DRILLING, BLASTING AND CUTTING – IS IT POSSIBLE TO QUANTIFY GEOLOGICAL PARAMETERS RELATING TO EXCAVATABILITY?

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ABSTRACT: Determining tunnel stability is a key issue during preliminary site investigation. In contrast, problems of excavatability have been largely ignored. While the choice of an economic tunnelling method is admittedly a clear priority in the planning stage, special investigations focussing on rock fragmentation (e.g. drilling or cutting performance, rock mass blastability or tool wear) are rarely carried out. This paper explores possibilities to quantify key parameters for rock mass excavatability in drilling, blasting and cutting by TBMs and roadheaders. Although rock mechanical properties play a key role, geological parameters are rarely fully included in most projects. In some cases, the influence of geological features on rock fragmentation can be more significant than varying rock properties. Geological difficulties can have a high impact on the economics of an underground construction project, especially when the chosen excavation system turns out to be unsuitable for the conditions encountered. Thus it can be argued that the geological and petrological characteristics of the rock mass should be evaluated with the same degree of effort as that for the geotechnical prognosis.

RÉSUMÉ: D´ordinaire lors d´études préliminaires aux grands projets de percement de tunnel, les pronostics sur la stabilité de l´excavation se trouvent au premier plein d´intérêt. Ce pendant ces dernières années les difficultés de prévoir correctement la résistence des roches lors de percement méchaniques et de forage. Encore des problèms revenaient en connexion avec la consommation des ciseaux et avec le progrès de couper de bas avec des machines de percement et de forage. Dans cet bulletin, sont exposées les corrélations fondamentales entre quelques propriétés géologiques, le progrès de couper et l´usage des ciseaux, utiliser l´assistance une étude allemande dans granites.

EXCAVATABILITY – A DEFINITION

Is it possible to put numbers to geological parameters concerning excavatability? Are only rock mechanical properties quantifiable? Is a classification system possible for excavation by drilling & blasting or cutting, including all necessary geological and geotechnical parameters? These questions arise when the behaviour of rock mass material has to be considered during underground excavation. Excavatability is a term used in underground construction to describe the influence of a number of parameters on the drilling, blasting or cutting rate (excavation performance) and the tool wear of a drilling rig, roadheader or TBM (wear or usage criterion). The interaction of the main factors involved is illustrated in Figure 1. These terms are used in underground as well as in surface construction. In this paper, only the aspects relating to tunnelling are discussed.

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In the first interaction, the excavation performance is influenced by the machine parameters of the chosen tunnelling rig – the installed power, the type of drilling rig or cutter head and the rock cutting tools mounted. Apart from technical parameters, the geological parameters may especially influence the cutting performance and tool wear. The specific characteristics of intact rock and rock mass material may be at least partly put into figures with the help of mechanical rock properties. But rock mass conditions also highly depend on the geological history, weathering conditions, hydrothermal decomposition and the structure of discontinuities.

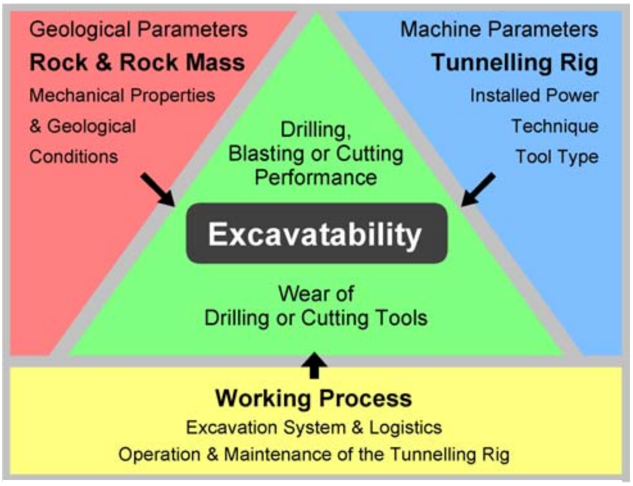

Figure 1. Conceptual overview of the three main parameters influencing excavatability.

The last important factor influencing rock excavation performance is the working process itself. Firstly, smooth operation and permanent maintenance of the tunnelling rig contributes to a successful cutting performance. Secondly, a high penetration rate at the tunnel face does not automatically lead to a high performance of the tunnel heading (Thuro and Spaun 1996a). Therefore, it is a matter of understanding the entire excavation system before applying expertise to the investigation of excavation performance.

EXCAVATION TECHNIQUES

For further discussion some elementary terms of underground excavation techniques must be explaned. The term “drillability” is used in the context of drill and blast tunnelling when drifting blastholes for explosives and rock bolting for support with diameters ranging from 32 to 100 mm. To study drillability, two key parameters have proved to be most valuable (Thuro 1997): the (net) drilling rate in meters per minute (i.e. the drilling performance, derived from the time of drilling one single borehole); and the bit life span in meters per drilling bit that can be drilled in a homogeneous tunnel section. Since wear occurs in six basic forms, generally in accord with rock mass conditions, some qualitative aspects of tool wear can be distinguished by analysis of worn-out drilling bits (Plinninger 2002).

The term “blastability” is only used in the context of drill and blast tunnelling and the consumption of explosives. Quality aspects of blasting and/or control of material fragmentation were not included. As a property relating to blastability, the specific consumption of explosives was recorded in the crown heading along homogeneous rock mass sections. The specific explosives consumed can be derived from the total consumption of explosives in one blow divided through the volume blasted. As a statistical value, the specific consumption of explosives only shows the amount of explosives needed to blast a certain rock mass volume. Since the blasting engineer has to estimate this amount according to rock mass conditons (quality of rock, discontinuity spacing etc.), experience shows that there is quite a variation in the used quantity and therfore in the values of specific explosives consumed.

The term “cuttability” is used both when excavating with roadheaders or with TBMs. In principle, the term is also valid for similar techniques using trench and dredge cutting (Deketh 1995, Verhoef 1997) and road pavement shaping. Analogous to drillability, two key parameters are invoked to describe roadheader cuttability (Thuro and Plinninger 1998, 1999a, b). In roadheader excavation the cutting performance is measured as the excavated rock volume in cubic meters per working hour, and the bit (or pick) wear is determined by the number of worn-out bits (or picks) that have to be changed after cutting a cubic meter of rock (specific bit/pick consumption). Since roadheader bit wear occurs in seven basic forms, relating to rock mass conditions, some qualitative aspects of tool wear can be distinguished by analysis of used bits (Plinninger 2002).

During TBM boring, the cutting performance is measured in this study as the specific penetration (penetration divided by thrust) in a rock material as opposed to of the excavated rock volume in cubic meters per working hour (Thuro and Brodbeck 1998). This allows for comparison to be made between different TBM types (eg. diameters, cutter geometry, power) in different rock materials (Gehring 1997). Cutter wear is taken as the spooling distance of a disc cutter in kilometers or the consumption of disc cutters per cubic meter of excavated rock material (specific disk cutter consumption). Since the possible spooling distance of a disc cutter is reasonably high, the resolution with respect to geological and petrographical variations is quite poor and not applicable to rock mass characterization.

QUANTIFICATION OF ROCK MASS PARAMETERS CONCERNING EXCAVATABILITY

Compared to geotechnical rock properties like unconfined compressive strength or Young's modulus, it is quite difficult to "put numbers to geology" in relation to quantifying geological rock parameters. In addition, geotechnical properties are often derived from rock samples rather than in situ where the rock mass includes discontinuity sets and water. The problematic nature of in-situ tests (eg. shear or triaxial tests on jointed rock specimens) has often been discussed in the literature. Indirect methods to gain rock mass properties (eg. geophysical logging) are very rarely made during site investigations and are more often made for research purposes since calibration of data with known direct rock properties is generally limited. In our opinion, this generates a knowledge deficit that should be addressed by research projects.

Table 1. Parameters that can be quantified based on excavatability (Brackets = indirect influence).

Parameters that can easily be quantified by laboratory testing of rock samples		**Influence on**	
Uniaxial compressive strength	UCS [MPa]	Performance	(Tool wear)
Destruction work / Strain energy	Wz [kJ/m³]	Performance	(Tool wear)
Modulus of elasticity	E [GPa]	(Performance)	(Tool wear)
Indirect tensile strength	ITS [MPa]	Performance	(Tool wear)
Dry density, Porosity	D [g/cm^2], P [%]	Performance	Tool wear
Equivalent quartz content	EQu [%] (compared with Quartz)	-	Tool wear
Rock abrasivity index	Index-value; RAI = EQu x UCS	-	Tool wear
Qualitative parameters that can easily be quantified, but their influence can´t yet be quantified		**Influence on**	
in-situ stress state	$\square_1$, $\square_2$, $\square_3$ [MPa], □□□□	Performance	Tool wear)
Water inflow & Water chemistry	Q [m^3/sec], Chemical signature	Performance	(Tool wear)
Swellability (Swelling strain & Swelling stress)	h [%], □ [MPa]	Performance	Tool wear)
Semiquantitative parameters, which are not physical parameters		**Influence on**	
Discontinuity spacing Degree of fracturing	Joint index (Stini 1950), Rock quality designation RQD [%], Scanlines (Priest 1993) Joint spacing [cm]	Performance	---
Anisotropy, Foliation	Angle [°] with respect to tunnel axis	Performance	---
Parameters that can be quantified with → indirect methods		**Influence on**	
Degree of interlocking	→ Destruction work (strain energy), UCS, RAI	Performance	Tool wear
Quality of cementation	→ Destruction work (strain energy), UCS, RAI	Performance	Tool wear
Weathering & Hydrothermal alteration	→ Dry density, Porosity	Performance	Tool wear
Influence of water-sensitive rock material	→ Content e.g. of clay-siltstone	Performance	(Tool wear)
Influence of inhomogeneity	→ Share as a percentage of the face area or the pull volume	Performance	Tool wear

Nevertheless attempts have been made to quantify key geological parameters by measuring geotechnical rock properties in the laboratory and to compare or even correlate them with qualitative or semiquantitative geological parameters. In Table 1, a distinction is made between quantitative parameters that can easily be quantified by laboratory testing of rock samples and qualitative parameters that indeed can be easily quantified, but their influence can´t yet be quantified. Correlation of these mechanical rock properties and petrographical properties with performance parameters (drilling / cutting / penetration rates / explosives consumption) and tool wear parameters (consumption or wear of drilling / cutting bits / disc cutters) can be established directly and quite easily (see next section). Exceptions are parameters, of which the influence is evident like the *in-situ* stress state (Thuro and Gasparini 2000, Thuro et al. 2001) or which obstruct excavation works (eg. as high water inflows or swelling rock). But it is not yet possible to quantify their influence in order to derive correlation charts that can be applied to performance prediction or tool wear.

Only a few rock mass properties are recorded in a semiquantitative manner, but do not represent physical properties. Influencing factors like joint spacing or the angle of drilling direction to foliation can be plotted directly onto diagrams (see Thuro 1997, Thuro and Plinninger 1998, 1999a, b), although standard deviation can be high.

Some geological and petrographical parameters can be assessed qualitatively, like the degree of interlocking in the rock microfabric or the quality of binder minerals (eg. in sandstone), but only very rarely in categories like the weathering or alteration stages in rock mass (IAEG 1981, ISRM 1978). One way to quantify these parameters is given when using strength properties (Thuro 1997) or the rock abrasivity index (Plinninger 2002) as a key parameter. The use of dry density and porosity as a key parameter for weathering is discussed further in this paper.

The influence of rock material with degradable characteristics (i.e. losing strength after contact with water) can be recorded by mapping the amount of clay-siltstone along the tunnel and correlating it directly with excavation rates (Thuro and Plinninger 1998, 1999a, b).

But to quantify the influence of inhomogeneity at the tunnel face, e.g. a sandstone – clay-siltstone interstratification, on excavation rates or tool wear becomes extremely difficult since not only the percent composition of rock mass but also the thickness of the layers and the orientation to the tunnel axis will be decisive. In these cases, and unless enough data is available, experience seems to be the only way to deal with it.

BASIC EXCAVATABILITY – MECHANICAL ROCK PROPERTIES

For the investigation of excavatability there has to be distinguished the basic excavatability controlled by the intact rock and the general excavatability controlled by the rock mass properties. In other words, the general rock mass excavatability also takes into account the discontinuity pattern and characteristics, and water seepage/flow (e.g. described in ISRM 1978). If the rock mass is homogeneous and isotropic, rock properties could be directly correlated with excavation performance and petrographic properties (e.g. equivalent quartz content, Thuro 1997) or index properties (e.g. rock abrasivity index, Plinninger 2002) with tool wear.

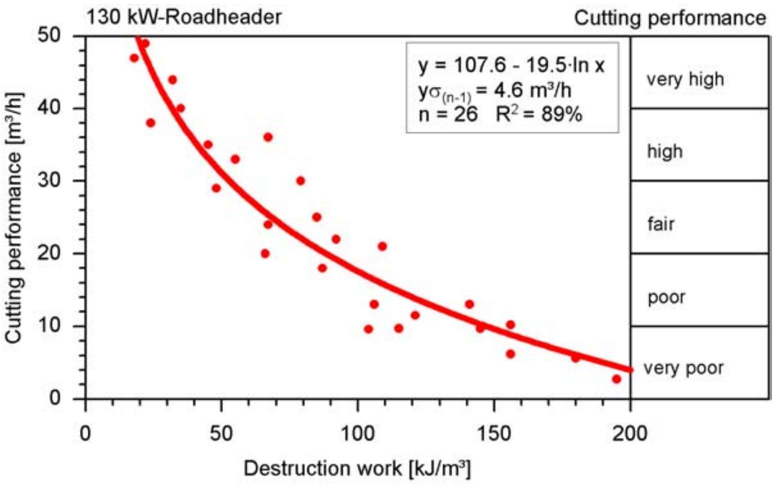

Figure 2. Cutting performance, correlated with destruction work (Slates and quartzites, Sewage tunnel Zeulenroda). Statistic parameters: $y\sigma_{(n-1)}$ - standard deviation, n - number of values, R^2 - square of correlation coefficient

In earlier papers the suitability of different rock properties for correlation with drilling rates have been discussed in detail (Thuro 1997, Thuro and Spaun 1996). Also when applying these techniques to other excavation processes, the best correlations were encountered using destruction work (strain energy, Thuro and Spaun 1996 b). From the physical point of view, the integral of the stress-strain-curve is a measure of energy (or work) related to the deformation volume. Because this is the work required for destruction of the rock sample, the newly defined rock property has been determined as "specific *destruction work* W_d [kJ/m^2]" (in short: destruction work), which is also referred to as *strain energy*. As a product of both stress and strain, destruction work represents the work of shape altering of the rock sample including the post failure region.

Figure 2 shows the correlation between destruction work and cutting performance in roadheader excavation with R^2 = 89% (square of correlation coefficient). In contrast, the significance of the correlation with unconfined compressive strength (Figure 3) is not as good (R^2 = 62%). Also a good correlation is found with TBM performance, when specific penetration rate is plotted against destruction work (Figure 4, R^2 = 87%). To obtain better correlations, only TBM pulls in those tunnel sections were included where fracturing by joints was low and orientation of foliation was constant. In drill and blast tunnelling a fair correlation was also encountered for the specific consumption of explosives (Figure 5) with destruction work. It is important to evaluate only homogeneous tunnel sections and explosives with comparable detonation characteristics (energy, velocity) and comparable blasting conditions (here: wedge cut, face profile & volume)

In summary, mechanical rock properties, especially destruction work, can be used as a good measure for excavation performance and therefore provide useful information when carrying out site investigations in regard to excavatability. The limitation is that the prerequisites, homogeneous and isotropic rock mass sections without changing geological structures are only very rarely encountered.

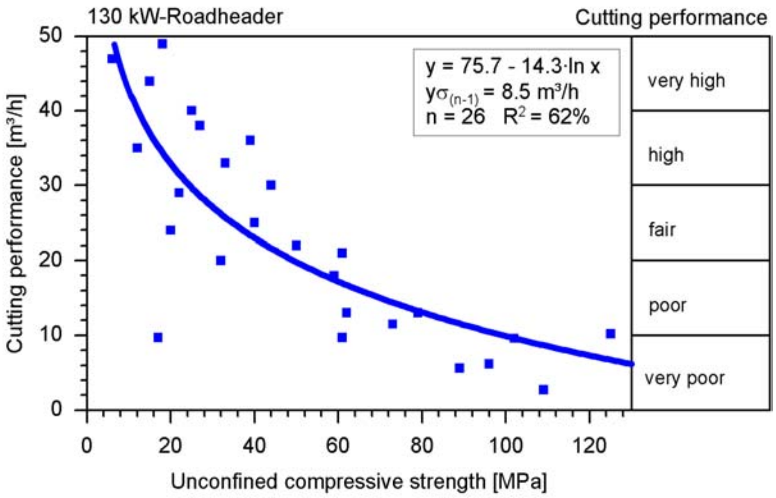

Figure 3. Cutting performance, correlated with compressive strength (Slates and quartzites, Sewage tunnel Zeulenroda).

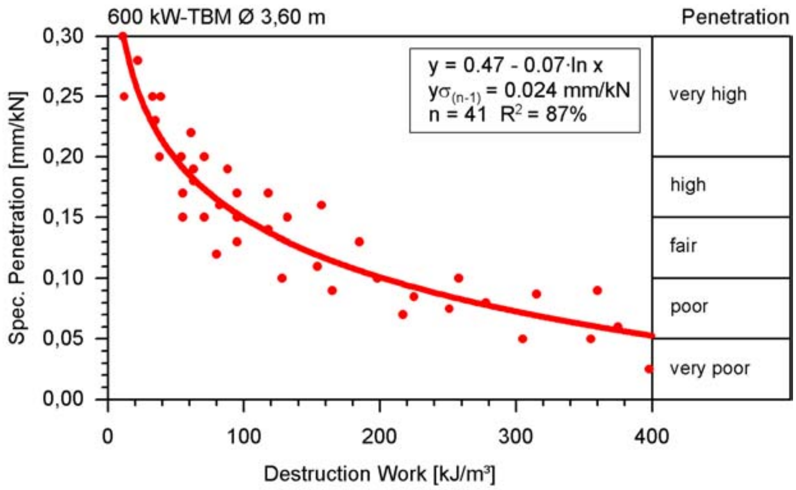

Figure 4. Specific penetration, correlated with destruction work (Phyllites & carbonate schists, Schönberg tunnel, Schwarzach).

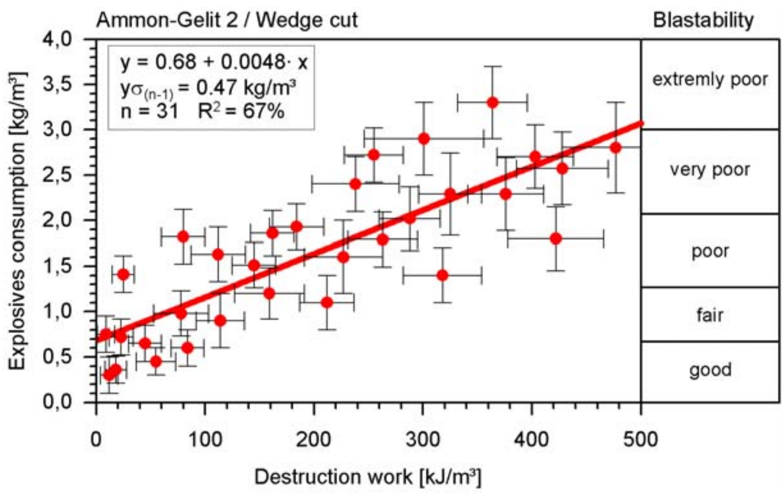

Figure 5. Specific consumption of explosives, correlated with compressive strength (31 case studies from 8 tunnel projects). Standard deviation as error margins

THE PROBLEM OF QUANTIFICATION – A CASE STUDY

In contrast to other studies, which try to include a variety of geological parameters in a rating system, a methology was developed to work with parameters that more closely related to the underlying physical processes. Intensivly weathered granites have been excavated during tunnelling works on two 3.3 km long motorway tubes in eastern Germany (Koenigshainer Berge Tunnel, 100 km east of Dresden). The opportunity was given to study these zones through the implementation of a detailed field and laboratory program (Bierer 1999, Scholz 1999).

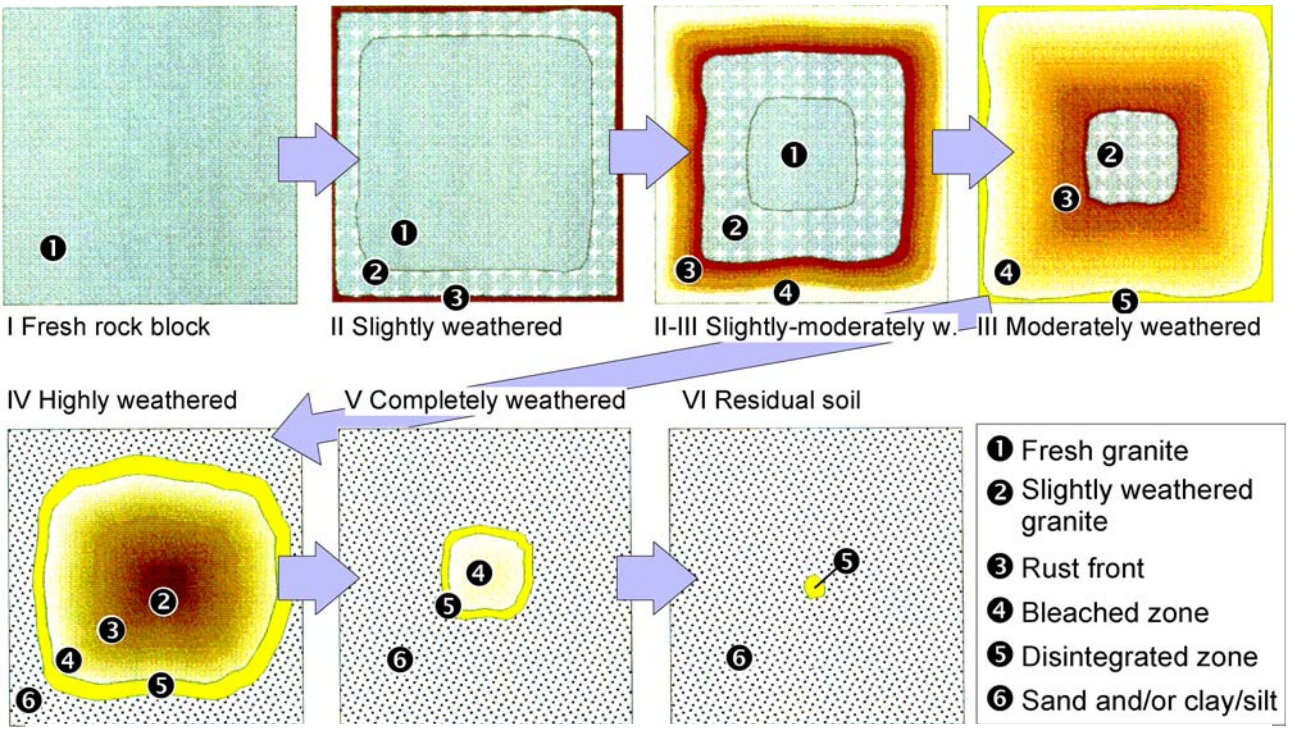

Figure 6. Grades of weathering according to (IAEG 1981, ISRM 1978) in a granite block (Thuro et al. 2000).

The discussion will be based on the weathering stages discribed in the IAEG and ISRM Suggested Methods (IAEG 1981, ISRM 1978) and is illustrated for the Königshain granite in Figure 6. Grades I – VI refer to the ISRM weathering grades. A grade called "II-III slightly to moderately weathered" was added to distinguish between granite with only slight changes in colour and granite that was already decomposed over 40-50% of the rock mass. In the following diagrams, the grades therefore are counted in arabic numerals from 1 to 7 (with VI = 7 residual soil, V = 6 completely weathered, IV = 5, III = 4, II-III = 3 und II = 2). Fresh granite was not encountered and is therefore not included.

The weathering process begins with the fresh granite ❶ (grade I = 1, which was not encountered during tunnelling works in this study). Subsequently, a typically reddish-brown rust front ❷ and a zone of microscopic weathered granite ❸ develops between the wall rock and into the rock mass (grade II = 2). A bleached light-brown to yellow-white zone ❹ then marks the end of the solid rock (grade II–III = 3). The disintegrated zone ❺ in grade III (= 4) consists mainly of clay and silt as the material of the wall rock decomposes. This proved to be the most hazardous material stage encoun-

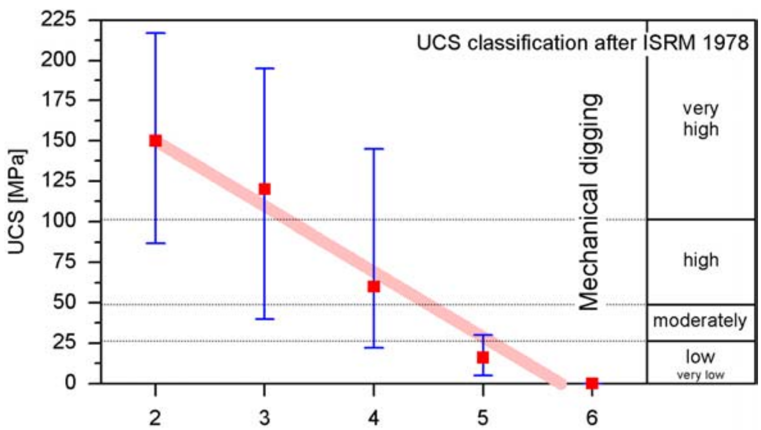

Figure 7. Unconfined compressive strength versus weathering grade (high/mean/low value).

tered, because of the low friction angle of the material and its tendency to shear along existing discontinuities. In grade IV (= 5) the granite disintegrates into a mixture of ❻ sandy and/or clayey and silty material. In the completely weathered material (grade V = 6) the rust colours have disappeared and the residual soil (grade VI = 7) only holds remnants of the disintegrated granite.

Accordingly, the physical properties of the rock change in a similar manner. Figure 7 shows the unconfined compressive strength correlated to the different weathering grades. Since the weathering classification is determined for the rock mass and be generally subjective, the correlation is poor with a large standard deviation between values. This broad variation of values is also present when correlating technical parameters (drilling rates, Figure 8, consumption of explosives, Figure 9) with weathering grades. The established trend curves are not satisfactory for quantification of the weathering stages.

But which rock property could be usefull for determining the stage of weathering, its mechanical disintegration and chemical decomposition? Which rock property could be used as a key parameter for weathering? Figure 11 shows the stages of weathering in the microfabric of the granite through its disintegration and decomposition into a clayey-silty soil material. Apart from mineralogical changes, porosity increases considerably due to loosening of the microfabric (high porosity of clay and other phyllosilicate aggregates, opening of microfissures) and dry density of the rock material is decreasing simultaneously (Figure 10). In simple terms, weathering and alteration of granites may be regarded as a decrease of dry density and an increase of porosity. Dry density or porosity could therefore be the key parameters for correlation with rock properties and excavation performance.

Using the values of dry density or porosity instead of the more subjective weathering grades for correlation with the unconfined compressive strength, a good correlation is found with a fitted curve in the diagram of Figure 12. For this chart, both the results of cylindrical specimen tests and point load tests were taken. The porosity scale is plotted on top of the

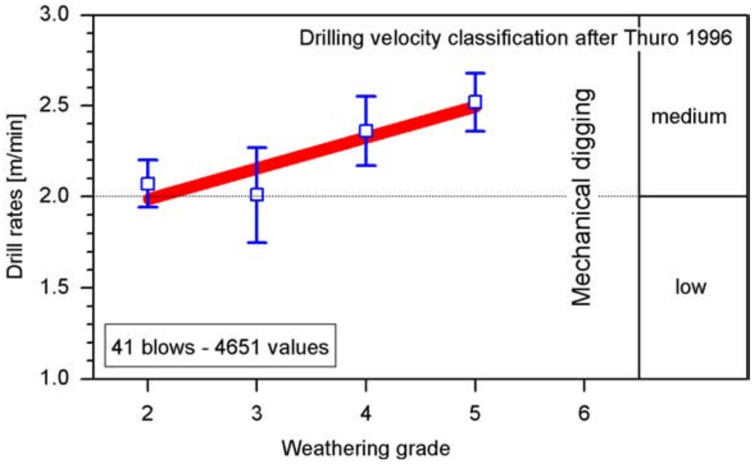

Figure 8. Drilling rates of blastholes versus granite weathering grade (with standard deviation).

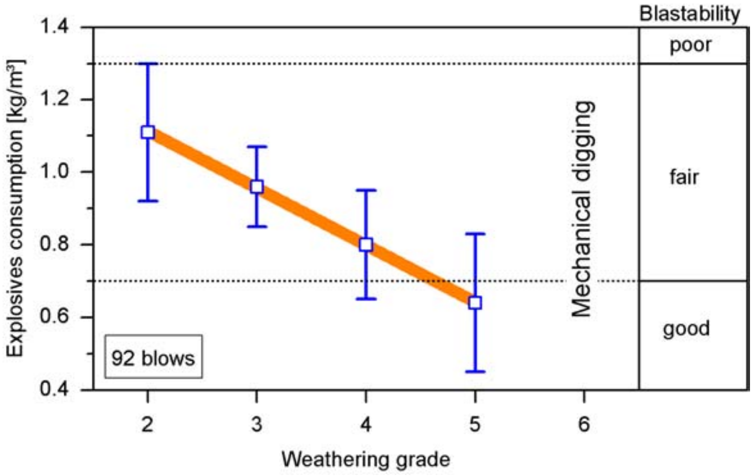

Figure 9. Specific consumption of explosives versus granite weathering grade (with standard deviation).

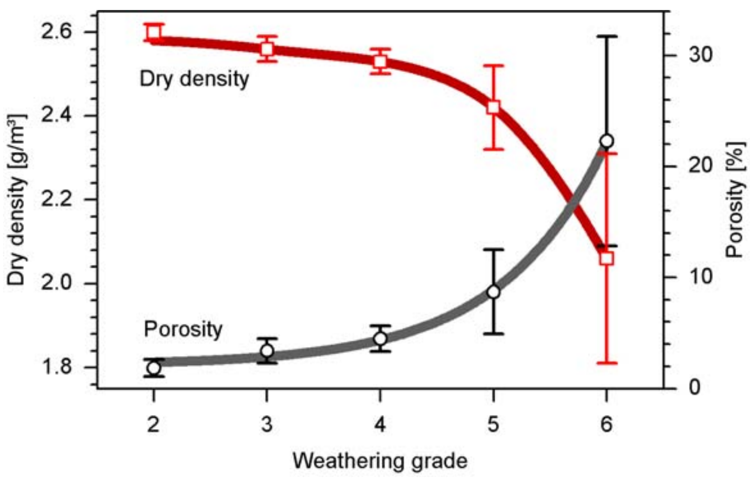

Figure 10. Connection of the weathering grade with dry density and porosity. High/mean/low values are plotted for each grade.

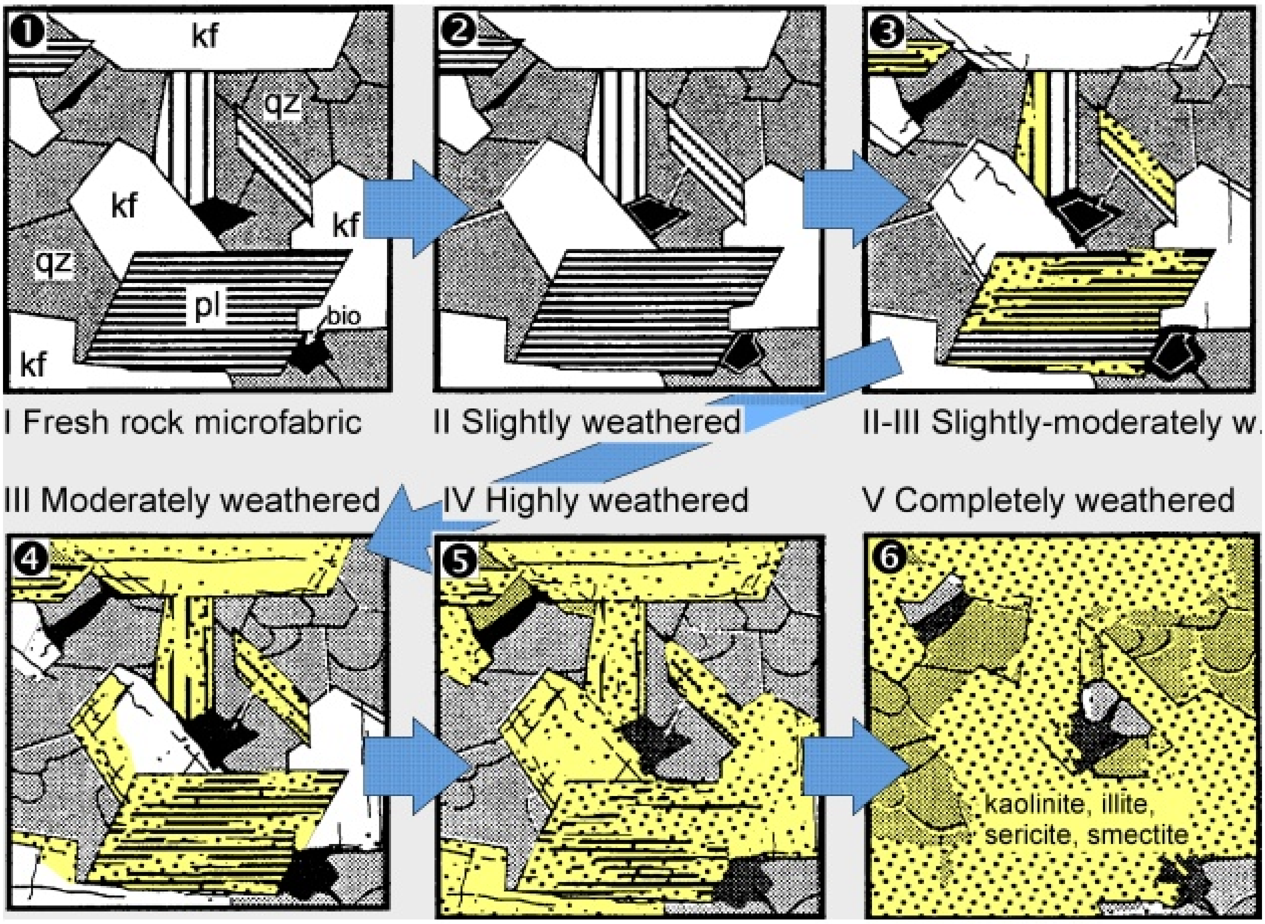

Figure 11. Weathering grades in the microfabric (omitting VI residual soil). kf – K-feldspar, pl – plagioclase, qz – quartz, bio – biotite.

chart using a mean dry density for fresh granite of 2.65 g/cm^3 (i.e. weathering = 0%). Due to the established correlation between weathering grade, dry density and material strength, drilling rates can be correlated directly with porosity (Figure 13). The result is a good fit of the regression curve and therefore a true quantification of weathering grades regarding drilling velocity with porosity as a key parameter.

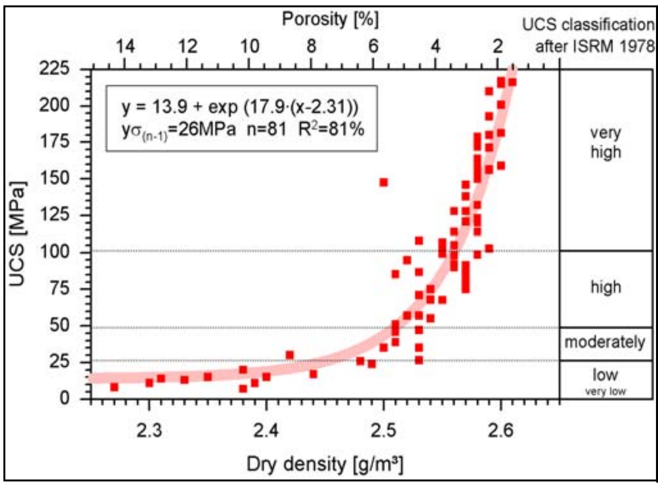

Figure 12. Unconfined compressive strength versus dry density and porosity (single values).

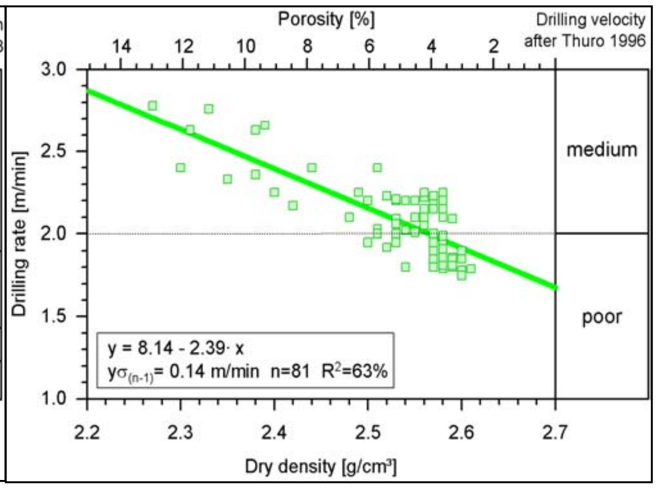

Figure 13. Drilling rates versus dry density and porosity (single values).

CONCLUSION

This case study establishes that true quantification is more than just finding categories for a descriptive rock mass property. However, developing quantitative key parameters for geological parameters such as weathering is labour-intensive and associated with problems. Although the link between weathering and porosity could be developed by closely looking at the weathering process, such procedures may not be possible for all the rock mass parameters listed in Table 1.

Nevertheless we suggest to investigate physical and mechanical connections between excavation parameters, rock strength properties and geological parameters rather than to introduce a new classification system with ratings and index values for excavatabilitiy. The followed course for sure is not the quickest nor the easiest, but it will be more decisive with respect to understanding more about the geological and geotechnical foundations of excavation processes.

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REFERENCES

Bierer, S. (1999). Gefügekundliche Untersuchungen an Graniten des Tunnelprojekts „Königshainer Berge“ unter besonderer Berücksichtigung der Verwitterung und Betrachtungen zur Bohrbarkeit und Sprengbarkeit in verwitterten Graniten beim konventionellen Sprengvortrieb. Diploma Thesis, Technical University of Munich.

Deketh, H.J.R. (1995). The wear of rock cutting tools. Laboratory Experiments on the abrasivity of rock. Rotterdam, Balkema.

Gehring, K. (1997). Classification of drillability, cuttability, borability and abrasivity in tunnelling. Felsbau 15: 183-191.

IAEG - International Association of Engineering Geology (ed) (1981). Rock and soil description and classification for engineering geological mapping. Report by the IAEG Commission on Engeneering Geological Mapping. Bull. Int. Assoc. Eng. Geol., 24: 235-274.

ISRM - International Society for Rock Mechanics (ed) (1978). Suggested methods for the quantitative description of discontinuities in rock masses. Commission on Standardization of Laboratory and Field Tests, Document No. 4. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., 15: 319-368.

Plinninger, R. J. (2002). Klassifizierung und Prognose von Werkzeugverschleiß bei konventionellen Gebirgslösungsverfahren im Festgestein, Doctoral Thesis, Technical University of Munich.

PRIEST, ST. D. (1993): Discontinuity analysis for rock engineering. London, Chapman & Hall.

Scholz, M. (1999). Über die Verwitterung im Königshainer Granitmassiv und ihre Auswirkungen auf den Vortrieb beim Bau der Tunnelanlage Königshainer Berge. Petrographische, fels- und bodenmechanische Untersuchungen. Diploma Thesis, Technical University of Munich.

STINI, J. (1950): Tunnelbaugeologie. Wien, Springer.

Thuro, K. (1997): Drillability prediction - geological influences in hard rock drill and blast tunnelling. Geol. Rundsch. 86: 426-437.

Thuro, K., Brodbeck, F. (1998). Auswertung von TBM-Vortriebsdaten - Erfahrungen aus dem Erkundungsstollen Schwarzach. Felsbau 16: 8-17.

Thuro, K., Eberhardt, E., Gasparini, M. (2001). Adverse tunnelling conditions arising from slope instabilities - a case history. Kühne, M. et al. [ed.]. Landslides – causes, Impacts and countermeasures. UEF Conference, Essen, Glückauf. pp 97-107.

Thuro, K., Gasparini, M. (2000). Tunnelling and rock drilling under high stress conditions. Nathpa-Jhakri Hydroelectric Project, northwestern Himalaya. Proc of the GeoEng2000 conference. Lancaster, Basel, Technomic Publ. Paper 0549UW, CD-ROM, 6 p.

Thuro, K., Hecht, L., Plinninger, R.J., Scholz, M., Bierer, S. (2000). Geotechnical aspects of weathered and hydrothermally decomposed granite in the Königshainer Berge tunnel project. Deutsche Gesellschaft für Geotechnik e.V. (ed) Proceedings of the Eurock 2000 Symposium, Essen. Glückauf, pp 177-182.

Thuro, K., Plinninger, R.J. (1998). Geological limits in roadheader excavation - four case studies. Moore, D.P., Hungr, O. (eds.). Proceedings 8^{th} International IAEG Congress, vol. 5, Rotterdam, Brookfield. Balkema, pp 3545-3552.

Thuro, K., Plinninger, R.J. (1999a). Predicting roadheader advance rates. Tunnels & Tunnelling International, 6: 36-39.

Thuro, K., Plinninger, R.J. (1999b). Roadheader excavation performance – geological and geotechnical influences. Vouille, G.; Berest, P. (eds.). Proceedings of the 9th ISRM Int. Congr. on Rock Mech., Rotterdam, Brookfield. Balkema, pp 1241-1244.

Thuro, K., Spaun, G. (1996a). Drillability in hard rock drill and blast tunnelling. Felsbau, 14: 103-109.

Thuro, K., Spaun, G. (1996b). Introducing `destruction work´ as a new rock property of toughness refering to drillability in conventional drill- and blast tunnelling. Barla, G. (ed.). Proc of Eurock ´96 conference. vol. 2, Rotterdam, Brookfield. Balkema, pp 707-713.

Verhoef, P.N.W. (1997). Wear of Rock Cutting Tools - Implication for the site investigation of rock dredging projects. Rotterdam, Brookfield: Balkema.