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QUANTIFICATION OF WEATHERING

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ABSTRACT: Weathering and especially future weathering after construction of a slope is a main cause for failure of a slope during its engineering life-time. In the course of developing a rock mass classification system for slope stability, large quantities of data have been collected for quantification of past and future weathering influences on rock mass geotechnical parameters. This research resulted in the determination of reduction values related to the degrees of rock mass weathering as described by the British Standard, that give the reduction of a geotechnical rock mass parameter if the degree of weathering increases. The large quantity of data allowed for a statistical analysis that assesses the reliability of the values found for the reduction values. These reduction factors are developed in the context of a slope classification system, however, there is no reason that these reduction factors are not valid for other engineering projects in or on rock masses.

1 INTRODUCTION

Weathering and especially future weathering after construction of a slope is a main cause for failure of a slope during its engineering life-time. In the course of developing a slope stability classification system: the Slope Stability Probability Classification (SSPC) system (Hack, 1996), large quantities of data have been collected for quantification of weathering influences on rock mass geotechnical parameters important in slope stability. The rock slope classification scheme classifies rock mass parameters in one or more exposures. These are compensated for weathering and excavation disturbance in the exposures and parameters important for the mechanical behaviour of a slope for an imaginary unweathered and undisturbed 'reference' rock mass are calculated. The slope stability assessment thence allows assessment of the stability of the existing or any new slope in the reference rock mass, with allowance for the influence of excavation method and future weathering. The influence of weathering is related to the degrees of rock mass weathering as described by BS 5930 (1981). The research has been done in the region around Falset and Salou, province Tarragona, Spain. In this area a large variety of different lithologies are present in different degrees of weathering. Lithologies consist of sandstone, limestone and dolomites, slates, shales, and intrusives such as granodiorite and aplitic dykes. Lithologies containing large quantities of gypsum are also present. The large quantity of data collected allowed for a statistical analysis to determine the reliability of the reduction factors.

2 DATA

Students and staff of ITC and the Technical University Delft, in total about 60 different persons, characterized rock masses by determining the degree of weathering (following BS 5930; 1981, Table 1), intact rock strength and spacing and condition of discontinuities in exposures. Four years of data collection resulted in 250 characterizations of rock masses in the Falset area. Obviously not all data were of high quality as students were in a learning process. This was, however, anticipated, for the involvement of a large number of different persons, not all experienced rock mechanics specialists, was a preset requirement to avoid operator bias in the data.

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Term	Description	degree
Fresh	No visible sign of rock material weathering; perhaps slight discolouration on major discontinuity surfaces.	I
Slightly weathered	Discolouration indicates weathering of rock material and discontinuity surfaces. All rock material may be discoloured by weathering.	II
Moderately weathered	Less than half of the rock material is decomposed or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework or as core stones.	III
Highly weathered	More than half of the rock material is decomposed or disintegrated to a soil. Fresh or discoloured rock is present either as a discontinuous framework or as core stones.	IV
Completely weathered	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact.	V
Residual soil	All rock material is converted to soil. The mass structure and material fabric is destroyed. There is a large change in volume, but the soil has not been significantly transported.	VI

Table 1. Degrees of rock mass weathering - BS 5930 (1981).

