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QUANTIFYING SLOPE STABILITY DECREASE IN ENGINEERING LIFETIMES USING BOOTSTRAP PERCENTILES

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ABSTRACT

To ensure the stability of a man-made slope in a rock or soil mass throughout its envisaged engineering lifetime, the decrease of relevant strength properties of the slope material has to be taken into account. Following the initial stress release after excavation, weathering and erosion processes will start acting upon the newly exposed slope material and as field data shows, this may have a significant effect in less than one hundred years.

In this study, a statistical approach to the trend analysis of actual weathering classification data is proposed, which makes use of the bootstrap percentile method and the Monte Carlo simulation technique. This methodology results in empirical relationships between strength properties and the age of the slope, with quantified probabilities. A fully quantified probabilistic slope stability assessment can then be made. In such an assessment, a slope design may be evaluated with regard to the slope stability over the full engineering lifetime of the slope and consequently different designs can be compared.

BACKGROUND

Man-made slopes in rock and soil masses, such as road cuts, are generally designed to be stable throughout the so-called engineering lifetime, typically fifty to one hundred years. During that period the materials exposed in the slopes are subject to weathering and erosion. Although these are commonly regarded as processes acting on geological rather than human time scales, practice shows that the rock or soil masses in the slope may be significantly affected even in relatively short periods of time. Thus, these time-related processes may lead to a loss of structural integrity and deterioration of the geotechnical mass properties, causing a degradation of the materials in the slope and a decrease of the slope stability.

To ensure safe construction of a slope, and to maintain a degree of stability that meets the requirements throughout the whole envisaged engineering lifetime, this degradation of the geotechnical mass with time should be incorporated in the initial design. However, the significance and extent of degradation of soil and rock mass properties within periods of up to one (or several) hundred years is only partially understood, and generally, relations are not quantified. In this study, a statistical evaluation of classification results provides us with an empirical relation between weathering degree and time with fully quantified uncertainties. From this, the decreasing slope stability is derived as a function of time as well.

RESEARCH AREA

The data presented in this paper was collected in the Tarragona province in North-eastern Spain. Here, the Southwest-Northeast orientated Catalanides mountain range separates the coastal plain from the Ebro river basin. It is bounded in the south by the Ebro delta. The stratigraphy of the area consists of a sedimentary sequence of essentially Devonian through to Quaternary age. Igneous rocks occur, intruded into Carboniferous formations as granodiorite bodies and aplitic dykes. The intrusions are from Carboniferous to Permian age and possibly associated with the Hercynian orogeny. The data used in this study was collected in the Triassic sediments of the Middle Muschelkalk. The Triassic corresponds with the Germanic facies type; it is characterized by massive or very thick bedded sandstones with some conglomerate beds at the base (Buntsandstone), followed by thick bedded limestones and dolomites (Lower Muschelkalk), deformed sandy clayey siltstone with gypsum (Middle Muschelkalk) and limestones and dolomites of the Upper Muschelkalk. The youngest formation in the Triassic (Keuper) is a sequence of shales and siltstones, in the lower part interbedded with limestones and dolomites.

The climate in the area is arid mediterranean, with dry, hot summers (temperatures from 15° to 35°C) and moderate winters (10° to 15°C), in which temperatures may reach below 0°C. Rivers and streams in the area are mostly dry from March until October/November. It may rain for long periods during the winter, sometimes torrential, and even up to March/April although this is not typical. The Catalanides rise up to about 1000 m above sea level. Extensive agricultural use is made of the soft soils and weathered rocks in the valleys, and the coastal plain. The more mountainous areas are covered with forests or are barren.

Many road cuts in the area have been constructed or renewed in the first half of the 20th century using several excavation techniques. In the period since 1988 new roads have been constructed, and some of the older roads have been realigned; at several locations construction works are carried out at present. Slopes dating from both these construction periods have been classified in the last ten years in the course of engineering geological fieldwork by ITC in cooperation with the Delft University of Technology. Especially for the recent constructions, detailed age information is available (e.g. Huisman, 2001). The actual exposure time for old road cuts and natural outcrops, that have been incorporated in the research as well, is harder to establish.

THE SSPC SYSTEM

The basis for the degradation analysis of the slopes in this study is the Slope Stability Probability Classification (SSPC) system, which was validated specifically for the research area (Hack, 1998). The classification involves a description of the rock material and rock mass properties according to the British Standard BS5930 (1981), together with a more elaborate description of the discontinuities. The SSPC method can be described as a three-step classification system and considers three rock masses (Hack et al., 2002):

1. The rock mass in the exposure: the "exposure rock mass" (ERM).
2. The rock mass in an unweathered and undisturbed condition prior to excavation: the "reference rock mass" (RRM).
3. The rock mass in which the existing or new slope is to be situated: the "slope rock mass" (SRM).

First, rock mass parameters of importance are described and characterized in an exposure resulting in the "exposure rock mass"; this is the actual field classification. This exposure rock mass is then converted into a theoretical rock mass that exists below the influence zones of weathering (thus fresh). Other disturbances due to local influences such as weathering and the disturbance due to the excavation method are corrected for. This theoretical mass is termed the "reference rock mass" (RRM). The actual stability assessment is made in the "slope rock mass" (SRM). This is derived from the "reference rock mass" (RRM) by correction of the parameters of the "reference rock mass" with the slope specific parameters. Slope specific parameters are correction parameters for the influence of future weathering within the engineering lifetime of the slope and for the influence of the method of excavation to be used (Hack et al., in press).

In the SSPC, the stability of a (future) slope in the slope rock mass is determined in two different analyses: orientation dependent or orientation independent. The first is related to the orientation of the discontinuities and the slope and considers sliding and toppling, the second considers slope failure that is not related to discontinuities.

ROCK MASS WEATHERING IN ENGINEERING LIFETIMES

Since the slope rock mass strength properties and the resulting slope stability as found with the SSPC system directly depend on the degree of weathering in the slope rock mass, this parameter has to be predicted when the stability is to be assessed for some time in the future. A first approximation can be found from a plot of the recorded degrees of weathering in different slopes cut into the same engineering geological units that are subjected to similar weathering conditions against their different exposure times.

The degree of weathering is quantified in the SSPC system with the parameters WE (for the exposure rock mass) and SWE (for the slope rock mass); WE and SWE are values smaller than or equal to one, representing the decrease in strength properties by weathering. The parameter is assigned to the different weathering degrees of the British Standard BS5930 (1981) according to Table 1 (after Hack & Price, 1997).

Table 1 - WE-values as assigned to different weathering degrees (validated for the research area).

Degree of weathering in slope	WE (SSPC)
Unweathered	1.00
Slightly weathered	0.95
Moderately weathered	0.90
Highly weathered	0.62
Completely weathered	0.35

Throughout this paper, observed WE values and exposure times for the slopes in the clayey Middle Muschelkalk of the Tarragona province in Spain are used as an example of the described methodology. This relatively weak unit shows in the field a clear decrease of mass strength within engineering times. Nine slopes were selected, all facing southward (from 87° to 271°). The groundwater situation is the same for all slopes: mostly completely dry, with surface runoff during rainfall. Vegetation, trees and land use above the slopes are comparable. The data is presented in Table 2.

Any trend fit should pass through a fixed WE-value at time = 0; the following general function satisfies this condition and closely resembles the observed trend in the data:

$$WE(t) = WE_0 - \left(WE_0 - WE_\infty\right)\left(1 - e^{-\alpha t}\right) \tag{1}$$

Table 2 - Observed WE-values for south-facing Middle Muschelkalk slopes in the Tarragona province.

Slope	Slope dip direction [°]	Year of observation	Year of excavation	Exposure time [years]	Observed WE [-]
1	260	1996	1992	4	0.95
2	225	1997	1992	5	0.95
3	271	1997	1992	5	0.90
4	87	1998	1988	10	0.90
5	134	1996	appr. 1925	71	0.62
6	170	1997	appr. 1925	72	0.62
7	190	1997	appr. 1925	72	0.62
8	90	1997	appr. 1850	147	0.62
9	200	2000	appr. 1850	150	0.62

In equation (1), WE_0 is the WE-value at time = 0; for rock masses that have not been affected by weathering before being excavated, this parameter is 1.00. WE_∞ is the WE-value at infinity, and represents the end stage of weathering for the considered rock mass in the setting and environment of the slope. The parameter α is a measure for the weathering rate. If WE_0 is taken to be 1.00, α and WE_∞ can be solved with a least squares regression method. For the nine selected slopes, the best fit is obtained with $\alpha = 0.038$ and $WE_\infty = 0.606$.

On first sight this empirical function could be used to predict the degradation in time for a new slope in the same type of rock mass and setting. In such a trend analysis however, it should be noted that both the recorded exposure times and the observed WE-values are in fact stochastic parameters with some uncertainty as to the true value. For the exposure time, the uncertainty comes from the fact that the age of a slope may not be known exactly, but only as an approximation; this is especially true for older slopes. For WE, the observer might over- or underestimate the degree of weathering. This means that the “true” relationship between WE and time may well be different from the best fit that is found for the original data. Only if we can quantify this uncertainty, a trend analysis is a valid tool to predict future weathering degrees, and only then the variability in a prediction of the future slope stability will become clear. In the methodology described below, this is dealt with using a Monte Carlo approximation of the bootstrap percentile estimate.

BOOTSTRAP / MONTE CARLO TREND ANALYSIS

In statistical analysis, the bootstrap method is a way to "pull oneself up by one's bootstrap": by generating a large amount of imaginary yet realistic data from a limited set of samples, it enables us to quantify statistical parameters that can only be determined with difficulty, or not at all, from the original samples (Efron and Tibshirani, 1998). Bootstrap percentiles such as used in this study are an accepted and effective method to determine reliability intervals (e.g. Chernick, 1999). In this case the percentiles will be derived for WE as a function of time.

To apply the bootstrap method to a trend analysis such as that we are dealing with here, probability distributions have to be assigned to the recorded exposure time and the observed WE. Various alternatives exist for this, such as a normal distribution (quantified with mean and standard deviation), a block distribution (quantified with upper and lower boundaries), and a triangular distribution (quantified with lower, most likely and upper values). The normal distribution and similar types do not have a fixed upper or lower boundary; in theory, any value is possible (albeit with a very small probability for extremely low or high values), whereas the block and triangular distributions do have a fixed upper and lower limit. In this case, the latter is more realistic, and the triangular distribution is preferred over the block distribution since some emphasis can be put on the observation itself (with the most likely-value).

In a Monte Carlo simulation, a random number between 0 and 1 is generated, for which the unique corresponding value from the appropriate inverse probability distribution function is taken as imaginary data; this is done for every data point, for both the exposure time and WE. The problem remains how to quantify the distribution and to find valid lower, most likely and upper values. For the exposure time, it is assumed here that the true exposure time falls within plus or minus 10% of the recorded time. For WE, trials with student groups during fieldwork training indicated that the weathering degree will be under- rather than overestimated in weak formations such as the Middle Muschelkalk; accordingly, WE is characterized in this paper with a one-sided triangular distribution, with upper limit and most likely value equal to the observation, and lower limit one degree higher (i.e. with a lower WE) than the observation.

With the triangular distributions defined above, for every data point a random value is selected for time and WE using a Monte Carlo simulation and by repeating this for the whole original data set, a simulated data set is obtained for which one best trend fit can be found with equation (1), described with $WE_0 = 1$ and the parameters WE_∞ and α. This process can be repeated over and over again for a specified number of Monte Carlo runs. We will thus find a set of trend fits for the time interval of interest. For this interval, we can define a line connecting the uppermost fitted points for every time in the interval; below this line we find 100% of the modelled values. Similarly, for every percentage between 0 and 100% we can define a line describing the upper limit for that percentage: these are the bootstrap percentiles (Chernick, 1999). The result of this operation is presented in Figure 1 for exposure times between 0 and 120 years.

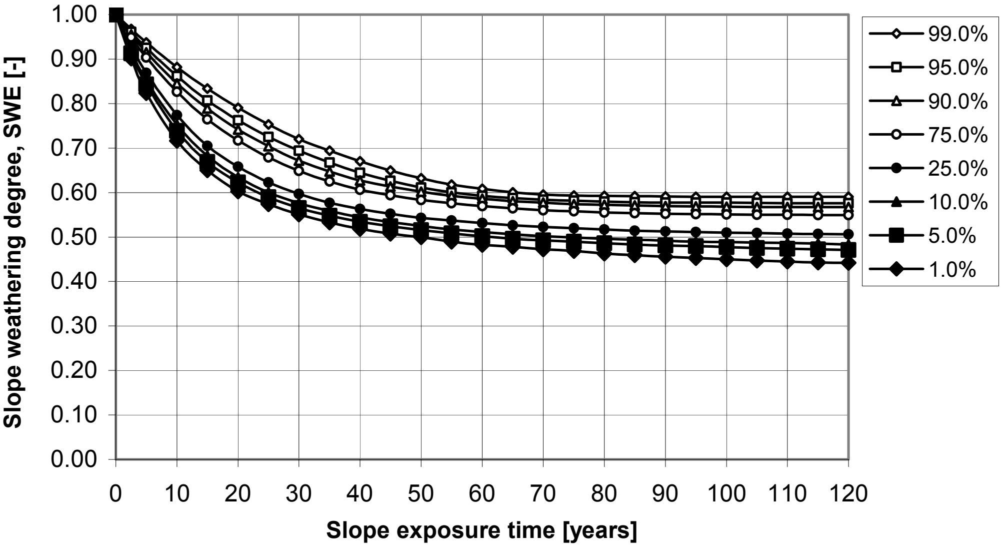

Figure 1 - Single-sided percentiles for SWE as a function of time. Percentages indicate the fraction of expected SWE values below the lines. Data resulting from 1000 Monte Carlo runs.

PROBABILISTIC SLOPE STABILITY ASSESSMENT

The graph of Figure 1 gives the percentiles for the slope weathering parameter as a function of the exposure time. In the SSPC system, this SWE-value is used to calculate the slope rock mass strength parameters that govern the stability and therefore we can obtain percentiles for these parameters and for the stability probabilities themselves as well. Combined with a slope design (slope angle, orientation, height, and method of excavation "SME"), the SSPC reference data that is obtained with a rock mass classification as described by Hack (1998) can be used for the stability assessment. An example of this will be given based on the design values in Table 3.

Table 3 - Data used in stability assessment example.

SSPC reference rock mass data			Slope data			Discontinuity data		set 1	set 2	set 3
RIRS	[MPa]	10	Slope dip	[°]	70	Dip direction	[°]	192	121	34
RSPA	[m]	0.50	Dip direction	[°]	180	Dip	[°]	30	44	58
RCD	[-]	0.70	Height	[m]	7.0	RTC[*]	[-]	0.38	0.38	0.38
			SME	[-]	1.00					

[*] condition of a single discontinuity set, according to SSPC classification

With the discontinuity and slope orientations listed in Table 3, we can expect the discontinuity set most prone to sliding will be set 1, and the one most prone to toppling will be set 3; this could of course also be inferred from a stereogram plot (not given here). Based on the SWE bootstrap percentiles given in Figure 1, corresponding percentile lines can be calculated with the SSPC system for all the relevant slope stability probabilities. Results of this are presented in Figure 2 to Figure 4. Figure 2 gives percentiles for the stability probability with respect to sliding over discontinuity set 1, Figure 3 for toppling over discontinuity set 3, and Figure 4 for the orientation independent stability. Whereas the percentiles for sliding and toppling are in a relatively narrow band, those for the orientation independent stability show a markedly wider spread. This spread decreases with increasing exposure time, and after a realistic engineering lifetime of about 75 years the percentiles are all at an approximately constant level.

At first sight, the interpretation of these figures might be considered complicated, incorporating percentiles (i.e. a probability of occurence) for a probability (for the slope to be stable). For the slope stability probability, a threshold value has to be defined as the lowest acceptable value. According to the U.S. Army Corps of Engineers (Anon., 1995), a 93% probability to be stable should be considered as “unsatisfactory”, and an 84% probability as “hazardous”.

From the figures, we can see that the threshold for a stability regarded as “hazardous” is reached with 99% probability after less than half a year for toppling, after 5 years for orientation independent failure, and after 43 years for sliding. Obviously, this design should be considered as unstable; although failure may not occur directly after excavation, toppling and orientation independent failure will occur with a very high probability level well before the end of an acceptable engineering lifetime.

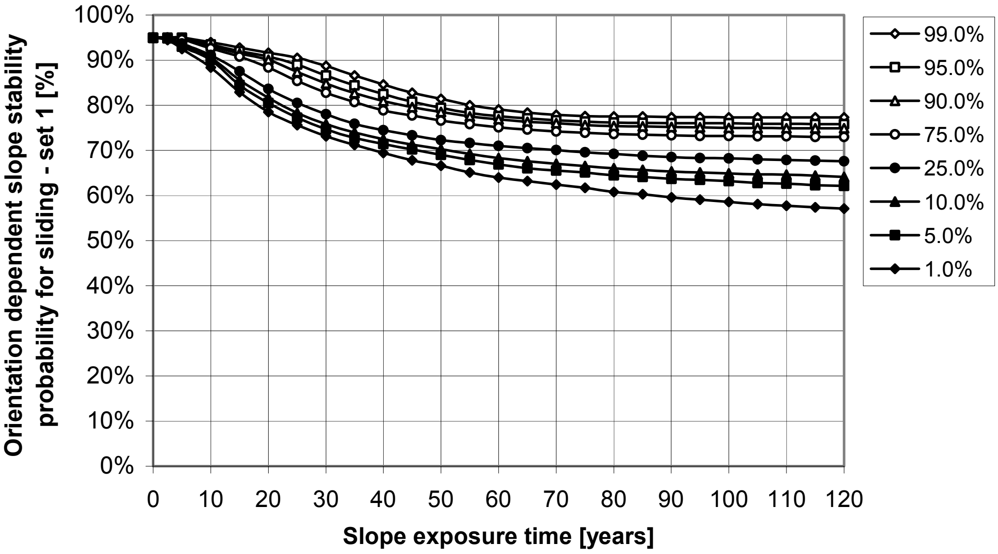

Figure 2 - Slope stability probability with respect to sliding over discontinuity set 1. Data resulting from 1000 Monte Carlo runs.

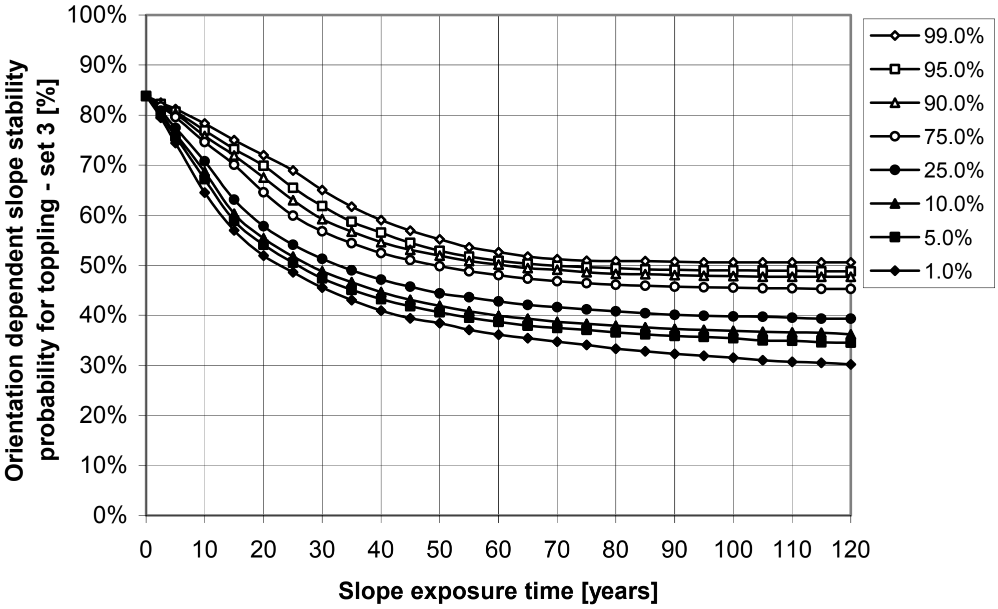

Figure 3 - Slope stability probability with respect to toppling for discontinuity set 3. Data resulting from 1000 Monte Carlo runs.

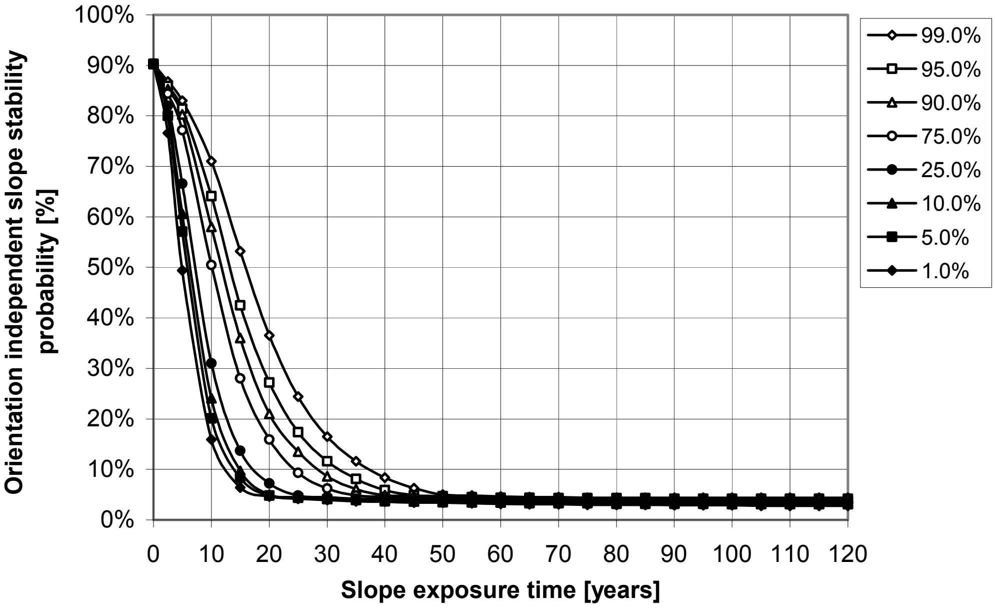

Figure 4 - Slope stability probability with respect to orientation independent failure. Data resulting from 1000 Monte Carlo runs.

CONCLUDING REMARKS

The stability of a man-made slope cut into a rock mass will decrease with time because of weathering and subsequent degradation of the rock mass strength characteristics. As data from the Middle Muschelkalk in the Tarragona province of Spain shows, the effects of weathering may be significant already within hundred years. Since the degree of weathering in a slope is incorporated in the stability models of the SSPC system, the effects of weathering on the stability can be assessed as a function of time. By taking into account the variability of the input data, the resulting slope stability can be quantified with bootstrap percentiles. This is demonstrated for three failure mechanisms (sliding, toppling, and orientation independent).

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