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Perspectives on laboratory rock testing procedures

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ABSTRACT: Quantifying the strength and deformability characteristics of rock and rock masses is essential in geotechnical engineering, since the risks, costs, performance, and safety of underground works depends on a realistic prediction of rock mass behavior. However, there are unavoidable accuracy limitations in forecasting behavior due to inherent inhomogeneties and the statistical nature of rock mass parameters. There are also uncertainties related to parameter measurements. It is therefore necessary to establish a general procedure for the consistent and coherent geotechnical design of underground structures, which is traceable and auditable. This paper summarizes a laboratory testing philosophy that is consistent with the Austrian Guideline for Geomechanical Design of Underground Structures, which has found significant application in engineering practice. Specific examples of this philosophy are also reviewed.

1. INTRODUCTION

Evaluating rock mass behavior is an essential aspect of geotechnical engineering. The accuracy of behavior evaluations is however limited, often involving an optimization process with multiple technical and non-technical variables. To facilitate the optimization process in complex geologic situations, a multi-disciplinary approach involving geologists, geophysicists, and engineers is advantageous. In characterizing the rock mass, consistent and coherent procedures should be adopted, allowing continuous updating an integration of exploration and design work phases.

The parameters necessary for rock mass characterization should be relevant to the anticipated rock mass behaviour, and are therefore project specific. Characteristic parameters that can strongly influence the behaviour of some rock mass types are shown in Figure 1, taken from the Austrian Guideline for Geomechanical Design of Underground Structures [1]. The Austrian Guideline recommends a procedure for rock mass characterization that commences with establishing a geological model. This is an essential first step for characterizing the rock mass. The model is utilized as a guide to establish exploration and lab testing protocol. The procedure continues by identifying geomechanically relevant (key) parameters for each rock mass type (Figure 1). Rock mass types are then established, the number being dependent on project-specific geological conditions and the design process stage. The key parameters selected should correlate to the anticipated rock mass behavior and reflect rock mass properties having significant influence on construction means and methods [2]. For example, abrasivity parameters for bit and disk wear, or chemical parameters for corrosion, may represent key parameters for some projects.

Information related to the identified key parameters should be updated, as necessary, during exploration, design, and construction project phases. Even if the parameters have highly statistical properties, the corresponding behaviour types can be aided with the use of probabilistic methods

All input parameters for geomechanical models (e.g. finite element and distinct element methods) should be defined prior to commencing a laboratory testing program.

Particularly for weak or highly fractured rocks, the acquisition and preparation of samples for strength tests often results in a biased selection of stronger samples due to difficulties in specimen preparation. One must therefore attach great importance to the exploration and sampling protocol to ensure that representative samples, including the influence of singular geological features and weak zones, are available for laboratory testing.

	BASIC ROCK TYPES	KEY PARAMETERS																		
		INTACT ROCK PROPERTIES													DISCONTINUITIES					
		Mineral Composition	Clay Mineral Composition (qualitative)	Clay Mineral Composition (quantitative)	Cementation	Grain Size	Texture	Ratio Matrix/Fragments	Porosity	Alteration/Weathering	Solution Phenomena	Swelling Properties	Strength Properties	Anisotropy	Block Shape	Block Size	Persistence	Aperture	Shear Strength/Roughness	Infilling
ROCKS	Plutonic Rocks	■				■	■			□			■		■	■	□	■	□	□
	Volcanic Rocks (massive)	□					□		■	■			■		■	■	□	■	□	■
	Volcano-Clastic Rocks	□	□		□	□		■	■	■		□	□							
	Coarse-Grained Clastic Rocks (massive)	□		□	■	■	□	■	□	□			■		□	□	□	□		
	Fine-Grained Clastic Rocks (massive)		■	■	■	■				□		■	□		□	□				
	Coarse-Grained Clastic Rocks (bedded)	□		□	■	■		■	□	□			■	■					■	
	Fine-Grained Clastic Rocks (bedded)		■	■	■	■				□		■	□	■					■	□
	Carbonatic Rocks (massive)	■									■		■		□	■	□	■		□
	Carbonatic Rocks (bedded)	■									■		■		■				□	□
	Sulfatic Rocks	■									■	■	□							
	Metamorphic Rocks (massive)	■				■	■			□			■		■	■	□	■		
	Metamorphic Rocks (bedded)	■				■	■			□			■	■	■	■	□		■	■
	Fault Rocks	□	■	■	■			■		□		■	■							
SOILS	Coarse-Grained Soils (gravel)					■		■	□				■							
	Coarse-Grained Soils (sand)					■		□	□				■							
	Coarse-Grained Soil Mixtures	□		■		■		■	□			□	■							
	Fine-Grained Soils (silt)					■			□				■							
	Fine-Grained Soils (clay)	□		■		■			□			■	■							

Legend: ■ Significant Parameter □ Less Important Parameter

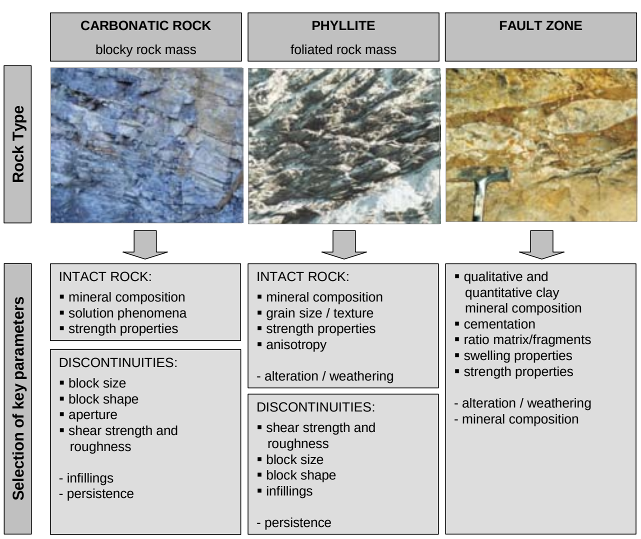

Fig. 1. Examples of key parameters for various rock and soil types (from Austrian Guideline for Geomechanical Design of Underground Structures [1])

2. LAB TESTING

Determining parameters in the laboratory and with in-situ tests is an essential part of the characterization process. Laboratory tests have some advantages over in-situ-tests. They are easier to obtain, various test set-ups with controllable boundary conditions are possible, and the costs are lower. For critical projects, large-scale in-situ tests may be warranted, but the suitability of quick index in-situ tests (e.g. vane shear, penetrometer) and geophysical techniques that are useful in confirming rock mass parameters should always be considered.

Laboratory work is part of the characterization process. As rocks and the rock masses are inhomogeneous, we must deal with wide distributions in parameter values and determine which parameters are necessary to properly correlate lab behavior to the actual field.

State-of-the-art testing equipment allows novel testing procedures to determine the mechanical parameters of joints and intact rock. High-response servo hydraulic systems with digital control technology, strain measurement equipment mounted onto the specimen, and programmable control modes, enable customized procedures, which are tailored to the specific problem [3]. The correct interpretation of test results depends on the quantity and especially on the quality of the laboratory tests. The goal of each test should be to obtain as much information as possible about the rock properties.

Table 1. Parameters for two rock types, including average value, standard deviation and number of specimens

	Rock Mass Type 1	Rock Mass Type 11
lithology	marble	phyllite
foliation / anisotropy	massive	flaky to platy, highly anisotropic
block size	> 20 cm	< 20 cm
joint properties	mainly rough	undulating, smooth
persistence	low	dominating low
aperture	closed	dominating closed
	intact rock	
parameter	average / standard deviation / number of samples	average / standard deviation / number of samples
UCS [MPa]	102,6 29,0 / 26	28,2 / 13,6 / 19
c [MPa]	24,2 / 8,2 / 20	10,8 / 3,1 / 3
?φ [°]	40,7 / 4,9 / 20	31,7 / 1,5 / 3
E [GPa]	68,3 / 17,6 / 23	26,7 / 19,1 / 18
CERCHAR Abrasivity Index	1,4 / 0,4 / 18	no value
?ν [ ]	0,19 / 0,4 / 18	0,43 / 0,18 / 2
Hoek constant m_i [ ]	13,4 / 6,2 / 20	14,5 / 6,0 / 3
	rock mass	
parameter	average / standard deviation	average / standard deviation
Geological Strength Index	70 / 10	40 / 5
UCS [MPa]	33,2 / 12,1	3,9 / 2,0
c [MPa]	8,0 / 2,8	1,1 / 0,5
?φ [°]	37,7 / 4,7	31,3 / 3,6
E [GPa]	35,0 / 19,4	3,0 / 1,0
	joint properties	
parameter		average / standard deviation / number of samples
friction angle [°]	35 - 45	33,7 / 6,3 / 15
residual friction angle [°]	30 - 40	28,5 / 5,6 / 23

.... estimated values

2.1. *Sampling for laboratory tests*

The techniques and methods for sampling by drilling and excavation should be selected according to the purpose of the investigations in relation to the expected geological and hydrogeological conditions. Different sample disturbance effects can be expected when various sampling methods are used, and the quality of samples taken with the same sampler can vary depending on the rock type to be sampled, the presence of groundwater, and the sampling operation. Some amount of sample disturbance is unavoidable, related to compression, shearing, flushing or vibration during drilling or excavation, sample disturbance due to release of in-situ stresses and related rebound, changes in material and chemical constituents such as water content and gases.

For various ground conditions categories of sampling methods related to the best obtainable sample class for laboratory testing are defined in the standard EN ISO 22475-1 [4], together with specification for handling, transport and storage. Nevertheless, it is necessary to make best efforts to achieve good quality samples of weak rock. In particular, the transition zone between rock and soil causes sampling difficulties, and this is often an important zone in geotechnical engineering. In weak rock types it is sometimes impossible to obtain undisturbed samples, even if a double or triple tube core barrel is used. In addition to existing joints, the fabric of composite minerals with different strength in a weak matrix is often responsible for a sample defect due to drilling. Another sampling method is block sampling. In this method the samples are obtained from a trial pit, heading, shaft etc. by using special samplers or manual work with a cutting procedure. If the material has no adequate cohesion we have to treat it like soil, but the existence of larger blocks should be taken into account. “Intact samples” are specimens that allow cylindrical or block shape preparation. Frequently used tools to dissect the specimens are diamond saws, wire or chain saws, handsaws, cutters, core drills and grinding tools. On very weak specimens the grinding of the end planes is sometimes not possible. Therefore it is necessary to reinforce the end plane area (e.g. with resin) to ensure a plan-parallel end plane for loading. The strain gages, however, have to be fixed onto the unaltered part of the specimen. Especially weak rock specimens need a careful handling, because a change in the natural environment can influence the later behaviour dramatically. The water content is for instance one important factor. Completely destroyed samples, such as sheared loose rock material, can be handled like soil but the existence of larger grain sizes (e.g. harder blocky materials) often causes difficulties.

A frequent problem with sampling and testing is the exploration schedule. The time from core drilling to testing should be as short as possible, because the samples alter under changing boundary and environmental conditions. Stress relief and inappropriate storage of the samples often lead to sample defects prior to testing.

2.2. Examples for determining geomechanical parameters

Geomechanical parameters characterize the strength of the rock. Because strength is an all encompassing term, specifications of the boundary conditions are necessary. In particular, for strength parameters the means for determining strength parameters need to be specified. Depending on the failure criteria adapted, different mechanical parameters are applied.

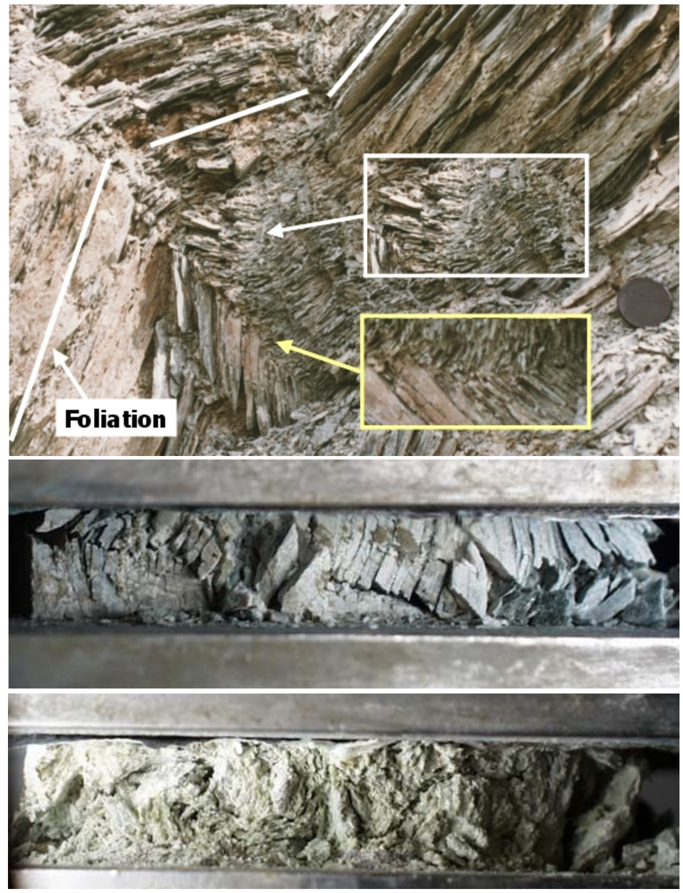

Fig. 2. Foliated rock with shear zone (above); shear test performed normal to foliation with tensile failures, interlayer shear and rigid block rotation (mid); shear test with cataclastic flow; (below) interlayer shear; shear box gap 20 mm for both cases.

There are many factors that influence rock strength, e.g. strain and/or strain rate, stress level, loading rate, water content, temperature, scale effects, etc. For differentiating peak- and residual strength parameters, a clear specification of boundary conditions is of particular relevance.

The ability to apply different stress paths and boundary conditions to a given sample or suite of samples allows different failure modes to be investigated in the laboratory. The uniaxial compressive test is the most frequently used rock mechanics test, but provides only elastic properties and a single failure value derived from a very simple stress path [6].

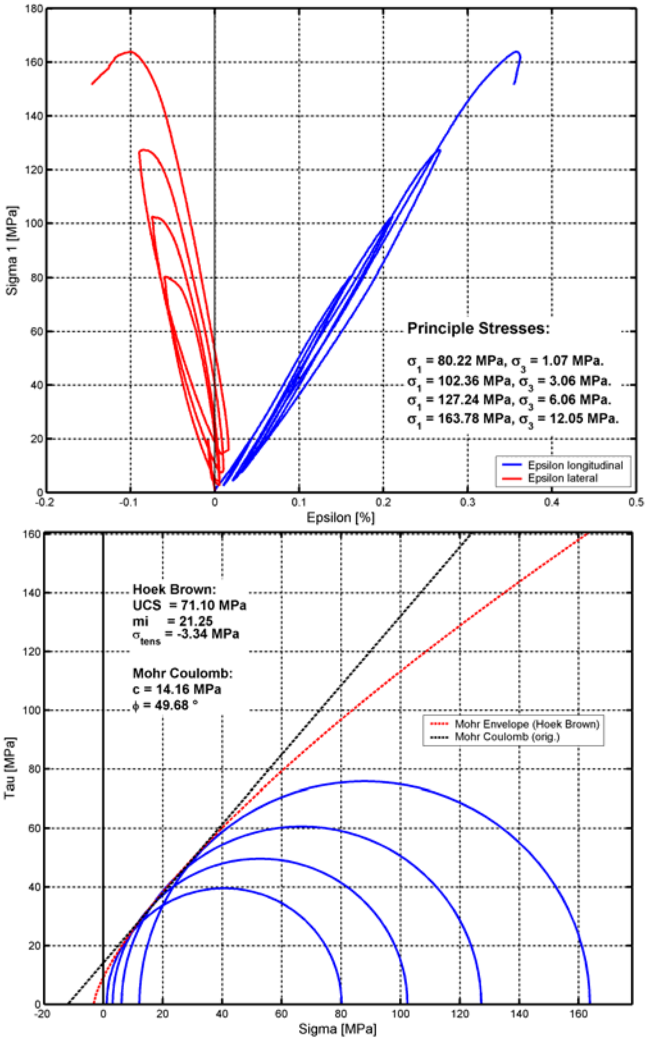

Figure 3. Example for multiple failure triaxial test.

With computer controlled feedback it is possible to follow different stress paths by varying the axial symmetric confining pressure and the axial compression of a rock cylinder. The use of computed automated controls, in combination with accurate stress and strain measurements, allows performing multiple failure cycles on the same specimen. After the peak load is indicated for a given confining pressure, the deviatoric stress is reduced to zero and the sample is loaded hydrostatically to the next confining level. Thus, the progressive stress history of a single sample can be monitored instead of using different samples (with perhaps different microstructure) at each stress state and to combine the results in order to estimate the progressive stress behaviour of the “intact” rock (Figure 3). This allows a more realistic evaluation of the intact rock strength, and therefore more realistic predictions and interpretations of the in-situ rock mass behaviour. Comparative studies for single and multiple failure tests, carried out on artificial rock samples, showed that the multiple failure control mode is capable of determining these parameters.

