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Multistep triaxial strength tests: Investigating strength parameters and pore pressure effects on Opalinus Clay

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ABSTRACT

Natural variability between rock samples often hampers a detailed analysis of material properties. For the investigation of strength parameters the concept of multistep triaxial strength tests was developed to avoid the impact of sample variability. The limit of linear elastic behavior, shear strength and residual strength were measured at different confining pressure on a single specimen.

Appropriate tools for near real time data analysis were developed to facilitate a precise and timely control of the test procedure. This is essential to minimize the problem of sample degradation during the test.

The feasibility of the test concept was proven on three samples of Opalinus Clay from the Mont Terri rock laboratory. Each investigated strength parameter displayed a distinct deviation from a linear dependency on confining pressure or mean stress respectively. Instead, curves consisting of two linear branches almost perfectly fit the test results.

These results could be explained in the framework of poroelastic theory. Although it is not possible to determine Skempton's B-parameter (Skempton, 1954) and the Biot–Willis poroelastic parameter (Biot and Willis, 1957) separately from multistep strength tests, the product of both parameters can be derived from the test results.

Although material anisotropy was found by the test results, numerous simple strength tests (Gräsle and Plischke, 2010) as well as true triaxial tests (Naumann et al., 2007) provide a more efficient way to investigate anisotropy.

1. Introduction

Any assessment of short and long term stability and safety of prospective underground repositories for radioactive waste requires a well-founded numerical modeling. Therefore, reliable strength and elasticity parameters of potential host rocks are of urgent need.

In case of argillaceous rocks the hydro-mechanical coupling is by far more pronounced than in other potential host rocks like crystalline rocks or rock salt. Thus, due to interaction between pore pressure effects inside the rock matrix (Tarantino, 2010) resulting from different saturation depending on the quality of sampling the experimental data base regarding THM-properties is still unsatisfactory. The distinct anisotropy of argillaceous rocks, particularly in indurated clays (Bock, 2009; Popp and Salzer, 2007), even complicates the investigations.

Furthermore, the lithological material scattering hampers the identification and quantification of influencing parameters on the rock mechanical properties, as data variation arising from heterogeneity between samples often obscures details of material behavior. Besides efforts to reduce this statistical noise by careful selection and treatment of samples, there are essentially two approaches to overcome this problem:

- To generate very large data sets for better statistics.
- To avoid the impact of natural variability by obtaining an extensive data set from a single sample.

The multistep strength test presented here follows the second approach to characterize the mechanical behavior of Opalinus Clay from Mont Terri and the possible impact of pore pressure effects.

While reducing the impact of natural variability, this test concept bears a serious risk of introducing additional disturbances into the data resulting from progressive sample alteration during the long and complex test procedure. Thus, avoiding a too fast sample alteration is a major challenge in multistep strength tests.

2. Experimental approach

Tests are performed on cylindrical samples (Table 1) from the shaly facies of Opalinus Clay from the Mont Terri rock laboratory (Bossart and Thury, 2008). As Opalinus Clay exhibits a distinct

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Table 1
Samples from the shaly facies of Mont Terri Opalinus Clay investigated in undrained multistep strength tests.

Sample ID	02075	09001	08021
Orientation (P = parallel, S = normal to bedding)	P	P	S
Drill hole	BHE-B1	BLT-16	BLT-15
Depth (m)	7.82 – 8.02	2.96 – 3.16	6.02 – 6.21
Length (mm)	200.01	201.60	190.20
Diameter (mm)	99.57	100.26	101.70
Density (kg/m^3)	2392	2471	2454
v_p (m/s)	2909	3363	No signal
Applied confining pressure (MPa)	1 – 21	1 – 35	1 – 30

Table 2
Elastic and strength parameters measured in multistep strength tests on Opalinus Clay. In case of sample 02075 the covered range of confining pressure was insufficient to determine the second branch for linear elastic limit and shear strength.

	Geometry Sample ID	P 02075	P 09001	S 08021
Linear elastic limit	σ_0 (MPa)		26.6	18.2
	c (MPa)	1.16	1.74	0.90
	φ (°)	4.2	2.6	3.6
	c_{app} (MPa)		2.95	1.83
	φ_{app} (°)		0.0	0.7
	α B (-)		1.00	0.81
Shear strength	σ_0 (MPa)		16.4	11.4
	c (MPa)	4.92	4.05	3.66
	φ (°)	24.9	19.5	16.7
	c_{app} (MPa)		9.72	6.81
	φ_{app} (°)		0.5	1.4
	α B (-)		0.98	0.92
Residual strength	σ_0 (MPa)	13.6	14.1	10.9
	c (MPa)	0.72	1.01	0.74
	φ (°)	26.7	24.4	24.2
	c_{app} (MPa)	4.59	6.74	5.17
	φ_{app} (°)	12.4	2.8	2.5
	α B (-)	0.57	0.89	0.90
Elasticity	E (GPa)	8.6	9.6	5.5

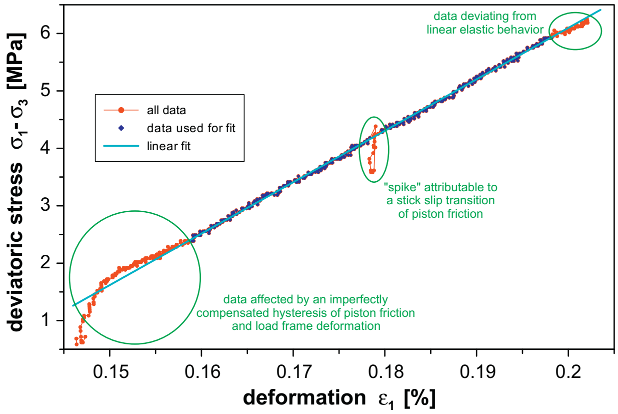

Fig. 1. Example of a loading phase performed with a confining pressure σ_3 = 19 MPa. The data show various types of common disturbances as well as the onset of non-linearity. Obviously, the sensitivity of this type of plot is insufficient to determine the deviation from linearity shown at the upper end of the curve.

anisotropy, there are samples drilled parallel to the bedding (P-samples) as well as normal to the bedding (S-samples). Since Opalinus Clay is very susceptible to damage by desiccation (Schnier, 2004) or the impact of oxygen samples are sealed in gas-tight foils immediately after drilling and stored in liners filled with nitrogen (3 bar) as a protective gas (for technical details see Gräsle and Plischke, 2010).

The tests are carried out in compression mode in Karman-type triaxial cell. Undrained boundary conditions are applied throughout the tests. More details about the experimental setup are given in Gräsle and Plischke (2007).

Shear strength as well as residual strength are affected significantly by strain rate, displaying higher values at higher strain rate (Hoteit et al., 1999; Jung and Biscontin, 2006). As conventional load controlled strength tests result in rapidly increasing strain rates when approaching failure, they are prone to overestimate material strength at low strain rate. To avoid this problem, tests are performed in strain controlled mode. Considering the very low strain rates expected in the context of long term stability of underground repositories, strain rate should be chosen as low as possible to avoid an overestimation of strength. Therefore, the applied strain rate is 10^{-7} s^{-1}, which is close to the lower limit for the used test apparatus.

The concept of the multistep strength test comprises three test sections, each focused on the investigation of one mechanical characteristic of Opalinus Clay. Any test section is composed of a series of strain controlled load cycles at various levels of confining pressure:

1. The linear elastic limit, i.e. the onset of non-linearity in the stress–strain-relationship $\sigma_{dev}(\varepsilon_1)$ during strain-controlled triaxial loading, is determined in Section 2.1.
2. Section 2.2 is focused on a multiple determination of shear strength at various confining pressures.
3. Test Section 2.3 is a conventional test of residual strength.

Unfortunately, the triaxial apparatus available for the tests is not equipped with a pore pressure sensor. Therefore, pore pressure effects can only be detected indirectly.

2.1. Test section A – limit of linear elasticity

Obviously, the onset of damage must be detected very carefully, if it should be investigated multiple at several levels of confining pressure. To avoid significant damage of the sample in the sequent steps, thus changing its properties significantly and impeding further investigations of an "undisturbed sample", a rather strict and well detectable criterion for the beginning of damage is required. Since sample deformations are fully reversible within the range of linear elastic behavior, the limit of linear elasticity might be the very first evidence for incipient damage (if one does not regard compaction occurring during loading and unloading cycles as damage). Although the linear elastic limit may be met far below any level of relevant material damage, it nevertheless characterizes the transition to another deformation regime, either to a non-linear elastic (i.e. nonlinear but reversible) behavior or to an irreversible inelastic (i.e. plastic) alteration of material properties.

To investigate the limit of linear elasticity test Section 2.1 consists of a sequence of loading cycles. Each cycle comprises three phases: first, the sample is loaded with a constant rate of deformation $d\varepsilon_1/dt = 10^{-7}$ s^{-1}. As soon as a deviation of the axial stress from a linear path can be detected the loading is stopped. The sample is unloaded at a rate of $d\sigma_1/dt$ = 0.1 MPa/min to an axial stress 0.5 MPa above the confining pressure of the subsequent loading cycle. In the third phase the confining pressure is increased while keeping the axial stress constant.

The main challenge of this concept is the reliable and "near real time" detection of the deviation from linearity (usually within a few minutes, with lowest tolerance at low confining pressure). There are several instances that make this task difficult: