Available online at www.sciencedirect.com
ScienceDirect
Physics and Chemistry of the Earth 32 (2007) 588–599
PHYSICS and CHEMISTRY of the EARTH
www.elsevier.com/locate/pce

The excavation damaged zone in clay formations time-dependent behaviour and influence on performance assessment

Peter Blümling [a,*], Frédéric Bernier [b], Patrick Lebon [c], C. Derek Martin [d]

[a] NAGRA, Hardstr. 73, CH 5430 Wettingen, Switzerland
[b] EURIDICE, Boeretang 200, B-2400 Mol, Belgium
[c] ANDRA, 1-7 rue J. Monnet, F-92260 Chatenay-Malabry, France
[d] University of Alberta, Department of Civil and Environmental Engineering, Edmonton, Canada T6G2G7

Received 11 July 2005; received in revised form 20 April 2006; accepted 28 April 2006
Available online 27 October 2006

Abstract

Clay formations in their natural state exhibit very favourable conditions for disposal of radioactive waste. 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 favourable properties of such formations could change and the host rock could lose part of its barrier function.

Stress redistribution will lead to the creation of a so-called excavation damaged zone (EDZ) which will be controlled by the initial stress field, the material properties (e.g., material anisotropy), the existence of natural fracture zones or local inhomogeneities of the rock mass and the geometry of the tunnel. Comprehensive investigations at different sites (e.g., HADES, Belgium, Mont Terri, Switzerland, Tournemire, France) have shown that an EDZ occurs in soft or plastic clays as well as in indurated and more brittle claystones. The short-term excavation-induced reaction of the rock during tunnelling, which leads to the initial EDZ, cannot be avoided but is reasonably well understood and the associated processes can be adequately modelled.

The long-term behaviour of the tunnel near-field can be significantly influenced by adequate support measures and the time-dependent evolution of the EDZ before the emplacement of the waste and the backfilling of the tunnel can be controlled. The properties of the initial EDZ alter significantly during the transient phase, when the buffer and rock mass are heated by the heat-producing waste and become saturated due to the flow of formation water from the host rock. Experimental results in the laboratory and in-situ clearly show that (self-) sealing leads to a significant reduction in the effective hydraulic conductivity of the EDZ with time, thus reducing the potential flow along underground excavations. Expected long-term conductivities within the EDZ are in the range of 10^{-10} to 10^{-12} m/s.

Performance assessment calculations for different repository designs in different clay host rock formations show that the influence of the EDZ on radionuclide release is quite limited. It has been shown that even for very conservative, so-called "what if?" cases the very stringent regulatory guidelines can be met.

Keywords: Excavation disturbed zone; Performance assessment; Radionuclide transport; Hydraulic conductivity

1. Introduction

Clay formations in their natural state exhibit very favourable conditions for disposal of radioactive waste, as they generally have a very low and uniform hydraulic conductivity, low diffusion coefficients and good retention capacity for radionuclides. An undisturbed clay or clay rock could thus be a particularly good host rock for a nuclear waste repository. 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 favourable properties of such formations could change and the host rock could lose part of its barrier function and thus negatively influence the

* Corresponding author. Tel.: +41 56 4371 293; fax: +41 56 4371 345.
E-mail address: peter.blumling@nagra.ch (P. Blümling).

1474-7065/$ - see front matter
doi:10.1016/j.pce.2006.04.034

performance of a repository. In addition, the associated de-saturation/re-saturation process, as well as heating of the rock and the potential engineered barrier systems, are of concern and need a detailed evaluation to assess their influence on the long-term behaviour of the repository system.

One of the challenges for constructing a deep geological repository in weak rocks is estimating the constructability, i.e., support requirements. Balancing the support requirements with the isolation requirements (repository depth) can only be achieved if the properties of the rock mass can be evaluated with confidence. This evaluation is difficult for any type of rock mass, as input data have to be inferred from standard laboratory tests. The test samples are in general of relatively small size and do not represent the rock heterogeneity and the influence of potential discrete features or discontinuities. Therefore, up-scaling procedures are necessary in nearly all rock types to evaluate deformation and fracturing associated with tunnelling. In addition to these general problems, clays, clay shales or claystone show even more severe problems. Rock-water interaction, severe influence of de-saturation/re-saturation cycles and mechanical micro-cracking during sample extraction, transport and preparation may lead to significant alteration of the rock properties or state changes. This increases the difficulties in realistically describing the rock mass behaviour and in deriving parameters for adequate constitutive laws. For example, Barla et al. (2004) have found that laboratory data of an Italian shale could not be used directly to assess the tunnel behaviour and that parameters needed to be scaled up significantly in order to obtain appropriate predictions.

Problems in predicting short-term rock mass behaviour during tunnelling are challenging, but can be solved in a learning-by-doing procedure during the construction of the first access tunnels and via adequate large-scale investigations in an on-site rock laboratory. The long-term behaviour of the rock cannot be observed under realistic scales in space and time but requires adequate process understanding and numerical modelling. In contrast to crystalline rocks, where deformation in the given stress / temperature regime is mainly elastic or elasto-plastic, clays and clay rock exhibit a much more complex behaviour. Questions on adequate rheological models, changes in time-dependent behaviour due to temperature, stress and associated water content changes, have to be addressed and answered.

The understanding of the creation of an EDZ around underground structures, the time-dependent processes during the transient stage (heat production from the decay of the waste, re-saturation processes etc) and the eventually reached equilibrium will provide the key to evaluate the influence of the EDZ on the long-term performance of the repository. This paper describes how process understanding with respect to EDZ development and performance for the different stages of the repository development were gained for clays and claystone and how the findings were incorporated in performance assessment calculations.

2. Mechanical behaviour of clay formations

The main information source for geotechnical parameters of any rock formation are borehole cores taken from deep boreholes. These rock samples are taken with great care by using double and triple core barrels but nevertheless, they will become disturbed when they are retrieved from their natural environment, where they are exposed to a certain stress field and pore pressure.

2.1. Sample disturbance

It is well known that creating any underground excavation disturbs the in-situ stress state. And, because stresses at the walls around an underground excavation are independent of the size of the excavation, the same stresses exist around a 100-mm-diameter borehole as those which exist around a 5-m-diameter tunnel. Fig. 1 shows the stress path followed by three points around a horizontal hole drilled parallel to the far-field σ_2: top line – along the top of the opening, side line – along the side of the opening, and centre line – along the centre of the opening. In Fig. 1, each of these points starts at the same in-situ stress state but ends at a very different stress state. For example the centre-line, which is equivalent to taking a core sample, shows the complete unloading process that a sample will go through, while the side-line results in large tangential stresses that may exceed the strength envelope of the material.

For the case of a drill hole, the centre line shows the stress path the sample follows before being collected. As shown in Fig. 1, the drill core will be subjected to a stress path that will create extensional loading conditions, particularly in the vicinity of the drill-bit. Such extensional loading can create microcracking and, in severe stress conditions, will lead to core disking (Fig. 2). Once the sample has been retrieved it may then be subjected to the laboratory triaxial stress path in order to quantify the in-situ strength and deformation properties.

Core retrieved from such stress conditions show characteristics that indicate that the properties of the clay have been disturbed. Fig. 3 shows typical axial stress–strain curves of disturbed samples. Such laboratory behaviour has been observed in thermally cracked marble (Rosengren and Jaeger, 1968) and microcracked granite (Martin and Stimpson, 1994). It is important to note that regardless of the amount of confinement, the deformation and strength parameters determined from such samples will be significantly less than the properties of undisturbed samples. When dealing with weak, tight rocks with very fine pores and high reactivity with water, environmental conditions (humidity), pore water pressure, drilling fluids (air or oil), and sample storage and handling, can also significantly decrease the quality of drill core. In weak rock Corkum (2005) has also shown that the unloading process during sampling can lead to the mechanical breakage of diagenetic bonds, which can cause a highly non-linear elastic response. Hence, it is easy to appreciate why Barla et al.