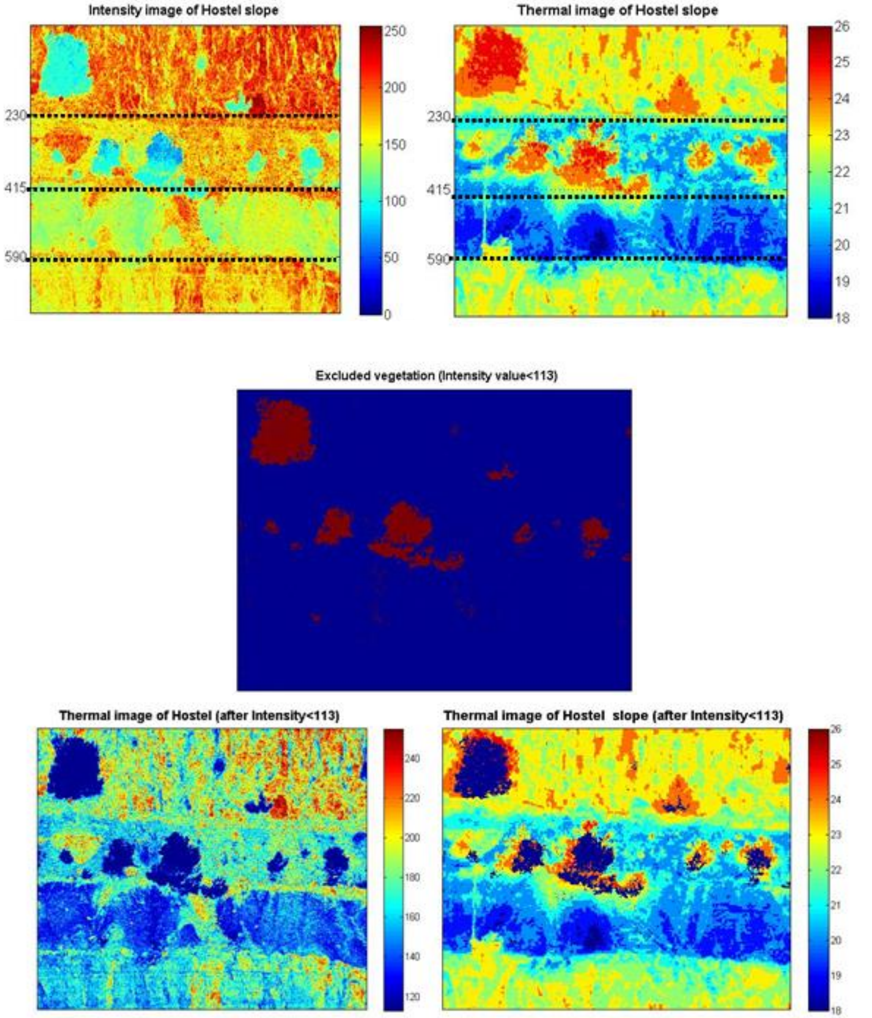
REMOTE SENSING

Remote sensing to detect weathering and weathering state:

- Possibly from UAV's (drones)
- Also inaccessible areas can be investigated

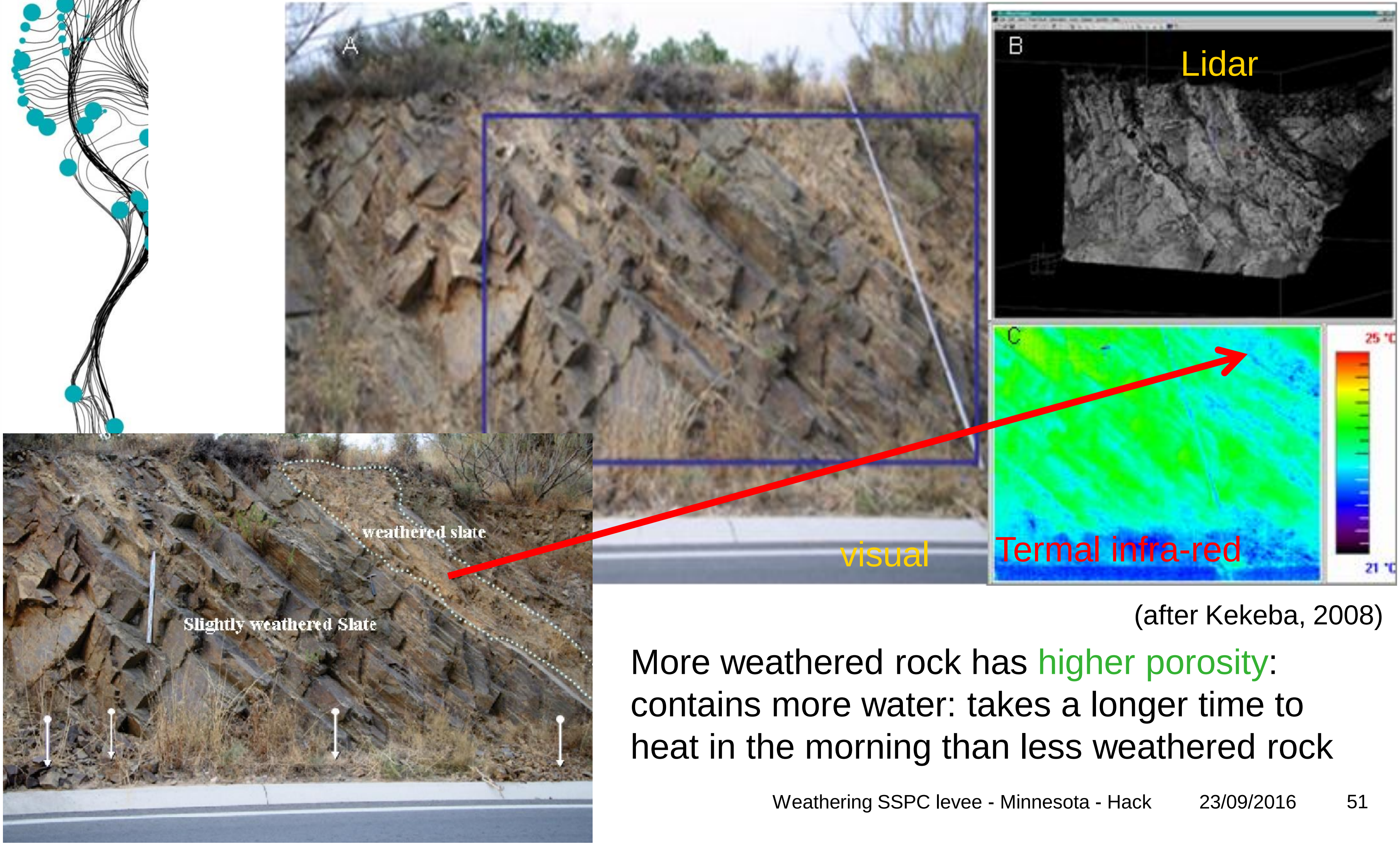
WEATHERING – TEMPERATURE REMOTE SENSING





Thermotracer
(thermal infra-red)

WEATHERING – TEMPERATURE REMOTE SENSING



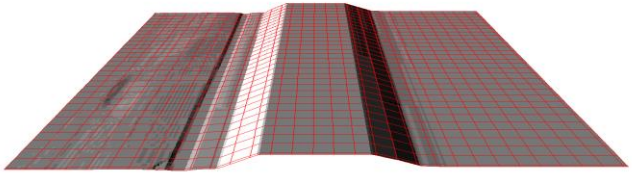
(after Kekeba, 2008)

More weathered rock has higher porosity: contains more water: takes a longer time to heat in the morning than less weathered rock

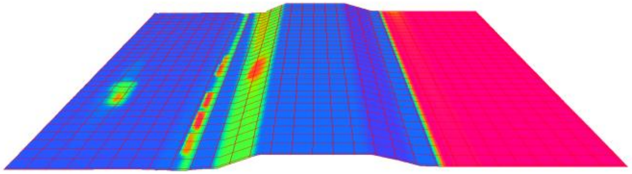
LEVEES

If remote sensing is an option to establish weathering than also it may be to establish geology in levees

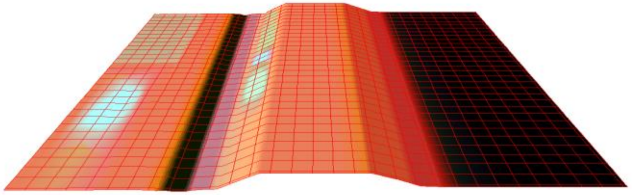
OPTIONS WITH REMOTE SENSING



Lidar
(geometry)

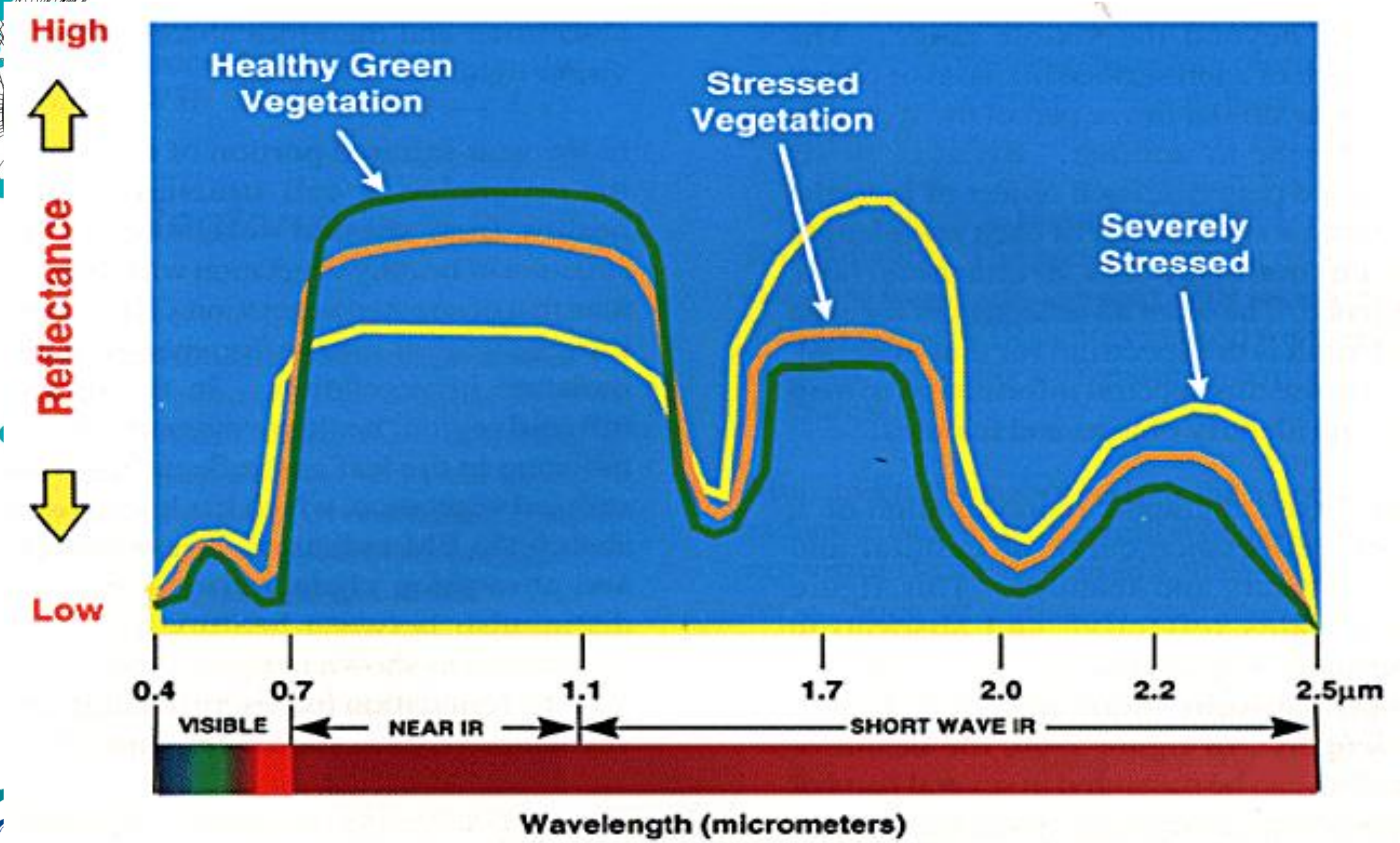


Thermal Infrared
(temperature differences, humidity)



Multi-spectral (vegetation, type of ground, humidity)

REFLECTANCE VERSUS VEGETATION STRESS



REFLECTANCE VERSUS VEGETATION STRESS

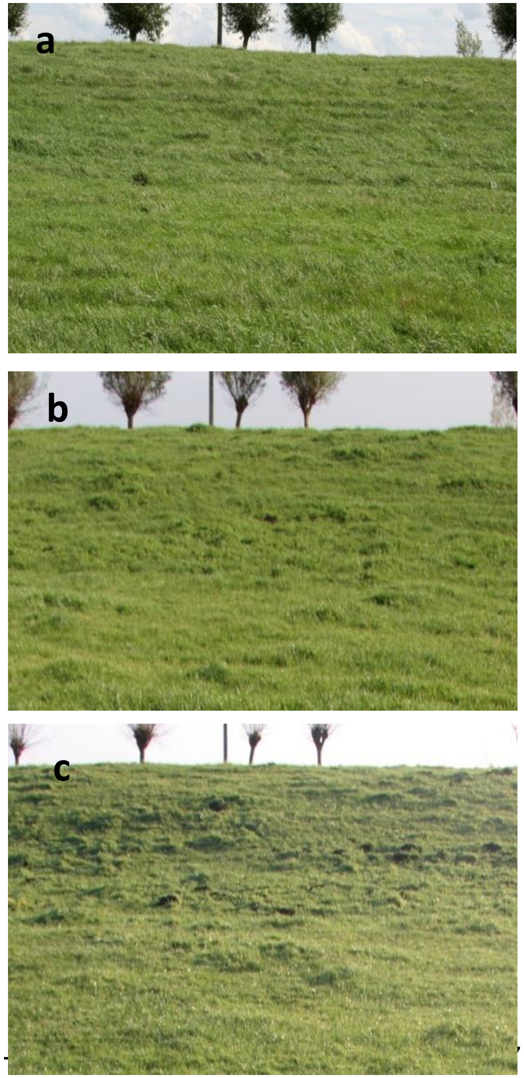
- Vegetation stress may be due to:

- Excess water
- Shortage water
- Vegetation unfriendly minerals or fluids (environmental pollution)

Shortage or excess of water may indicate weak areas in a dike

PEAT EXCAVATION

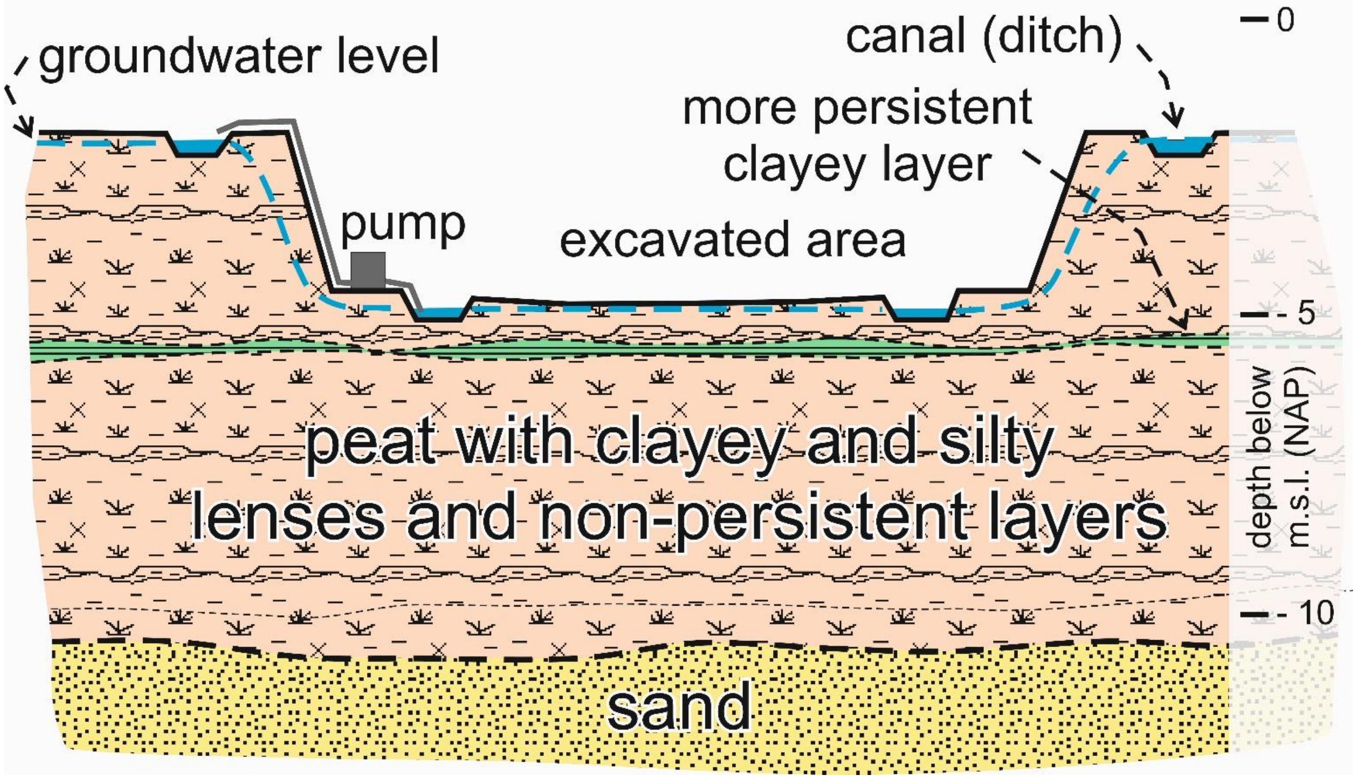
- The Reeuwijk area is a typical “polder” area in the peat excavation region of Zuid-Holland, The Netherlands
- Peat has been excavated for fuel and sometimes table salt since the early Medieval times (since 800 AD)
- Peat was excavated “under water” by scooping the peat down to a depth of about 4 - 6 m below the water level
- The peat was brought by boat to not-excavated strips of land with paths and roads left behind in-between the excavation areas



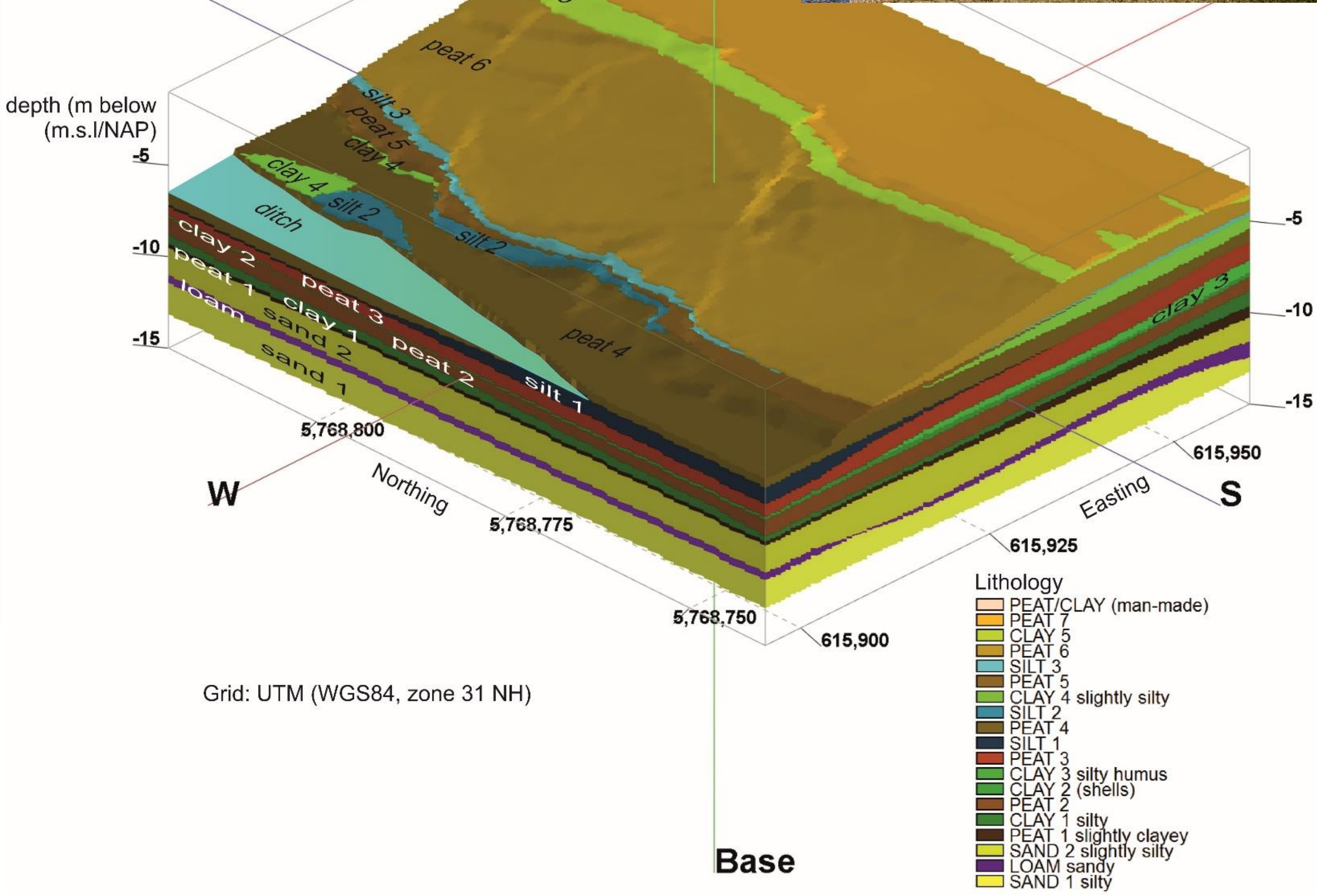
Visual images of Tempeldijk-South showing the difference in the apparent surface roughness in:
(a) August 15, 2007,
(b) October 31, 2007 and
(c) December 13, 2007

POLDER

In the 16th through 19th centuries, land shortage and increasing prices for agricultural land triggered pumping-out the water from the lakes by windmills; the "polders" were created

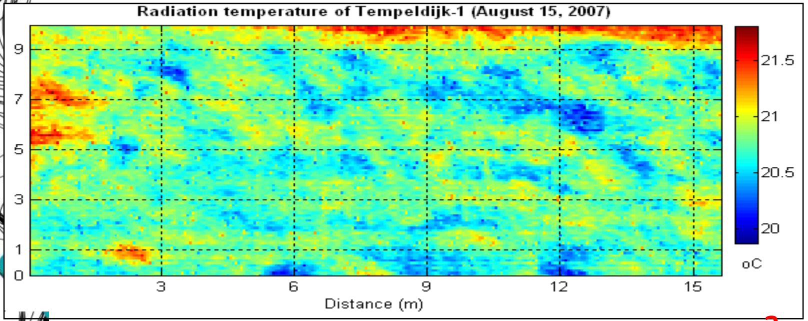


SUBSURFACE GEOLOGY - TEMPELDIJK-SOUTH LOCATION



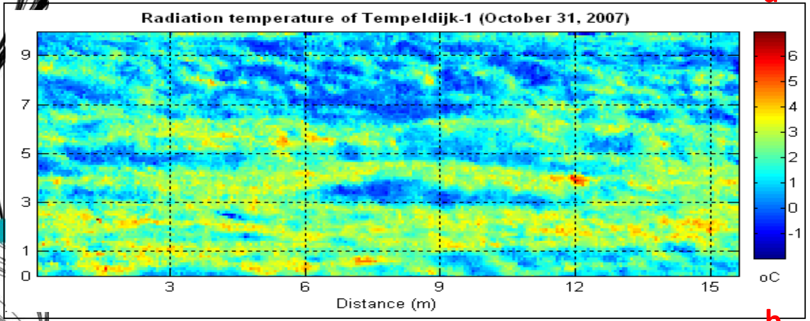
Grid: UTM (WGS84, zone 31 NH)

TEMPERATURE



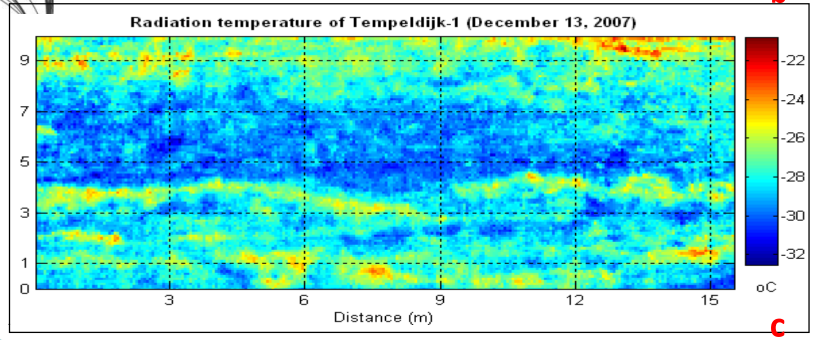
Radiation temperature of Tempeldijk-1 (August 15, 2007)

a



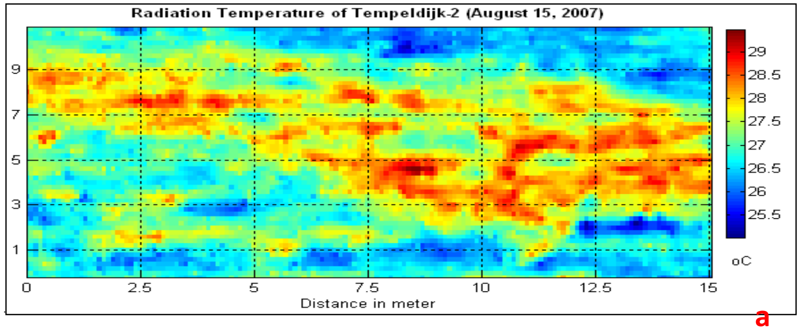
Radiation temperature of Tempeldijk-1 (October 31, 2007)

b



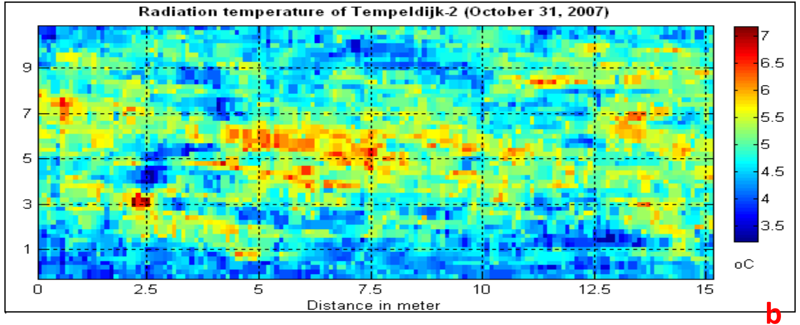
Radiation temperature of Tempeldijk-1 (December 13, 2007)

c



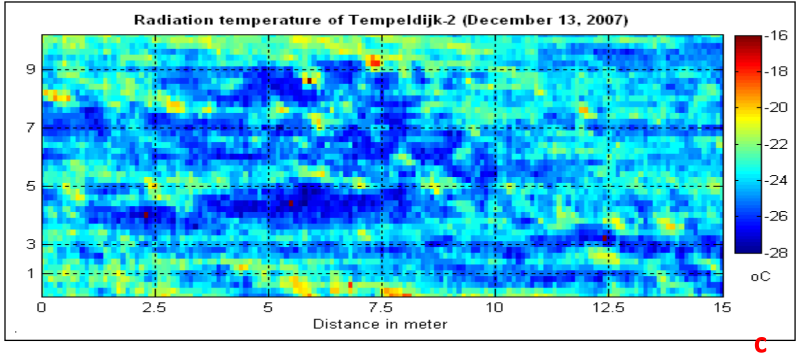
Radiation Temperature of Tempeldijk-2 (August 15, 2007)

a



Radiation temperature of Tempeldijk-2 (October 31, 2007)

b



Radiation temperature of Tempeldijk-2 (December 13, 2007)

c

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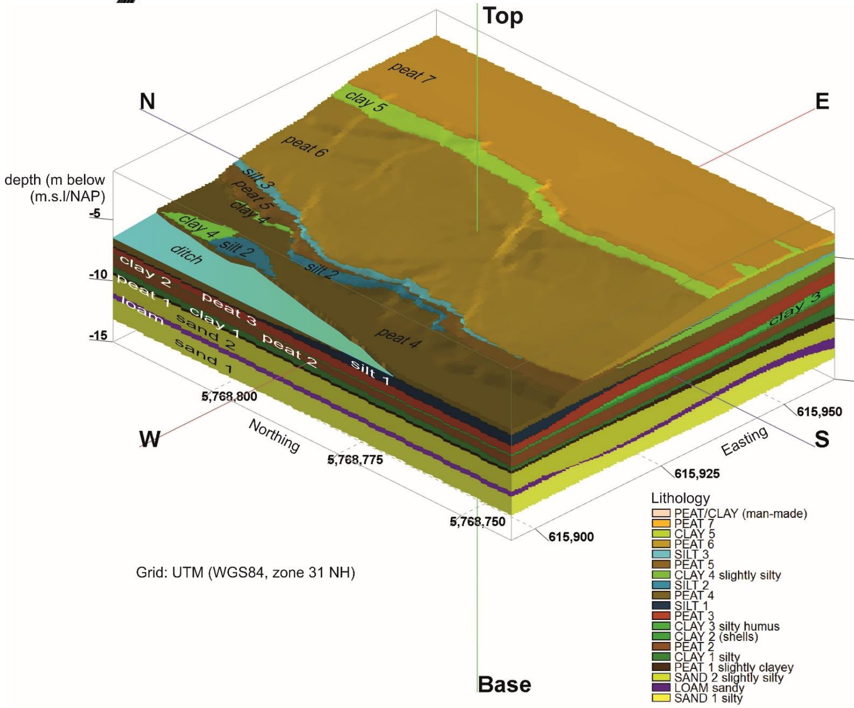

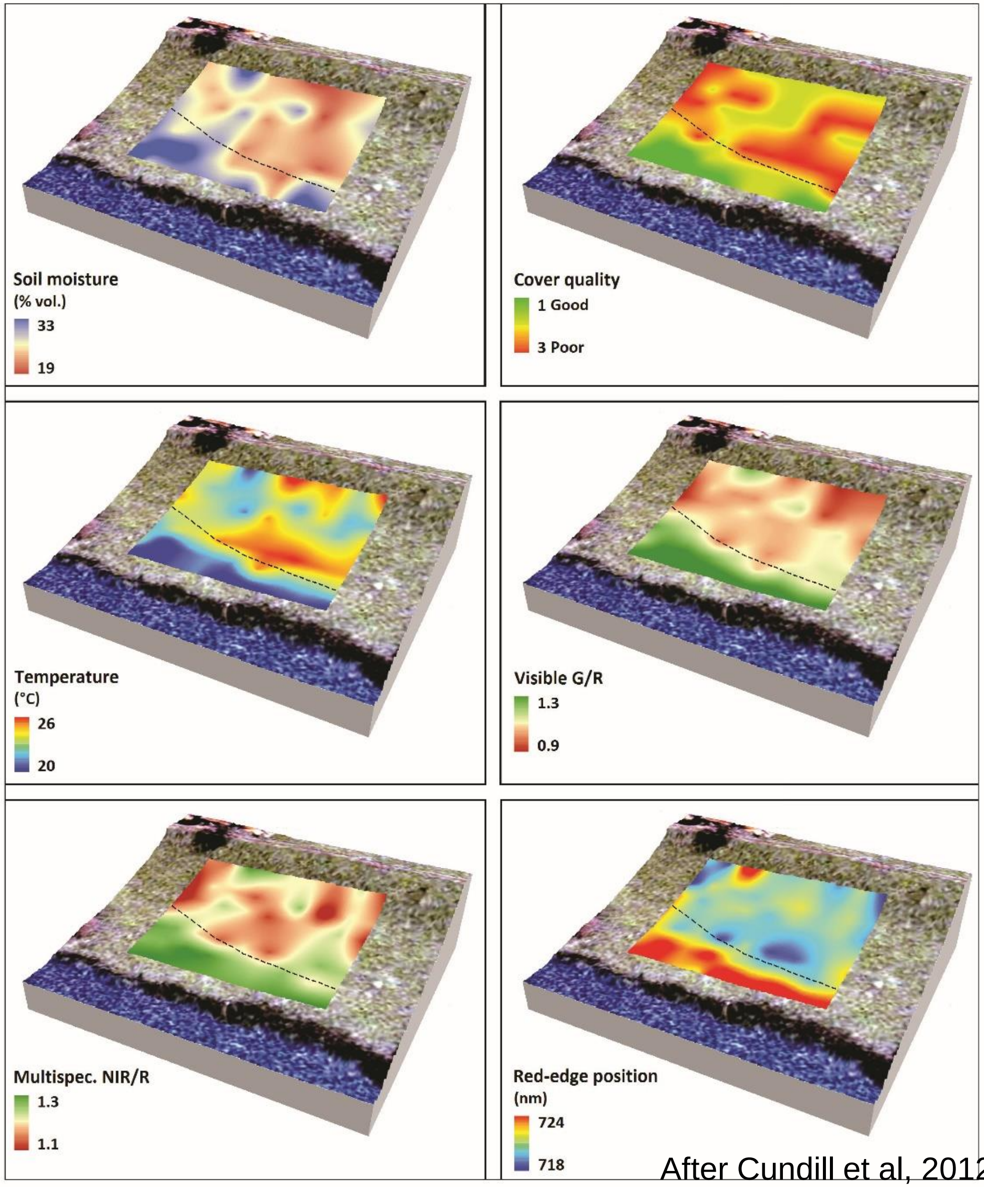

After Cundill et al, 2012

CONCLUSIONS

- Weathering can be quantified with help of rock mass classification systems
- SSPC seems suitable
- Quantified effects of weathering can be forecasted
- Remote sensing may be an option to establish different degrees of weathering
- Remote sensing may (with the same methodology) be suitable to detect weak areas in levees

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