To investigate the shear behaviour and the failure characteristics for different boundary conditions of both fracture surfaces and weak intact rock, automated direct shear testing procedures are used. This enables the execution of modified shear tests, which are behaviour specific. To determine the anisotropic behaviour, a sample can be placed at any orientation within the shear box (Figure 2, 4). The strength and failure processes associated with a shear direction that is not directly parallel to the pre-existing discontinuity structures can be evaluated [7]. The simplest case for shear failure is a single block resting on a plane. In this simple case we need a failure criterion in which the principal stress situation is not changed. This can be performed in the laboratory with a constant normal load direct shear test. In many cases, the failure mechanism will not be these simple and more representative boundary conditions should be used. Usually we have to deal with embedded blocks side by side where the acting normal stresses, due to the dilation, are changed and so the overall principal stress distribution varies.

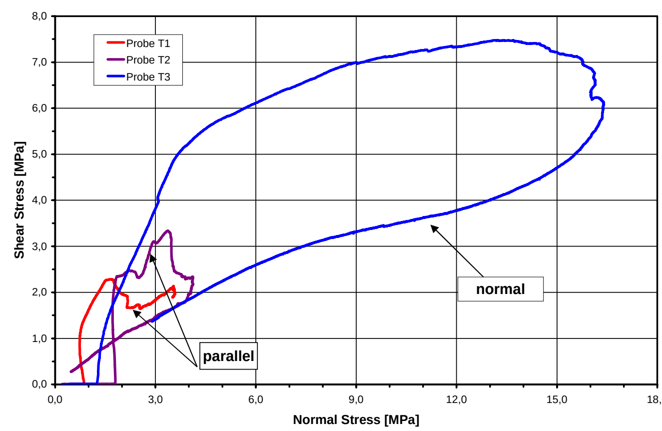

Figure 4. Diagram of stress paths from stiffness controlled shear test on Phyllite, depending on shear direction.

For example, stiffness controlled tests can be used to evaluate the ultimate shear strength for different boundary conditions, and also enable the recognition of different failure modes that occur during shearing (Figure 4). The volumetric strain behaviour (dilation or contraction) is used as a feedback control mode for the vertical stress [8]. This method of testing is most appropriate for evaluating a material’s shear behaviour and provides estimates of shear and normal stiffness, dilation potential, cohesion, and the peak and residual friction angles. Multiple failure state shear tests (under constant normal loads) as well as various combinations of test control procedures can be performed on a single sample, thus the effects of sample variability on the failure envelope can be minimized. Constant normal load shear tests do not test the rock strength, but the resistance to shear at a certain normal load, which may be appropriate under certain boundary conditions. Constant normal stiffness testing procedures can be used to define a sample's "peak shear strength" which is the natural response to simple shearing.

3. CONCLUSION

Due to the plethora of geotechnical boundary conditions, most underground constructions are merely prototypes. Therefore project specific key parameters, which are not based on a fixed rating system, are selected for the rock mass characterization process. These filtered relevant parameters combined with probabilistic methods are the fundamental input data for the definition of different rock mass types. When consistent and coherent procedures are used to adequately simplify complex geotechnical conditions in a sound geotechnical model, error detection and correction for deviations of the predicted rock mass behavior becomes feasible. The geotechnical model is the basis for all examinations and will be updated during exploration, design and construction.

The limited accuracy in prediction of rock mass behavior is partly related to the difficulty of obtaining representative samples and test results, and to the strong influence of singular features and the over simplified modeling techniques. Foremost, we must make every effort to recover samples of a quality sufficient to assess the general suitability of a site for geotechnical engineering purposes. The quality of a sample is influenced by the geological, hydro-geological and chemical conditions, sampling methods, the skill of the sampling crew and by the sampling equipment. The techniques and methods for sampling by drilling and excavation should be selected according to the purpose of the investigations in relation to the expected geological and hydrogeological conditions. The quality class of a sample taken with the same sampler can also vary depending on the rock type to be sampled, the presence of groundwater, and the sampling operation. Different reasons can lead to sample disturbance: mechanical sample disturbance due to compression, shearing, flushing or vibration during drilling or excavation, sample disturbance due to release of in-situ stresses and related rebound, changes in material and chemical constituents such as water content and gases.

Additionally to the sampling difficulties weak rock material due to its genesis is mostly heterogeneous and highly anisotropic. Sophisticated test procedures are therefore essential to obtain better information regarding the mechanical behavior of weak rock.

The laboratory testing philosophy herein provides a significant aid in studying the behavior of weak rock, with the opportunity to simulate various boundary conditions. Thus it is possible to obtain the peak shear stress and strain, and the dilatational behavior as a natural response to the shearing process for the generated failure mechanism under specified boundary conditions.

Quantifying the rock and the rock mass behavior will always be a challenge, yet appropriate testing procedures and analyses are a step toward a more realistic evaluation.

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