«Rock Mechanics and Rock Engineering of Geological Repositories in Opalinus Clay and Similar Claystones»

«Felsmechanik und Bautechnik von geologischen Tiefenlagern im Opalinuston und ähnlichen Tonsteinen»

Date: Friday, 14 February 2014

Location: ETH Zurich, Department of Earth Sciences, Room C60, 8092 Zürich

Time: 09:00 am – 6:00 pm

Abstracts

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Challenges associated with laboratory testing on Opalinus Clay, test interpretation, and definition of rock mechanical properties

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Claystones are among the most difficult rock types to characterize in a laboratory setting. These difficulties are primarily related to the strong hydro-mechanical coupling, the extremely low and anisotropic permeability, the anisotropy in strength and stiffness, the brittle (dilatant) failure behaviour, and the sensitivity of mechanical properties to moisture changes. Characterizing the Opalinus Clay suffers the same difficulties.

Our contribution is primarily related to rock mechanical test results on Opalinus Clay specimens obtained at the Mont Terri research laboratory. Based on a comprehensive series of laboratory test results obtained in the past six years, together with published data, we provide general insight into the hydro-mechanical behaviour and key rock mechanical properties of Opalinus Clay relevant for the construction of a repository drift. Using a comparative study of laboratory tests results we illustrate and discuss aspects altering the representativeness of rock mechanical laboratory data for short- to medium term hydro-mechanical processes in the near-field of a repository drift. We also focus on the state-dependency of strength, stiffness and mechanical anisotropy, and we quantitatively illustrate its significance.

A further aspect of our contribution is associated with previous testing procedures where relatively fast loading rates were utilized. As a consequence of these fast loading rates compared to the characteristic diffusion time (extremely low permeability), the obtained test results are essentially undrained. Since pore pressure changes were not measured during these undrained tests, the effective rock strength properties remain unknown, and the derived strength properties should not be used for effective stress calculations.

We also provide results from conceptual numerical models which illustrate how rock mechanical properties used in standard constitutive models affect our ability to reproduce results from full-scale experiments in terms of pore pressure response or failure localization. These difficulties will be qualitatively addressed based on often used constitutive models and related constitutive properties derived from to date laboratory test results.

Micro- and mesomechanical simulations in respect to deformation behavior of claystones

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Besides the macroscopic (m- up to km-scale) and more phenomenological considerations, the micro- and mesomechanical and more physical based view becomes more important.

The understanding of micromechanical damage and deformation processes is a key prerequisite for a reliable prediction of HTM-coupled longterm behavior of rock masses and consequently for a profound longterm safety analysis.

First part of the lecture presents the potential, different techniques and some selected interesting results of micro-mechanical simulations in rock mechanics. The focus is on micromechanical Discrete-Element approaches and such for subcritical crack growth and corresponding life time predictions.

Second part of the lecture shows own results in respect to Opalinus Clay simulations at the micro- and meso-scale. This involves HM-coupled simulations at the level of clay plates (compaction behavior, formation of anisotropy, damage processes until macroscopic fracturing) as well as EDZ development based on HM-coupled particle simulations with interesting insight into this processes at the grain size level.

Overview of geomechanical test results from Opalinus Clay core samples

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In 2011 Opalinus Clay core samples were recovered in the geothermal well Schlattingen-1 from a depth of between 830 to 950m below ground. Extensive geomechanical testing was conducted on these core samples over the past two years, including constrained and unconstrained uniaxial, undrained triaxial and constrained and unconstrained swelling tests. Substantial efforts were also made to characterize unsaturated samples and investigate the effect of suction on the geomechanical behaviour.

This contribution provides an overview of the Schlattingen-1 core test results, highlighting many of the typical characteristics in the mechanical behaviour of the Opalinus Clay. These characteristics include a distinct strain softening and localized deformation, anisotropic rock strength and stiffness, but also aspects more pertinent to normally consolidated clays such as a moderate swelling pressure and swelling heave, and complex non-saturated behaviour.

The results of Schlattingen-1 core tests are then compared with those from cores of the Benken borehole, where Opalinus Clay was sampled at a more shallow depth interval of 540 to 650m. It is shown that the quantitative results for the two sites are similar, despite the difference in present depth. In contrast, significant differences exist between the integrated test results of Benken and Schlattingen-1 cores and results from the Mont Terri underground laboratory in western Switzerland with present overburden of typically less than 300m.

To account for the observed depth dependency in strength and stiffness, two different geomechanical data sets are recommended for addressing the technical feasibility of underground structures at potential high level waste repository sites in Northern Switzerland. The geomechanical data set derived from Mont Terri is considered more representative for Opalinus Clay at relatively "shallow" present burial depth (<500m), whereas the combined data sets from Benken and Schlattingen-1 are considered more representative of the Opalinus Clay at "intermediate" to "deep" present overburden (500-900m).

Lab experiments for the mechanical behavior of different shales and claystones

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Determining the mechanical behaviour of shales and claystones is still challenging for practitioners who have to deal with engineered rock structures. This is particularly true for underground structures designed for deep geological disposal of high-level radioactive waste since delayed deformations and time-dependent damage to the rock mass have to be predicted over long periods of time in order to ensure human and environmental safety.

In this context, any numerical simulations require appropriate constitutive models that can account for the more relevant phenomena (e.g. Chemo-Hydro-Thermo constitutive equations) [1], [2], [3]. Most of the time, rate dependent constitutive models belonging to the visco-plasticity family are used [4]. Whatever the chosen constitutive model, it is necessary to properly identify and calibrate the geomaterial parameters. In a first stage, lab tests performed on core specimen are the best option, although later field measurements and back analyses can be used to account for any scale effect.

This presentation summarizes the results of lab tests performed on three rocks characterized by a high clay content [5]. The time-dependent behaviour of these sedimentary rocks was studied under different loading conditions in uniaxial compression. Static or cyclic creep tests and strain rate controlled tests were performed across various orientations of the fabric of the specimens. The tests carried out under a low strain rate showed similarities in the mechanical response for all three argillaceous rocks, with a late phase of dilation and a linear development of volumetric deformation before the onset of unstable crack propagation. The development of secondary and tertiary creep phases during the creep tests highlighted the existence of a stress deviator threshold, below which only primary creep is observed. Long-term creep tests also showed that the volumetric variation is not constant during the development of time-dependent deformations.

In addition, ultrasonic measurements gave valuable information about the development of specimen damage [6]. The longitudinal and transverse wave velocities are clearly related to the physical and mechanical characteristics of the rock. Throughout the experiments, the dilating behaviour of an argillite could be correlated with a decrease of the P-wave velocity. The results show that P-wave velocity measurements during a creep test can distinguish the three different phases of creep. During primary creep the P-wave increases due to pore closure. The secondary creep phase, characterized by a constant strain rate, is identified by a linear decrease of the wave velocity; this trend accelerates during tertiary creep.

The analysis of crack patterns in argillaceous rocks, induced by time-dependent mechanical deformations, was based on observations of thin sections extracted from specimens after testing [7]. The micro-structural observations, made using an Optical Microscope (OM) and a Scanning Electron Microscope (SEM), highlighted the fact that the crack patterns and failure modes of the specimens are dependent on the rate of loading. For slow loading rates, the macroscopic deformations appear to be mainly due the development of a sub-vertical network of persistent macro-cracks in the argillaceous matrix, while for the fast loading tests, a second network of micro-cracks appear, controlled by the rock's structural anisotropy. When the specimens undergo fast loading, the observed failure is more brittle with cataclastic deformation and grain crushing in evidence within the samples. Observations of the crack width and crack orientations clearly show how the crack patterns influence rock properties, such as permeability, which is a key parameter in the Damage Zone that develops around many geo-engineered structures.

The last part of this experimental investigation dealt with the shear strength of rock discontinuities, which strongly depends on the water content especially when the rocks contain clay minerals [8]. To assess the decrease in the mechanical properties of clay-infilled discontinuities due to water saturation, a series of direct shear tests was performed using an advanced shear box that allows the injection of water into the discontinuity. Results show that both the friction coefficient and the cohesion decrease when the discontinuity is saturated. Overall, the shear strength of the discontinuity is considerably reduced, to approximately 50% of its original value. This reduction has to be accounted for when conducting stability analyses of rock slopes, dam foundations or underground openings.

These experimental investigations can be used together to ascertain the mechanical properties of shales and claystones. As mentioned previously, field measurements conducted at a true scale in underground structures, as well as geophysical monitoring, are required to adjust the final mechanical parameters in the numerical simulations.

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Digital Image Correlation experiments at the Tournemire Underground Rock Laboratory

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Clay rocks are considered in several industrial countries as potential repositories for high-level radioactive wastes. Among the critical issues related to the long-term safety assessment of such geological repositories, the study of the so-called excavation damaged zone (EDZ) is of particular importance. The initiation and extension of the EDZ are governed by many parameters: the material properties of the rock (e.g., material anisotropy), the initial stress field, the existence of natural fracture zones in the rock mass, the geometry of the gallery, and the hydric state existing in the gallery. With regard to the latter, fractures associated with the desaturation of argillaceous medium have been observed on gallery fronts in several underground research laboratories, e.g., in the experimental platform at Tournemire and in the Mont Terri laboratory. This hydric fracturing process is evidenced in situ by sub-horizontal cracks spaced at several decimeters on all vertical walls in contact with ambient air. In winter (dry state), the corresponding crack apertures can reach a few millimeters; in summer (wet state), these cracks are closed. These cracks induced by drying are parallel to the bedding planes, suggesting that they are partially controlled by sedimentological patterns (e.g., vertical differences in sediment granulometry and/or mineral composition).

These observations of clay-rock damage induced by drying have been obtained in the field using conventional crackmeters or jointmeters, and one may wonder whether similar observations could have been made using non-invasive optical methods, such as the digital image correlation (DIC) technique. This communication presents an application of the DIC method in the East1996 underground gallery at the experimental platform of Tournemire; during this study, the Relative Humidity (RH) and temperature (T) were measured for more than one year. The objectives of this experimental investigation were (a) to assess the ability of the DIC method to measure displacement (figure 1) and strain fields and crack apertures induced by climatic changes in an underground gallery, and (b) to correlate the measured strain fields and crack apertures with climatic fluctuations (here RH only) in the gallery.

Our results demonstrate the ability of the non-invasive DIC method to monitor (a) clay-rock strains for at least four months and (b) the opening and closure of desiccation cracks for more than one year. Moreover, our study provides the following phenomenological results. First, as observed in the laboratory, the hydric strains were anisotropic; the strains perpendicular to the desiccation cracks were almost homogeneous and much larger than those parallel to the same cracks. Second, the changes in crack apertures calculated from the displacement fields (at an accuracy of approximately 26.9 µm) and the strain fields were clearly correlated and concomitant with changes in RH and T (with 25%<RH<99% and 6°C<T<14°C). Third, contrary to direct measurements acquired at the Mont-Terri site, the crack apertures of the desiccation cracks were reversible after one year of data acquisition. Moreover, although the main desiccation cracks were sub-horizontal and associated with the direction of bedding planes, our work demonstrated the existence of sub-vertical cracks.

Mine-by experiments and subsurface excavations in claystones

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The term weak rock has been used to identify Argillaceous materials such as Claystones. Claystones have more than 2/3 of their mineral grains smaller than clay-sized fraction (<4µm). Claystones are also referred to as clay-shales, an engineering term that was introduced in the early 1960s to emphasize that these weak rocks were transitional between soil and rock. The ISRM (International Society for Rock Mechanics) classes for weak rock are identified as R0 (Extremely Weak), R1 (Very Weak) and R1 (Weak), with uniaxial compressive strengths ranging from 0.25-1 MPa, 1-5 MPa and 5-25 MPa, respectively. What is not captured in this simple strength-based classification is the changing and complex behaviour of these materials as they transcend from Weak to Extremely Weak.

The behaviour of underground excavations in the weak rock Claystones is often characterized by time-dependent deformations. These deformations are associated with (1) overstressing and strain-weakening, (2) swelling and squeezing and (3) environmental effects. While many tunnels have been excavated in these materials, their successful completion was often achieved after finding solutions to manage the time-dependent behaviour. In most cases our ability to characterize the behaviour of Claystones based on extensive laboratory tests was seldom adequate in forecasting the underground in-situ behaviour. These differences in laboratory and in-situ behaviour are often attributed to complex unloading/loading stress path experienced around the underground excavation compared to the simplified loading/unloading stress path used in laboratory tests. An additional complication is the hydromechanical behaviour of Claystones, which is challenging to capture in laboratory experiments. Consequently, Mine-by experiments are sometimes carried out to establish the characteristics and behaviour of the Claystones around underground excavations. Mine-by type experiments involve installing instrumentation in a volume of rock and excavating a tunnel through the instrumented volume. The results from the instrumentation when combined with the geometry of the tunnel and observations made during excavation typically provide new insights into the behaviour of these complex materials. In order for a Mine-by experiment to be successful it must be carried out with the same care and control that is used in laboratory experiments. This makes successful Mine-by experiments difficult to accomplish and costly to execute.

In this presentation three Mine-by type experiments will be reviewed: (1) An 11-m-diameter test chamber carried out in Western Canada in the Shaftsbury Shales and two Mine-by experiments in the Opalinus Clay, (2) one perpendicular to strike of the bedding and (3) one parallel to the strike of the bedding. The review will focus on the contributions each experiment have made to our understanding of Claystone behaviour and lessons learned. Despite the efforts of the geo-engineering community over the past 50 years, our ability to predict the short-term hydromechanical behaviour of Claystones, remains a challenge.

Transient deformation and excavations in claystones

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Transient behaviour is dominated by two parallel phenomena: pore water pressure dissipation and the «viscous» contribution. The presentation discusses first the characterization of permeability, which is a fundamental property to interpret and predict flow-related transient behaviour. Some tests are first reviewed to illustrate the dominant role of existing or induced discontinuities. Microscope and Mercury Intrusion Porosimetry observations underline the relevance of cracks and planar defects.

Accurate modelling requires procedures to include the effect of discontinuities on the hydraulic characterization of shales and claystones. Cracks originate as a result of tensile straining. This, in turn, has different origins: shearing, drying, tensile straining. A simple but powerful model to include them into a general Thermo-Hydro-Mechanical computational model will be outlined. Then, as an illustration of the model, the results of tests performed on anisotropic shale will be presented.

In the final part of the presentation the recent modelling of a large scale test (HGA test at Mt. Terri Laboratory), performed on Opalinus clay, will be described. The test was designed to monitor flow of water and gas in the disturbed zone around a 1 m diameter horizontal excavation. Particular attention was paid to the effect of confining stress. The analysis performed indicates the relevance of a correct characterization of permeability for an accurate reproduction of «in situ» observations.

Rock mass behavior during excavations in the Mont Terri Underground Rock Laboratory

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The Mont Terri rock laboratory was constructed during several stages between 1996 and 2012. At present, a total length of 650 m of galleries and niches in Opalinus Clay are available for experiments. The rock laboratory is located at a depth between 280 and 320 m below the surface.

Excavation techniques: Different excavation techniques were applied and tested: 1) blasting, 2) excavation of niches using a hydraulic hammer and 3) excavation with road header techniques. The first 2 techniques resulted in horseshoe-shaped profiles, whereas the latter created circular profiles. Excavations involving horizontal raise boring and steel auger techniques with circular profiles were locally applied.

Lining: It consists mainly of a shotcrete layer with a mean thickness of 15 cm. The shotcrete can be reinforced with metal (about 30 kg/m3) or synthetic fibres (about 6 kg/m3). In sections of reduced strength, such as tectonic faults, or in sections excavated parallel to bedding strike, where buckling and breaking apart of bedding planes often occurs, steel meshes were fixed onto an initially thin shotcrete layer. Different types of rock bolts (metallic or fiberglass bolts sealed with cementitious grout or resin cartridge) were used. They typically have a length of 2 to 3.5 m. At particular locations, self-drilling bolts 6 meters long were implemented. Certain sections required the installation of steel arches (full or triangular) in order to allow transfer of the load to the invert or to close the profile.

Rock mass behaviour during and after excavation: The orientation of galleries relative to the stress field and the bedding anisotropy, as well as the heterogeneity such as the facies and tectonic faults, have a great impact on the tunnel stability. Enhanced deformations were observed not only when galleries where excavated parallel to bedding, in the shaly facies or in the foot- and hanging walls of tectonic thrusts, but also when excavation progressed too quickly or when shotcrete was applied too late. The least deformations were observed in the sandy facies normal to bedding strike with rapid implementation of lining. An example of a major breakdown, which occurred in the shaly facies parallel to bedding strike, is presented.

Of special interest is the excavation damaged zone (EDZ), which develops in the tunnel walls during and shortly after the excavation. Stress redistribution leads to changes in pore water pressures. Extensile fracturing and bedding parallel slip were confirmed by several mine-by tests. The EDZ can be limited in extent when rounded or even circular profiles are obtained (e.g. with road headers). Blasting results in higher fracture frequencies in the EDZ. Several experiments were carried out in order to characterise the dynamic formation and the final geometry of the EDZ [1, 2, 3].

Key experiences gained during excavations in the Mont Terri rock laboratory. No use of water: major wet excavation and drilling cause deformation due to swelling phenomena. Thus the use of water in the Opalinus Clay should be avoided. Dry excavation and rapid coverage of the Opalinus Clay are recommended. Dust evacuation: dry excavation causes huge dust clouds. A powerful air circulation combined with a dust extraction system is required to keep dust concentrations minimal and to obey SUVA norms. Drying-out of the Opalinus Clay: the strong air circulation causes partial desaturation of the claystone and, at the same time, a significant increase in the uniaxial compressive strength. These changes may result in slower excavation progress than initially planned.

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Experience from tunnelling in Opalinus Clay in tabular and folded Jura

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Traffic tunnels cross Opalinus Clay proper only over short stretches, most of the sections are located in other Jurassic formation such as limestone, marls and other claystones. The development of tunnelling with TBM started in the 1960 with the construction of the network of Swiss motorways (National Roads) and new railway tunnels on the Swiss Plateau (Mittelland). This development has to be considered in order to understand the development of mechanized tunnelling with full-face shielded TBM's followed by a lining of precast unbolted and not expanded segments. This technique was later, beginning in the 1990's, also applied to construct several longer tunnels in the Jura for motorways and railroads.

The first major tunnels excavated in Tertiary (Molasse) rock were the dual two-lane tunnels of motorway N1 through Baregg near Baden. They were constructed with a horse-shoe shaped shield and drill-and-blast excavation, giving some particular problems. The excavation of the Heitersberg railroad tunnel with open Robbins TBM with precast segments in the invert followed by a shotcrete robot followed. The advance rate was below expectation, as instabilities occurred prior to the possibility of application of shotcrete and wirefabric, and steel sets had to be placed immediately above the cutting head. The Sonnenbergtunnel of N2 in the City of Lucerne with a pilot tunnel and a dual stage reamer followed. Then the series of tunnels constructed with shielded TBM's and precast segmental lining started with the Gubrist tunnel, the Zürichberg Tunnel of Zürich S-Bahn (Cross-Rail) followed by other tunnels [1]. The stability problems in the crown with loosening rock could be overcome with the backfilling technique (grout in the invert and pea gravel in the crown) developed by experienced Swiss contractors, achieving high rates of advance.

Tunnel construction with TBM’s in the Jura started with the Bözberg Tunnel of motorway N3 between Basel and Zürich with a Herrenknecht-Robbins Shield TBM. An identical Shield TBM was ordered to construct the Mont Russelin Tunnel of N16 immediately east of the Mont Terri. The Adlertunnel of the railway Muttenz – Liestal was constructed with a shield TBM manufactured by Herrenknecht. Recently (2006 – 2008) the Bure tunnel of motorway N16 in the north-western part of Switzerland was constructed with a shielded TBM.

Little detailed information on the practical experience has been published; the information that will be presented has been gathered mainly from interviews with personal contacts. Tunnelling Opalinus Clay presented apparently few problems when tunnelling with shield TBM, many problems experiences with conventional tunnelling and drill and blast did not appear. The circular cross section with a continuous segmental liner prevented swelling problems. In retrospect one may conclude that the stability problems close to the face were caused by stress driven instabilities. Major instabilities at the face developed when fault zones were crossed, in particular when these were carrying water.

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In situ stress in potential siting areas in northern Switzerland from stress data and 3D geomechanical-numerical models

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For the geological documentation in phase 2 of the search of a deep geological repository site stress data for Switzerland and adjacent regions from the World Stress Map database release 2008 were re-assessed and updated. Furthermore, the revised data base contains 107 new data records; 34 data records were eliminated. In particular in northern Switzerland 15 new data records from 11 borehole locations from depth up to 2.5 km are of importance as well as the re-analysis of seven old Nagra boreholes. The stress pattern of Switzerland shows a long wave-length trend with a mean SH orientation of 155° ± 30°; in northern Switzerland the mean SH orientation is 160° ± 21°. Northeast of the Bodensee SH is N-S oriented and rotates gradually by ~ 40° along the alpine front from East to West to a WNW-ESE orientation in west Switzerland. The regional trend of the stress pattern as well as the mean SH orientation is independent from the chosen sub datasets and show no general difference when e.g. data records only from the basement or sediments are taken into account. SH is oriented perpendicular to the strike of the Alps and sub-parallel to the indentation direction of the Adriatic plate with Eurasia and the gradient of the Eurasia Moho. The main stress sources are the topography of the Alps and the lateral density contrast, respectively and, of probably smaller importance, the large-scale plate tectonic.

In order to describe the 3D in situ stress state in potential siting areas geomechanical-numerical models are essential. For the Nördlich Lägern and Zürich Nordost existing geological models of the subsurface, consisting of lithological interfaces and faults are used as a basis for geomechanical numerical models for the characterization of the state of stress in the siting area. Due to uncertainties regarding geometries and rock properties in the subsurface, the models presented exhibits generic features. Accordingly, the focus of the models is not so much on the precise quantification of the state of stress rather than on the estimation of the influence of individual factors contributing to the stress state and its spatial variability.

The model results show in general, that the relevant stress ratios SH/SV, Sh/SV and SH/Sh are considerably reduced in the Opalinus Clay in comparison to the formations lying above or below. In particular the competent formations of the Upper Malm and the Upper Muschelkalk are characterized by higher stress ratios and higher differential stress than the weak formations, show a more compressive stress regime and greater horizontal stress anisotropy. Therefore, they support the tectonic push from the far field.

To investigate the impact of topography, friction coefficient, fault geometry and potential ice loads a number of model variants are calculated. The model results show that higher fault friction coefficients increases stress ratios in the host rock. Particularly the horizontal stress anisotropy is increased because the fault's ability to slip and thereby weakening the push from the far field is reduced at higher friction. Whether faults reach below the Mesozoic sediments or not has little impact on the stress state within the sediments. Topography influences the stress state due to the spatially varying weight acting on the subsurface. Of great importance are those stresses that are induced by the topography as a response to the northward directed push from the far field. These induced stresses are positive below topographic depressions and negative below topographical highs and appear to depths of up to several hundred metres. An ice cover significantly lowers stress ratios and their lateral variability, particularly the ratio of horizontal to vertical stress is reduced.

Construction aspects of nuclear waste repositories layout

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The layout of nuclear waste repositories is influenced by a considerable number of parameters. Among others, type of waste to be stored, overburden, rock mass quality and structure in the repository level and above, as well as the size of the repository and the time of construction and operation until closure play a role.

The size of the storage galleries is dictated by the size of the containment plus required operation clearance, as well as by constructive issues. The distance between the single storage units depends on thermal and rock mechanical conditions.

The orientation of the underground openings is determined by the geometry of the available unit, but also by the anisotropy of the rock mass. Practice and theoretical studies have shown that the displacement characteristics and magnitude are significantly influenced by the relative orientation between underground opening and geological features, like bedding or foliation. Dominant mechanisms are shearing along the foliation and dilation perpendicular to the foliation. The foliation also influences the longitudinal displacement development. While for an orientation of the tunnel perpendicular to a steeply dipping foliation, displacement rates are relatively high near the face, but rapidly decrease, a considerable influenced length has to be expected in case of tunneling parallel to the foliation strike.

This again influences the required support and damage of the rock mass due to excavation.

Issues related to the design of a deep geological repository in Opalinus Clay: Parameter study with a conventional design model

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Within the current phase of the Swiss Sectorial Plan for Deep Geological Repositories construction feasibility has to be assessed for a variety of potential boundary conditions such as host rock mechanical properties and in-situ stress conditions or overburden respectively. Construction feasibility can be defined as meeting the design requirements in terms of stability and safety of the openings in accordance to the Swiss Codes and serviceability according to the needs of a geological repository (e.g. long-term safety). The requirements related to serviceability include performance indicators such as deformation (convergence) and size of the plastic zone.

The design is assessed based on rock mechanical and structural analysis for relevant hazard scenarios on an ultimate limit state (stability) and a serviceability state level (operational and long-term safety requirements), using standard design tools.

The tools used are:

- Closed form solutions: E.g. ground reaction curves, Barlow's formula etc. to develop an understanding about the general response of a system and to countercheck the results of the more sophisticated types of analysis as mentioned below.
- Frame Analysis: The response of a potential lining of the tunnels to several load cases and load combinations was simulated assuming elastic and/or elasto-plastic beams bedded on compression springs representing the surrounding rock mass.
- Continuum Analysis: Numerical tools were used to take into account the interaction between the rock-mass, represented by its specific characteristics - e.g. strength anisotropy, hydro-mechanical coupling and post-failure softening - the lining system and the excavation process.

The host rock exhibits an inherent variability in its relevant geo-mechanical properties, e.g. matrix and bedding strength, structural variability, in-situ stress regime etc. Besides a sound understanding of the mechanisms and processes relevant for ensuring stability and serviceability addressing the variability and its implication on the analysis is one of the key issues for design. The study is not an accurate and precise prediction of the system's response to the most probable loading scenario, but rather rock-mass behavior and lining characteristics that include scenarios which are unlikely but still plausible to assess stability and serviceability of underground structures; the requirements have to be met also for unfavorable conditions. The presentation will reveal and discuss some intermediate results of parametric studies covering a variety of rock mechanical conditions using different design models and tools.

Rock mechanics of Callovo-Oxfordian claystones at the Meuse Haute Marne URL and consequences for the Cigéo repository design

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Clay formations in their natural state exhibit very favorable conditions for repository of radioactive waste, as they generally have a very low hydraulic conductivity, small molecular diffusion and significant retention capacity for radionuclide. Nevertheless, one concern regarding waste disposal is that, due to the necessary underground excavations and the associated disturbance and damage in the area close to these excavations, the favorable properties of such formations could change and the host rock could lose part of its barrier function and thus negatively influence the performance of a repository. That is why, in order to demonstrate feasibility of a radioactive waste repository in a claystone formation, the French national radioactive waste management agency (ANDRA) started in 2000 to build the Meuse/Haute-Marne underground research laboratory (URL) at Bure (at nearly 300 km East of Paris). The host formation consists of a claystone (Callovo-Oxfordian argillaceous rock) lying between 420 m and 550 m in depth, which is overlain and underlain by poorly permeable carbonate formations.

One of the main purposes for geomechanical experimental programme is to provide the data, with supporting evidence, required for the safety assessment of a repository: extension, features and hydraulic properties of excavation damaged zone (EDZ). The excavation worksite in the host layer is a scientific experimentation in itself to characterize the impacts of digging, to understand the hydro mechanical behaviour of the claystone and to study the EDZ. Furthermore, understanding the impact of support and excavation methods on the hydro-mechanical behavior of the drift at short and long term is necessary to optimize the design of the support for the CIGEO repository.

A huge program of experiments is planned to characterize the response of the rock to different shaft and drift construction methods. Numerous experiments and direct measurements were performed in the laboratory drifts starting in 2004 (drift at a depth of -445 m excavated from the main shaft) and in 2005 (drifts at a depth of -490 m excavated from an auxiliary shaft), and also during the excavation and construction of the main shaft between -445 m and -490 m. A set by step approach, started in 2006, is carrying on today based on comparison of HM behavior of parallel drifts excavated/supported by different construction methods. These various configurations give insight of the influence of construction method on the EDZ extend and evolution and on the loading of the support.

At the main level located at 490 m, the orientation of the scientific drifts has been determined according to the orientation of in situ stress field. Pneumatic hammer technique was first used for excavation. Bolts, sliding arches and 10 cm-thick layer of shotcrete were set in place immediately following a two-meter maximum progression. Other techniques have been and will be used, like road header (drift GET, GCS GCR), stiff and flexible support. A tunneling machine has been also tested (GRD drift) in 2013 to test segments emplacement technique with different gap filling materials. All the new experimental drifts are instrumented in order to measure the short and long term hydro mechanical behavior and the EDZ. When it is possible, measurements have been emplaced in field previously to excavation work to follow the HM impact of the digging.

For example, in order to understand the impact of different support's stiffness on the long term behavior of the rock mass, it was planned to compare hydro mechanical behavior around at least 60 m length drifts: one, called GCS drift, experiments allowing deformation supports, a second, called GCR drift excavated with the same method, but with a stiff support placed a few months after its excavation in order to stop deformations and a third with concrete segment emplaced under a shield during the excavation work. The comparison will enable to understand relationship between rock deformation in the EDZ and support loading. Those data gives insight to CIGEO drift design.

All those experiments also provide an important data-base which will be useful to check the ability and capacity of numerical models to reproduce and simulate the hydro mechanical behavior of the rock mass.