Session 10A

Excavation Damaged Zone - 2

Chair: Hans-Joachim Alheid / Patrick Lebon
SIMILARITIES IN THE HYDROMECHANICAL RESPONSE OF CALLOVO-OXFORDIAN CLAY AND BOOM CLAY DURING GALLERY EXCAVATION

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INTRODUCTION
The coupled hydromechanical response and the fracture pattern around excavations are of much interest in the feasibility studies of high-level and long-lived radioactive waste repository. This response was characterised during recent excavation works performed at the Meuse/Haute-Marne URL in the indurated Callovo-Oxfordian clay and at the HADES URL in the plastic Boom clay.

THE OBSERVATIONS PERFORMED IN CALLOVO-OXFORDIAN CLAY
Two major experiments were carried out in order to understand the rock response in the Meuse/Haute-Marne URL: the REP experiment, during shaft sinking (Armand et al., 2006), and the SUG-SMR1.1 experiment (Wileveau et al., 2006)) at the main level (-490 m depth).

For both experiments, the impact of the excavation on the hydromechanical response was clearly identified. As expected, the amplitude of the pore water pressure jumps increased with the proximity of the working face. In REP experiment, a strong hydromechanical coupling was observed for the two directions of principal horizontal stress. In the SUG-SMR1.1 experiment, the piezometer chambers installed far away in the rock mass showed a smooth over pressure 20 meters ahead the front face.

The excavation of the horizontal drifts induced shear fractures herringbone shaped ahead of the excavation front. The shear fractures are symmetrical to the horizontal plane crossing the gallery at the middle. The pattern is oriented towards the front face with a dip of approximately 40-45°. They extent around the galleries between 2 and 2.5 m at the vault and at the floor for the galleries oriented parallel to the maximum horizontal stress (fig. 1). They are generally less pronounced when the galleries are parallel to σ3. Herringbone shaped fractures were also observed on drill-cores from one horizontal borehole parallel to σH (fig. 1).

![Figure 1: Similararities of fracture patterns of Boom clay (at left) and of Callovo-Oxfordian claystone.](image)

THE OBSERVATIONS PERFORMED IN BOOM CLAY
The characterization of the hydromechanical behaviour of the Boom clay has been undertaken mainly using data from in situ measurements. Major progresses were made during the construction of the connecting gallery excavated using a tunnelling machine in 2002. The EC CLIPLEX instrumentation programme provided a unique opportunity to monitor the hydromechanical response of Boom clay during the excavation (Bernier & al. 2002).
All piezometers installed ahead of the excavation front registered a similar regular evolution of the pore water pressure with the approach of the excavation front: a progressive increase followed by a sharp drop as the excavation front approached closely. The pressure response and mechanical displacement were strongly coupled. An unexpectedly extended disturbed zone (both hydraulic and mechanical) due to excavation was observed. The pore pressure and displacement sensors began to register regular variation when the excavation front was still more than 60 metres (i.e. 12.5 tunnel diameters) distant.

Evidences of fractures induced by the excavation have been gathered during the construction of the connecting gallery. The systematic observations of the front and the sidewalls allowed the characterisation of the fracture pattern in the surrounding formation. The orientation of the encountered fractures is consistent along most of the excavation. It consisted of two conjugate fracture planes: one in the upper part, dipping towards the excavation direction, the other in the lower part, dipping towards the opposite direction. The two planes were curved and intersected at mid height of the gallery. Some cored borings indicated a radial fracture extent of about 1 m. It is interesting to note that the observed herringbone fracture pattern is similar to the fracture pattern observed on a smaller scale along cores as a result of the drilling of these cores (Figure 1).

DISCUSSION
Despite the important difference in the characteristics between the Callovo-Oxfordian clay and the Boom clay (especially in terms of water content, uniaxial compression strength and hydraulic conductivity), the observed hydromechanical response and the fracture pattern around excavation are quite similar (Blümling et al., 2005). For both clays, the pore pressure evolved regularly during excavation of a gallery with the coming excavation front. Important findings were the unpredicted hydraulic perturbation at large distance from the excavation inside the formation, and the herringbone fracture pattern ahead of the excavation front. The clear difference of fracture pattern can be correlated with the ratio between in situ stress state and compressive strength of rock mass.

Taking note that two different research teams, working separately and using different instrumentation devices, are able to point out similar hydromechanical processes, built our confidence in the reliability of our results.

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References
WHY ARE THE GEOMETRIES OF THE EDZ FRACTURE NETWORKS DIFFERENT IN THE MONT TERRI AND MEUSE/HAUTE-MARNE ROCK LABORATORIES? STRUCTURAL APPROACH

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RATIONALE AND SETTING
The main concern of this study is to compare, on the base of structural evidence, the fracture networks associated with the EDZ in the Mont Terri and Bure URLs and to understand why significant geometric differences can be observed. The datasets for both sites are provided by tunnel and drillcore mapping and structural analyses of impregnated cores obtained using the in-situ resin impregnation technique.

The Mont Terri and Bure URLs have different geological and structural settings. The Mt Terri is located in the Jura thrust and fold belt, where the Opalinus Clay formation was tilted by 45° during the anticline folding. In contrast, the Bure URL is located in the Paris basin, where the sediment layers of the Callovo-Oxfordian formation are sub-horizontal, slightly tilting by 1.5° towards the south-west.

THE EDZ FRACTURE NETWORK AT MONT TERRI BASED ON STRUCTURAL EVIDENCE
EDZ at Mt Terri (Fig. 1a) is made of two parts (Bossart et al., 2002):

1) The “inner zone” (extent = 1 m), consists of unloading fractures (extensile brittle fracturing) subparallel to the tunnel wall, developed where the tangential stresses due to stress redistribution are considerably higher than the uniaxial compressive strength. They are linked by shear fractures, giving an interconnected fracture network connected to the tunnel.

2) The “outer zone” (from 1m to about 2 m), is composed of isolated unloading joints not - or only partially - The bedding anisotropy also contributes significantly to the EDZ fracture network. Bedding within the Opalinus Clay ranges from some millimetres thick to metres and there is ample opportunity for bedding slip to occur if the shear strength along these planes is exceeded (observed in the tunnel in roof, floor and tunnel face). Mechanical breakouts develop where bedding planes are parallel to the tunnel circumference (Gibert et al., 2006). The EDZ fracture network at Mt Terri is therefore the result of extensile fracturing and bedding plane slip.

EDZ FRACTURE NETWORK AT BURE BASED ON STRUCTURAL EVIDENCE
The EDZ fracture network at Bure is composed of at least three fracture systems (Armand et al., 2007):

1) The fracture planes associated with “chevron” fracturing (red in fig. 1b) are characterised by slickenside lineations (shear fractures) oriented along the tunnel axis, thus indicating shear displacement in the excavation direction. These fractures have been found up to 5 m behind the excavation face.
2) A system of subvertical “oblique” fractures with respect to the tunnel axis (green in fig. 1b). Fracture surfaces are dark and polished and can be clearly recognised by the occurrence of subhorizontal slickenside lineations (shear fractures) formed by scratching and gouging of the fracture plane.

3) A system of unloading joints, all around the gallery (not visible in fig. 1b), are subparallel to the tunnel wall. Their extent does not exceed 1 m. Geometry and related kinematics point to a transtensional system (combination of extension and shear components), where the pure extension component is dominant.

**DISCUSSION AND INTERPRETATION**

A system of unloading joints (extensile fracturing) has been recognised at Mont Terri and Bure. At both sites, this system is dominated by pure extension mode fractures connected together by shear mode fractures. The two shear fracture systems (“chevron” and “oblique” fracturing) recognised at Bure have not been identified so far at Mont Terri, whereas bedding plane slip has been detected only at Mont Terri. Pre-existing natural discontinuities such as well developed, inclined bedding planes and tectonic faults, as observed at Mont Terri, create a strong anisotropy and seem to act as limiting structures which hinder the development of EDZ fractures. The occurrence of these natural heterogeneities at Mont Terri could explain the absence of “chevron” and “oblique” fracture systems, both characterised by shear fracturing. At Mont Terri, the shear component associated with tunnel excavation is accommodated along pre-existing natural discontinuities such as fault planes and bedding planes, which are reactivated and activated, respectively. Therefore, the generation of new EDZ structures is controlled mainly by extensile fracturing, since part of the EDZ fracture network is inherited from pre-existing heterogeneities which are reactivated by shear mode. In contrast, the absence of natural faults and subhorizontal bedding planes at Bure do not seem to represent an obstacle that might interfere with the development of the EDZ fracture network. Consequently, at Bure the newly formed EDZ structures consist of both shear and extensile fracturing systems. Another significant factor is the initial stress field, which is higher at Bure (Wileveau et al., 2006) compared to Mont Terri, while the compressive uniaxial strength is assumed to be similar at both sites. This ratio could favour the development of shear fracturing at Bure. However, other factors are also relevant for fracture generation in the EDZ, such as rock behaviour and properties, pore pressure, compaction-subside history and mineralogy.

**References**


CHARACTERISATION
OF THE EXCAVATION-DAMAGED ZONE
IN THE MEUSE HAUTE MARNE
UNDERGROUND RESEARCH LABORATORY

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Excavation of underground drifts generally causes damage to the rock in the vicinity of the openings. The level of damage depends, among other factors, on the rock properties, the stress field, the geometry of the openings, the excavation method and time. Due to the stress redistribution during the excavation and subsequent rock convergence, an EDZ fracture network, consisting of unloading joints and shear fractures appears around the openings. The hydraulic conductivity of these fracture networks may be orders of magnitude higher than the one of the undisturbed host rock and may form a preferential pathway (Bauer et al 2003).

EDZ characterization has been performed during shafts excavation and around drifts at the main level of the Meuse/Haute-Marne URL. Several methods were used to assess the extension of the damaged and disturbed zones, according to different parameters (permeability, velocity of P-wave, density fractures…). The structural analysis provides a good understanding of the fracture mechanisms. Results of different analysis are presented, discussed and compared in order to determine a conceptual model. They are also discussed based on EDZ definition given by Tsang et al (2005) with consideration on safety assessment.

EXCAVATION DAMAGED ZONE CHARACTERIZATION

In the Meuse/Haute-Marne URL, in-situ stresses in the argillite layer are anisotropic with a ratio close to 1.2 (varying with depth). The horizontal major stress is oriented NE155. In order to assess the effect of stress anisotropy, characterisation has been performed around drift parallel and perpendicular to the major horizontal stress. Different EDZ characterization techniques have been used in the laboratory such as:

- Structural analysis of the core samples,
- Geological survey of the drift face and of sidewalls,
- Interval velocity logging measurements to study the evolution of P and S wave velocity according to the distance from the drift wall,
- Seismic cross holes tomography,
- Thin layer analysis of core after fluoresceine resin injection,
- Permeability measurements through gas and hydraulic tests.

EDZ characterization is coupled with convergence and deformation measurements in order to understand their initiation and propagation mechanisms. The structural analysis provides a good understanding of the fracture mechanisms and their succession order. The geometry of EDZ can be conceptualized as follows:

- The “chevron” fractures are initiated ahead of the excavation face during work. They are generally more pronounced when the drifts are parallel to σh. The chevron fractures form symmetrically to the horizontal plane crossing the gallery axis. The dip of this pattern with respect to the horizontal plane is
around 45°. Extension of the chevron zone ahead of the excavation face is close to 1 drift diameter (about 4 m). On the cross section, the extension is different according to the orientation of the drift.

- Vertical and oblique fractures which form beyond the chevron fractures stop at them. They are oriented at a low angle (10° to 30°) with respect to the wall.
- In addition to these shearing fractures, unloading tensile fractures similar to those observed at Mont Terri (Bossart et al 2004) can be observed.

Some microseismic loggings have not only revealed the continuous increase in velocity with respect to the radial distance but also a strong local decrease in velocity which may correspond to an isolated shearing fracture. Seismic refraction coupled with multiple acquisitions of surface waves analysis exhibits a non continuous increase of velocity with depth at the floor of a drift (along σ3), with nearly virgin rock (in term of velocity) over and underlain by zone with weak velocities (linked with shear fractures).

The hydraulic tests in the EDZ zone show an increase in hydraulic permeability (by 4 to 5 orders of magnitude) in the extension fracture zone close to the wall. A small increase in hydraulic permeability is measured in the “chevron” sheared fracture zone which indicates that the sheared fractures are mechanically closed. Pneumatic cross holes measurements were performed at a drift floor between nine two meter deep boreholes in an area of 9 m². Single borehole analysis exhibits very heterogeneous permeability to gas in a range from 10⁹ m² to 10²² m². Cross holes response were observed in the first meter under the floor, but not for all the couple of boreholes, and no one was detected lower.

ANALYSIS AND COMPARISON

Seismic logging and structural analysis provide a coherent view of the EDZ, which emphasizes that the fracture network constitutes a 1-m-thick ring around the drift. The part of the shear fractures out of this ring appears as localized single fractures. Permeability measurements show the heterogeneity of the EDZ and emphasize that high permeabilities are localized in this fractured ring. Decrease of EDZ permeability with time can be observed when the EDZ is rehydrated (Blümling et al 2007).

References


EDZ CHARACTERISATION WITH ULTRASONIC INTERVAL VELOCITY MEASUREMENTS IN THE URL MEUS/HAUTE-MARNE – PERFORMED BETWEEN DEPTH OF 85 M AND 504 M

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INTRODUCTION
The knowledge of the properties of the excavation damaged/disturbed zone (EDZ/EdZ) around underground openings is of importance for safety assessment considerations. Several seismic parameters change significantly in rock with progressive failure. Thus, high resolution ultrasonic methods, with emitted frequencies between 50 and 100kHz, can help analysing changes in rock properties in the EDZ/EdZ around underground openings.

Between summer 2001 and winter 2005 ultrasonic interval velocity measurements were performed by BGR in the URL Meuse/Haute-Marne in 43 different boreholes at 14 different locations between 85m and 504m depth level in the PA-shaft as well as in the 445m level experimental niche and in the GKE and GMR drift at the main level at 490m (experiments: SET-1 – SET-3, SMGR-K, SET, SMR2.1, SMGR1 – SMGR-4, SMR1.1 and KEY). The majority of the work was conducted in the Callovo-Oxfordien and aimed at the characterisation and the determination of the extent of the EDZ/EdZ (Schuster, 2005a,b,c).

ULTRASONIC INTERVAL VELOCITY MEASUREMENTS
For a seismic characterisation of the EDZ/EdZ ultrasonic interval velocity measurements in boreholes with diameters of 86mm and 101mm and lengths between 4m and 20m were performed with a BGR-mini-ultrasonic probe. The seismic wave field is measured along short borehole intervals between a seismic source and three receivers at distances of 10, 20 and 30cm. With the help of a set of derived seismic parameters the EDZ/EdZ can be characterised (Schuster et al., 2001a). For local anisotropy studies in several boreholes additional rotational interval velocity measurements were performed.

Before the ultrasonic measurements, in a first step, most of the boreholes were inspected with a BGR-borehole video camera immediately after the boreholes were drilled. With it the condition of the borehole wall could be rated and the visual analyses of the borehole videos helped later for the interpretation.

RESULTS AND INTERPRETATION
With the help of the visual borehole camera analyses the borehole breakout pattern was assessed systematically. For example, the borehole breakouts with different intensities and symmetrical pattern started at borehole depths greater than 3 m for all six boreholes drilled in the GKE drift within the KEY-experiment. Furthermore, a clear symmetry between the two vertical, the two sub-horizontal and the two 45° downward inclined boreholes can be seen.

From seismic first arrival phases (P-waves) and vertical polarised shear wave onsets (SV-waves) different parameters were derived, including seismic P- and SV-wave velocities, amplitudes, apparent frequencies and dynamic pseudo elastic parameters like Poisson’s Ratio and Young’s Modulus.

With the help of several criteria, based on different seismic parameters, the extents of the EDZ/EdZ are determined. In terms of these relative assessments different degrees of damage can be identified. The transition between seismically identified EDZ and EdZ is fluxionary and still under discussion. According
to our experiences, reduced seismic velocities and strong amplitude damping indicate a rather damaged part of the rock whereas lower, but constantly increasing velocities, point to a rather disturbed part of the rock. The undisturbed rock shows normally a stable velocity plateau and is encountered at deeper parts of the borehole. In the Callovo-Oxfordien we regard a constant P-wave velocity of 3200 m/s as an indicator for an undisturbed rock mass. Both types of parameter distributions are found in our data (Fig. 1).

With ultrasonic interval velocity measurements the vicinity of the borehole is scanned. According to finite difference modelling, the depths of penetration of the seismic wave field lies between 5 and 1 cm, depending on the properties of the small scale EdZ around the borehole wall. So the question remains, how representative are these results for the rock mass? Are the changes in rock properties caused by stress redistribution or/and de-saturation along the borehole wall? Cross hole measurements between two boreholes could help to answer this question. In former experiments, e.g. at the URL Mol, we found a very good agreement between results from ultrasonic interval velocity and cross hole measurements (Schuster et al., 2001b). This supports the reliability and the actual interpretation of the results from interval velocity measurements at the URL Meuse/Haute-Marne.

Furthermore, several rotational interval velocity measurements are indicating the existence of seismic anisotropy due to fine bedding or/and stress redistributions. At least in one case a very clear correlation between seismic parameters and the horizontal minimum and maximum stress directions can be observed. Similarities and symmetries in the parameter distribution can be seen for example in SUG and in KEY data as well as between SUG and KEY-data.

References: