WEATHERING DETERIORATING AND SLOPE STABILITY CLASSIFICATION FOR THE FUTURE

Robert Hack

Geo-Engineering, ESA, International Institute for Geoinformation Sciences and Earth Observation (ITC) The Netherlands

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Slopes in The Netherlands?
Dykes have slopes!

(Brouwersdam, The Netherlands)
Also real rock slopes in the Southern part of The Netherlands!

(ENC 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
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.
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
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 tunnels:

- 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

Existing systems did not give satisfactory results – hence development of a new system
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.
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
roughness

small scale

- stepped
  - amplitude roughness > 2 - 3 mm

- undulating
  - amplitude roughness > 2 - 3 mm

- planar

  ≈ 0.20 m
  (dimensions only approximate)

large scale

- wavy
  - $i = 14 - 20^\circ$
  - amplitude roughness: ≈ 5 – 9 cm

- slightly wavy
  - $i = 9 - 14^\circ$
  - ≈ 5 – 9 cm

- curved
  - $i = 4 - 8^\circ$
  - ≈ 3.5 – 7 cm

- slightly curved
  - $i = 2 - 4^\circ$
  - ≈ 1.5 – 3.5 cm

- straight
  - $i = 1^\circ$
  - ≈ 1 m

(i-angles and dimensions only approximate)
Infill:
- cemented
- no infill
- non-softening (3 grain sizes)
- softening (3 grain sizes)
- gauge type (larger or smaller than roughness amplitude)
- flowing material
Orientation dependent stability

Stability depending on relation between slope and discontinuity orientation
- Instability caused by discontinuities

Orientation independent stability

Stability not depending on relation between slope and discontinuity orientation
- Instability not caused by discontinuities (for example, failure of intact rock, water run off moving blocks from the slope, etc.)
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)
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)

- Laboratory test: $\phi=45^\circ$
- SSPC: $\phi\approx35^\circ$
- Stability assessed using:
  - SSPC – 55% stability probability, failure imminent ($\phi\approx35^\circ$)
Landslide in harbour – Saba – Dutch Antilles
### SSPC results

<table>
<thead>
<tr>
<th>Pyroclastic deposits</th>
<th>Calculated SSPC</th>
<th>Laboratory / field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock mass friction</td>
<td>35°</td>
<td>27° (measured)</td>
</tr>
<tr>
<td>Rock mass cohesion</td>
<td>39 kPa</td>
<td>40 kPa (measured)</td>
</tr>
<tr>
<td>Calculated maximum possible height on the slope</td>
<td>13 m</td>
<td>15 m (observed)</td>
</tr>
</tbody>
</table>

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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)
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 – Lidar imagery

Unit 1

Unit 2

Unit 3

(modified after Slob et al, 2002)
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.
Weathering rates

Weathering degree index (WE) vs. Exposure time (t)

- Data points
- Dynamic weathering rate
- Apparent weathering rate

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Weathering rates

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

- \( WE(t) \) = degree of weathering at time \( t \)
- \( WE_{\text{init}} = (\text{initial}) \) degree of weathering at time \( t = 0 \)
- \( R_{WE}^{\text{app}} \) = 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 intensity rate

SSPC system with applying weathering intensity rate:
- original slope cut about 50° (1998)
- now around 44° (2007)
- in 15 years decrease to 35° (2013)
New developments - Future
Remote sensing for assessing “degree of weathering”

Lidar intensity

thermal
Conclusions

• SSPC classification works for slope stability
• Classification can incorporate uncertainty
• Rates of weathering can likely be quantified

• be not afraid to abandon inherited methodologies and parameters
Future

- more objective (remote sensing) tools to determine heterogeneity and degree of weathering
- classification systems for earthquake areas
- influence of snow and ice
- submersed marine slopes?