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”
Homogeneous 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 homogeneous....”

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?
design error

Excavated slope

Present "naturally" formed slope

Shale
Dolomite
Dolomite
Shale
Dolomite
Shale
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 in April 1992.
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
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.

UCS = 150 MPa

clay-filled discontinuity
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?

\[
\text{UCS} = 150 \text{ MPa}
\]

clay-filled discontinuity

35°
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)

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

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 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

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

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

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

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

SLOPE GEOMETRY
Orientation
Height

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

- Degree of weathering
- Method of excavation
Rock mass Parameters

- Intact rock strength
- Spacing and persistence discontinuities
- Shear strength along discontinuity:
  - Roughness  - large scale
    - small scale
    - tactile roughness
  - Infill
  - Karst
- Susceptibility to weathering
Slope specific parameters for the new slope to be made

• Expected degree of weathering at end of lifetime of the slope
• Method of excavation to be used for the new slope
Intact rock strength

By simple means test:

hammer blows, crushing by hand, 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

(i-angles and dimensions only approximate)

amplitude roughness:

- Wavy: $i = 14 - 20^\circ$, $\approx 5 - 9 \, \text{cm}$
- Slightly wavy: $i = 9 - 14^\circ$, $\approx 5 - 9 \, \text{cm}$
- Curved: $i = 4 - 8^\circ$, $\approx 3.5 - 7 \, \text{cm}$
- Slightly curved: $i = 2 - 4^\circ$, $\approx 1.5 - 3.5 \, \text{cm}$
- Straight: $\approx 1 \, \text{m}$
Shear strength

roughness

small scale

stepped
amplitude roughness > 2 - 3 mm

undulating
amplitude roughness > 2 - 3 mm

planar

≈ 0.20 m (dimensions only approximate)

≈ 0.20 m

amplitude roughness > 2 - 3 mm
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

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

\[ TC = 0.0113 \times AP \text{ (deg)} \]

\( TC \) (discontinuity condition parameter) (-)

\( AP \) (apparent discontinuity dip in direction slope dip) (deg)

stable

unstable
Orientation dependent stability

Sliding criterion

sliding occurs if:

$$TC < 0.0113 \times AP$$
Orientation dependent stability

Sliding probability

![Graph showing discontinuity stability with respect to sliding]

- Discontinuity stable with respect to sliding
- Discontinuity unstable with respect to sliding

Orientation dependent stability

Sliding probability

![Graph showing discontinuity stability with respect to sliding]

- Discontinuity stable with respect to sliding
- Discontinuity unstable with respect to sliding
Orientation dependent stability

Discontinuity related shear strength failure
Toppling
Orientation dependent stability

Toppling criterion

\[ TC < 0.0087 \times (-90^\circ - AP + \text{dip}_{\text{discontinuity}}) \]

- TC = discontinuity condition factor
- AP = apparent discontinuity dip in direction of slope dip
- DIP_{discontinuity} = dip of discontinuity
Orientation dependent stability

Toppling probability

Fig. 9. Toppling criterion.

- Toppling probability graph showing the relationship between the TC (condition of discontinuity) and the slope dip (deg) for different orientations.

- Discontinuity stable with respect to toppling
- Discontinuity unstable with respect to toppling

- Orientation dependent stability
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

\[ CD = \frac{TC_1}{DS_1} + \frac{TC_2}{DS_2} + \frac{TC_3}{DS_3} \]

\[ = \frac{1}{DS_1} + \frac{1}{DS_2} + \frac{1}{DS_3} \]

\( TC_{1,2,3} \) 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

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

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

else

$$H_{max} = 1.6 \times 10^{-4} \times coh'_{mass} \times$$

$$\frac{\sin \left( dip_{slope} \right) \times \cos \left( \phi'_{mass} \right)}{1 - \cos \left( dip_{slope} - \phi'_{mass} \right)}$$
Probability orientation independent failure

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

- probability to be stable > 95 %
- probability to be stable < 5 %
Comparison between SSPC and other classification systems
SSPC stability probability (%)

- < 5
- 7.5
- 15
- 25
- 35
- 45
- 55
- 65
- 75
- 85
- 92.5
- > 95

Number of slopes (%)

- 0
- 20
- 40
- 60
- 80

Visually estimated stability:
- Stable (class 1)
- Unstable (class 2)
- Unstable (class 3)

SSPC

Haines' slope dip - existing slope dip (deg)

- -45
- -35
- -25
- -10
- -5
- 5
- 15
- 25
- 35
- 45

Haines safety factor: 1.2

Number of slopes (%)

- 0
- 20
- 40
- 60
- 80

Visually estimated stability:
- Unstable
- Stable

SMR

Romana's SMR (points)

- 5
- 15
- 25
- 35
- 45
- 55
- 65
- 75
- 85
- 95

Number of slopes (%)

- 0
- 20
- 40
- 60

Visually estimated stability:
- Completely unstable
- Unstable
- Partially stable
- Stable
- Completely stable

Comparison

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)
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).


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)
- Dip direction and dip
- Spring
- Contour thickness slope debris (m)
- Land slide of February 1997
- Instable blocks
- I-II-III-IV Geotechnical zone
- Topography (m)

University Twente.

2011-04-08 - Kota Kinabalu - Recent SSPC - Robert Hack
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>39kPa</td>
<td>40kPa (measured)</td>
</tr>
<tr>
<td>Calculated maximum</td>
<td>13m</td>
<td>15m (observed)</td>
</tr>
<tr>
<td>possible height on the slope</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
Widening existing road in Bhutan (Himalayas)
Widening existing road in Bhutan (Himalayas)

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)

(unit 1)

(unit 2)

(unit 3)

(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.
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

<table>
<thead>
<tr>
<th>Degree of weathering in slope (BS5930, 1981)</th>
<th>WE [-] (SSPC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unweathered</td>
<td>1.00</td>
</tr>
<tr>
<td>Slightly weathered</td>
<td>0.95</td>
</tr>
<tr>
<td>Moderately weathered</td>
<td>0.90</td>
</tr>
<tr>
<td>Highly weathered</td>
<td>0.62</td>
</tr>
<tr>
<td>Completely weathered</td>
<td>0.35</td>
</tr>
</tbody>
</table>
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 degree index (WE) vs. Exposure time (t)

- Data points
- Dynamic weathering rate
- Apparent weathering rate
Weathering rates

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

\( WE(t) \) = degree of weathering at time \( t \)
\( WE_{init} \) = (initial) degree of weathering at time \( t = 0 \)
\( R_{\text{app,WE}} \) = 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 $R(\text{app}WE)$ for Middle Muschelkalk, siltstone (gypsum cemented), versus slope dip-direction (after Huisman)
Weathering intensity rates $R(\text{appWE})$ for Middle Muschelkalk, gypsum, versus slope dip-direction (after Huisman)
Weathering intensity rate

SSPC system with applying weathering intensity rate:
- original slope cut about 50° (1998)
- in 15 years decrease to 35°
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:

<table>
<thead>
<tr>
<th>Material</th>
<th>Friction (deg)</th>
<th>Cohesion (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slightly (5 years)</td>
<td>4</td>
<td>2.4</td>
</tr>
<tr>
<td>Moderately (10 years)</td>
<td>2</td>
<td>1.1</td>
</tr>
<tr>
<td>Sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slightly (5 years)</td>
<td>20</td>
<td>10.0</td>
</tr>
<tr>
<td>Moderately (10 years)</td>
<td>11</td>
<td>6.3</td>
</tr>
</tbody>
</table>
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 ???????