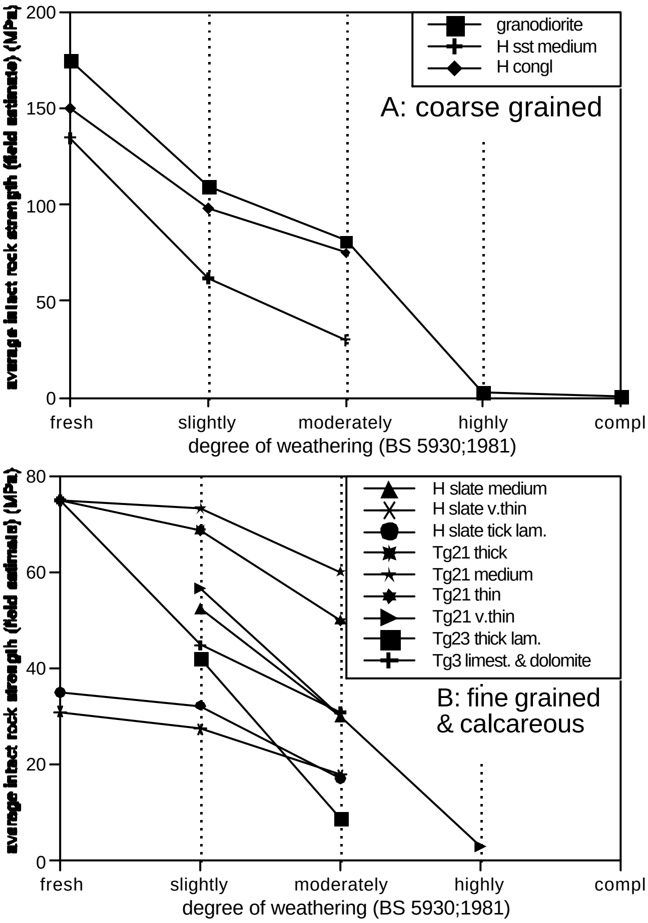

Fig. 1. Examples of the influence of weathering on intact rock strength and spacing of discontinuities.

3 WEATHERING

Weathering is the chemical and physical change in time of intact rock and rock mass material under the influence of the atmosphere and hydrosphere. In this research also the effects of stress relief, intact rock creep and rock mass creep are included in the definition of weathering. Intact rock, and rock mass creep and stress relief can lead to new cracks in intact rock, develop integral discontinuities into mechanical discontinuities and open existing discontinuities. Weathering of intact rock discolours the material and decreases intact rock strength. Further progressive weathering of minerals and cement may lead to a decomposition of the intact rock ultimately resulting in a residual soil. The discontinuity wall material and the infill material in discontinuities are, in general, weakened, resulting in lower shear strength along the discontinuities. The material resulting from weathering of the discontinuity walls will often form an infill in the discontinuities. The discontinuity wall loses its asperities and becomes smoother. The discontinuities become visible and can therefore be measured, resulting in lower values for discontinuity spacings. Thus, weathering causes lower values for intact rock strength, spacing of discontinuities and the shear strength along discontinuities. Examples of the averages of intact rock strength versus the degree of rock mass weathering are shown in Fig. 1. Similar results are obtained for other rock mass properties. The trend of the decrease is roughly the same for different units and lithologies. Calcareous units show a similar decrease of the values of geotechnical properties with weathering independent of the contents of other than calcitic minerals, e.g. clay minerals. It should, however, be noted that pure limestones or dolomites do not occur in a 'highly' and 'completely' weathered form. The values for calcareous units for 'highly' and 'completely' weathered are therefore based on units that contain a certain quantity of other than calcitic minerals.

4 METHODOLOGY

In principle, it is very simple to quantify the influence of weathering on a geotechnical parameter. A simple comparison of a rock mass parameter (for example: intact rock strength, spacings or conditions of discontinuities, etc.) in an exposure in which different degrees of weathering are present in the same unit should give the quantitative reduction values (WE_j):

$$WE_j = \frac{rock\ mass\ parameter_j}{rock\ mass\ parameter_{fresh}} \qquad j = degree\ of\ weathering \tag{1}$$

In some locations it is indeed possible to follow a unit through different degrees of weathering in one exposure and to establish with certainty the influence of rock mass weathering. The number of locations where this is possible is, however, generally small and not enough to establish the reduction values with a high degree of certainty. Alternatively the reduction values can be determined from spatially independent exposures if units can be identified that are the same in different exposures except for the degree of weathering. Usually the number of exposures in which units are found that are 'fresh' is limited and a calculation of the reduction values based a comparison with fresh units results in a small number of observations. Therefore the ratios are used of a geotechnical parameter between any two degrees of weathering.

For example, assume a unit *u1* with degree of weathering 'fresh' (*f*) the parameter value is: $(par)_{u1,f}$. In this unit another observation is available in a moderately (*m*) weathered exposure: $(par)_{u1,m}$; the ratio between the two is $ratio_{u1,m,f}$. If is accepted that the influence of weathering is independent of the unit, the ratio found for 'moderately' over 'fresh' is independent of the unit. Hence, the reduction value for 'moderately' weathered (WE_m) is:

$$ratio_{u1,m,f} = ratio_{m,f} = WE_m \tag{2}$$

No further observations are available in this unit with this degree of weathering. Therefore it is not possible to establish ratios for other degrees of weathering in this unit. Assume another two observations in unit *u2*. In this unit no 'fresh' exposures have been found, but say, only one moderately weathered exposure with $(par)_{u2,m}$, and one highly weathered exposure with $(par)_{u2,h}$. The ratio between these two is $ratio_{u2,h,m}$. If, however, is assumed that the ratio is independent of the unit then:

$$ratio_{h,m} = \frac{(par_{mass})_{u2,h}}{(par_{mass})_{u2,m}} = \frac{\dfrac{(par_{mass})_{u2,h}}{(par_{mass})_{u2,f}}}{\dfrac{(par_{mass})_{u2,m}}{(par_{mass})_{u2,f}}} =$$

$$\frac{ratio_{u2,h,f}}{ratio_{u2,m,f}} = \frac{ratio_{h,f}}{ratio_{m,f}} = \frac{WE_h}{WE_m} \qquad or:\ WE_h = ratio_{h,m} \times WE_m \tag{3}$$

Hence, a combination of eqs [2] and [3] gives the option to calculate a reduction value (in this example: WE_h) even if no 'fresh' exposures are available in a particular unit. Another benefit of calculating ratios rather than calculating the reduction values directly, is that all ratios can be used between any two degrees of weathering in any unit. This increases the accuracy of the reduction values considerably because more observations can be used.

The above is implemented as follows. The parameter investigated is averaged per unit (*u*) and degree of rock mass weathering (*i*) resulting in: average $(rock\ mass\ parameter)_{u,i}$. Then the ratios are determined between any two degrees of weathering per unit:

$$ratio_{u,i,j} = \frac{average\ (rock\ mass\ parameter)_{u,i}}{average\ (rock\ mass\ parameter)_{u,j}} \qquad u = unit \quad i,j = degree\ of\ weathering \tag{4}$$

The ratios are independent of the unit; hence, the $ratio_{u,i,j}$ can be averaged:

$$average\ ratio_{i,j} = \frac{1}{U} \times \sum^{U} ratio_{u,i,j} \qquad U = number\ of\ units \tag{5}$$

The calculated average ratios are formulated in the following set of equations:

$$\begin{aligned} x_i &= average\ ratio_{i+1,i} & i &= 0,1..3 \\ x_{i+1} \times x_i &= average\ ratio_{i+2,i} & i &= 0,1..2 \\ x_{i+2} \times x_{i+1} \times x_i &= average\ ratio_{i+3,i} & i &= 0,1 \\ x_{i+3} \times x_{i+2} \times x_{i+1} \times x_i &= average\ ratio_{i+4,i} & i &= 0 \end{aligned} \tag{6}$$

and the values for $x_{0,1..3}$ are found by optimization. The values for weathering are then:

$$WE_{fresh} = 1.00 \qquad WE_{j+1} = \frac{1}{\prod_{i=0}^{j} x_i} \quad j = 0,1,..,3 \tag{7}$$

$$j = 0:\ slightly,\ j = 1:\ moderately,\ etc.$$

A weighting factor is used in the optimization of $x_{0,1..3}$ because the numbers of exposures for each particular degree of weathering are not all the same.

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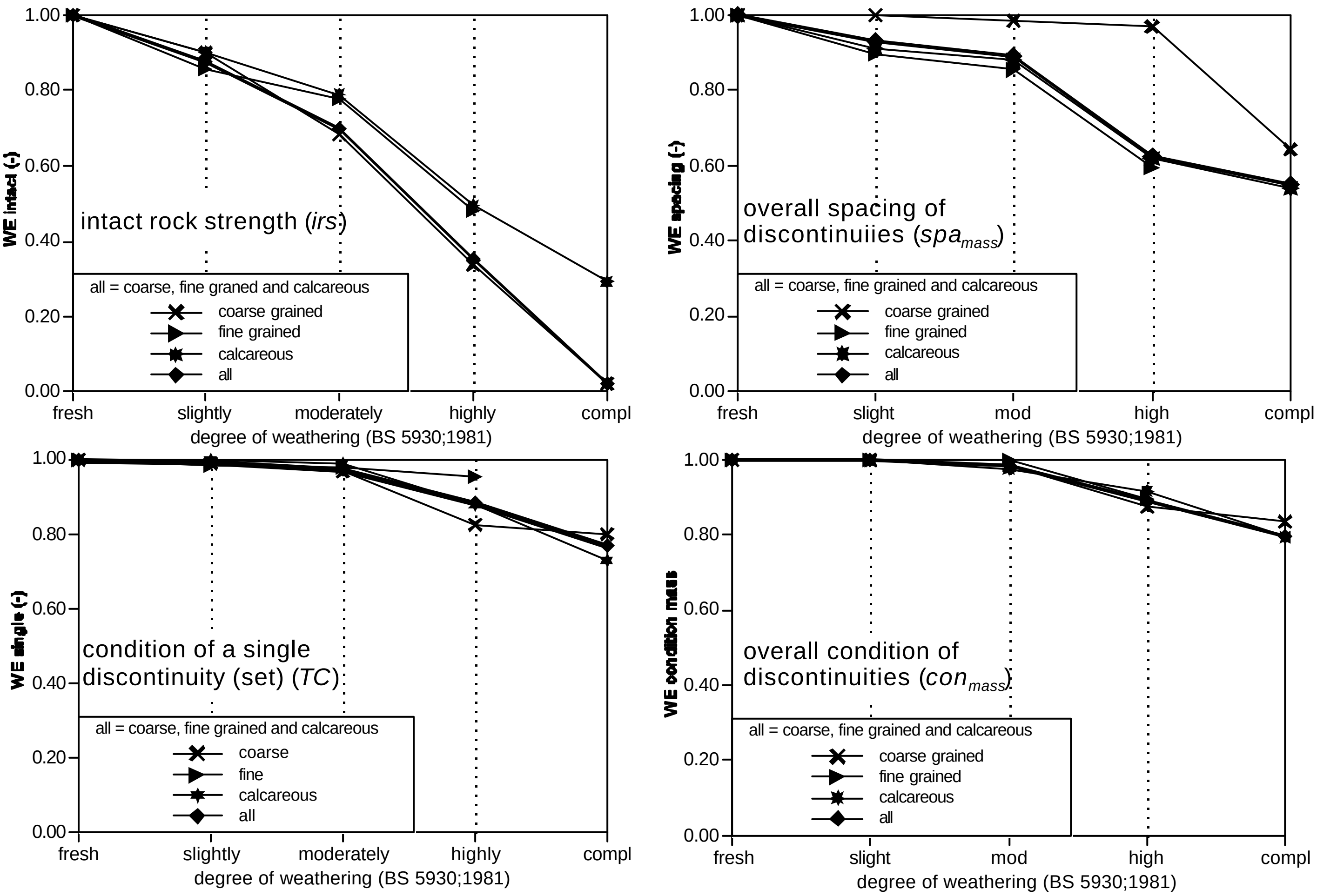

Values for *WE* are shown for the different groups of lithologies and for the weathering influence independent of the lithology which is denoted with 'all'.

Fig. 2. Overview of the influence of weathering on different geotechnical parameters.

5 DEFINITION OF UNITS

The formations and different lithologies in the area were the research has been done, are divided in units which have the same lithology and broadly the same bedding or cleavage spacing. The lithologies have been divided following the British Standard (BS 5930; 1981) division for spacing, e.g. massive: no bedding or cleavage visible, very thick: spacing > 2 m, etc.. Some lithologies have over the whole area broadly the same bedding or cleavage spacing and did not need to be divided in different (sub-) units. The result are 24 different units with a large variety in lithology and bedding or cleavage spacings.

6 INTERDEPENDENCIES BETWEEN WEATHERING AND DEFINITION OF UNITS

The reduction values for weathering should indicate the reduction of a geotechnical parameter of the rock mass compared to the same value before weathering; thus fresh. Determining the reduction values from spatially independent exposures requires that the definition of the unit which is compared, is not dependent on the influence of rock mass weathering. As weathering influences the discontinuity spacing this may also change the unit as defined above. This problem cannot be solved completely, however, it is likely that the influence is not too serious and can be neglected. This is based on the following observations:

1 A change in unit cannot occur in a lithostratigraphic unit that contains only one typical bedding or cleavage spacing over the whole research area. Calculation of the reduction values with only these units results in values which are in the same order as those calculated with all units.

2 Calculation of the reduction values with only the units found in the research area with the most widely spaced bedding or cleavage, results in values which are in the same order as the values calculated for all units. Units with the most widely spaced bedding or cleavage found after weathering have a discontinuity spacing which is the original discontinuity spacing (which was likely also

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degree of rock mass weathering (BS 5930; 1981)	intact rock strength	spacing of discontinuities (*spa mass*)	condition of a single discontinuity (set)	condition of discontinuities (*con mass*)	number of observations	units
fresh	1.00	1.00	1.00	1.00	12	7
slightly	0.88	0.93	0.99	1.00	168	20
moderately	0.70	0.89	0.98	0.99	27	12
highly	0.35	0.63	0.89	0.89	6	3
completely	0.02	0.55	0.77	0.80	2	1
				Total:	215	24

notes: - Columns 'lithostratigraphic units' and 'units' are respectively the number of lithostratigraphic units and the number of lithostratigraphic sub-units found in exposures used for the calculation of reduction values.
- Used for the calculation of WE values and included in the column 'lithostratigraphic sub-units' are only those in which at least two different degrees of weathering have been observed so that weathering effects could be compared in the same 'lithostratigraphic sub-unit'.
- 'completely weathered' is assessed in granodiorite only.

Table 2. Values for the parameter for weathering.

the most widely spaced unit) influenced by the weathering (there are no 'wider' spaced units).

3 The reduction values for weathering (calculated with all units or with the units as calculated in points 1 and 2 above) are generally (far) smaller than the ratios between minimum and maximum bedding or cleavage spacing allowed within one unit. This reduces the chance that a rock mass belongs to a different unit before and after weathering.

The change in geotechnical parameter due to weathering may be dependent on another property of the unit. The dependency between the degree of weathering and rock mass lithology, structure or material could, however, not be proved in this research. For some units (very) vague relations with other rock mass properties may be present but statistically these relations are not significant. For all practical purposes may thus be assumed that the reduction values are independent from the unit definition and are independent from other properties of the rock mass. This is also shown in Fig. 2 for the different groups of units (fine, coarse and calcareous) which show approximately the same reduction values.

7 INFLUENCE OF WEATHERING ON ROCK MASS PARAMETERS

The influence of weathering is investigated for the following parameters: intact rock strength, spacing of discontinuities (spa_{mass}) (calculated following Taylor, 1980), the condition of a single discontinuity (set), and the condition of discontinuities in a rock mass (con_{mass}). The condition of discontinuities is the weighted mean of the condition of a number of discontinuity sets in a rock mass, weighted against its spacing:

$$con_{mass}\ (condition\ of\ discontinuities) = \frac{\dfrac{condition_1}{spacing_1} + \dfrac{condition_2}{spacing_2} + \dfrac{condition_3}{spacing_3}}{\dfrac{1}{spacing_1} + \dfrac{1}{spacing_2} + \dfrac{1}{spacing_3}} \qquad [8]$$

Table 2 and Fig. 2 present a summary of the influence of weathering on all investigated geotechnical parameters in the form of reduction values (*WE*). It should be noted that the degrees of weathering described as moderately, highly and completely weathered imply that a proportion of the rock mass has decayed to a geotechnical soil. The intact rock strength is that of rock blocks remaining in the particular degree of weathering. It is clear that as expected, the intact rock strength decreases with increasing degree of weathering.

8 RELIABILITY

The values established for weathering are as good as the number of exposures (observations), the number of different lithologies, and the number of units on which they are based. The values for 'slightly' and 'moderately' weathered are based on a large number of exposures and different units, but the values for 'highly' and 'completely' weathered are based on fewer exposures and units. Highly and completely weathered exposures have not been found for all formations. This is because: 1) Highly and completely weathered rock masses are generally weak and not resistant to erosion, and form a good ground for vegetation and agricultural use. The number of exposures is therefore limited. 2) Some formations do not exist in a highly or completely weathered form. For example pure (for 100 % consisting of calcium carbonate or dolomite) limestones and dolomites do not as such weather but the material dissolves and is flushed away. Highly or completely weathered exposures of pure limestone or dolomite are thus non-existent. and consequently the reliability of these is expected to be less.
Units consisting of weakly cemented grains, seem not to be influenced by weathering or it is not possible to determine quantitative values for weathering. The scatter is very large and overprints a possible decrease of intact rock strength, spacing or condition of discontinuities.

9 SUSCEPTIBILITY TO WEATHERING

The susceptibility to weathering of a rock mass as a factor of time is one of the most difficult parameters to determine. Not only is the parameter dependent on the rock mass material, texture and structure but also on the climate, quantities of water percolating through the rock mass, chemicals and salts dissolved in the water, the orientation of the exposure or slope face, etc.. These influences may also change with time, for example, the type and quantity of chemicals and salts dissolved in groundwater percolating through the rock mass might change (change of landuse, change in fertilizer use, etc.). The influence of future weathering on slope stability is such that if no future weathering is accommodated for, it is very likely that failure will occur due to the degradation of the rock mass that happens to be prone to weathering within the engineering life-time of the slope. The values reported in this research give some indication as to which account rock mass properties are degraded with time.

10 CONCLUSIONS

Weathering influences the intact rock strength, the spacing of discontinuities and the condition of discontinuities. Weathering is of obvious importance in the estimation of the stability of many present engineering structures and in the forecasting of the stability of new structures for which the degree of weathering may increase during their economic life-time.
The condition of a discontinuity or of the discontinuities in a rock mass are considerably less influenced by weathering than the intact rock strength and the spacing of discontinuities.
The influence of weathering is low for 'slightly' and 'moderately' weathered for all rock mass parameters studied, but strongly increases for 'highly' and 'completely' weathered. This corresponds to the percentage of the rock material which is decomposed or disintegrated into a soil following the definition of the degrees of rock mass weathering (BS 5930; 1981).

The reduction factors for rock mass weathering have been developed in the context of a slope classification system, however, there is no reason that these reduction factors are not valid for other engineering projects in or on rock masses. The reduction values may also be used as a guide for defining weathering classes that represent decay of geotechnical properties more evenly than the present classes of BS 5930: 1981.

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