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ELASTOPLASTIC MODELLING OF A VENTILATION TEST IN ARGILLACEOUS ROCK

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Abstract. A full scale field test to evaluate the effects of ventilation in a tunnel excavated in Opalinus clay has been performed in the underground laboratory of Mont Terri in Switzerland. The test involved several stages of wetting and drying under controlled conditions. To aid interpretation, coupled hydromechanical analyses have been performed taking into account the specific features of the test, especially the conditions in the boundary between air and clay. An elastoplastic model has been used to describe the mechanical behaviour of the rock. The results have revealed the existence of two different zones around the tunnel: a desaturation zone reaching only about 50 cm inside the clay and a larger zone, extending 2.5-3m from the tunnel wall, in which the Opalinus clay is under suction. Observed ventilation effects on Opalinus clay have been modest and reduced to zones quite close to the tunnel.

1 INTRODUCTION

Argillaceous material are commanding increasing attention in recent times [1], particularly concerning deep underground excavations. This enhanced interest is partly due to the fact that argillaceous materials are one of the main potential geological hosts for the storage and/or disposal of high level radioactive waste [2]. Such materials exhibit a number of favourable characteristics such as low permeability, high retardation properties, significant self-healing capacity and, in most cases, negligible economic value. A drawback of these materials, however, is the potential effects of sustained periods of ventilation. Indeed, ventilation may lead to damage bringing about cracking and permeability increases. A number of chemical effects may also be triggered by ventilation. It is expected that those effects will only affect a restricted zone behind the tunnel wall which makes them of limited significance in conventional civil engineering works. However, the same ventilation effects may prove to be important in the context of radioactive waste disposal as they may affect the potential migration paths of radionuclides. In this paper, a field ventilation test carried out in the Mont Terri (Switzerland) underground laboratory is described together with the presentation of some selected monitoring results. Observations are examined and interpreted with the help of hydromechancial numerical analyses performed using a coupled formulation.

2 THE VENTILATION TEST

The Ventilation Test has been performed in a 10 m section of a 1.3m diameter unlined tunnel excavated in the Mont Terri underground laboratory [3]. The tunnel has been excavated in Opalinus clay, a stiff strongly-bedded overconsolidated clay found in Northern Switzerland. The layout of the test is shown in Figure 1. A ten-meter section was sealed off by means of two double doors. The controlled ventilation during the test was achieved using a system consisting of a blowing device, located outside the test section. The inflow and outflow pipes were equipped with flowmeters, hygrometers and thermometers. Measurement of airflow mass and relative humidity (RH) of ingoing and outgoing air allowed the establishment of the global water mass balance of the test section. More information on the test is given in [4].

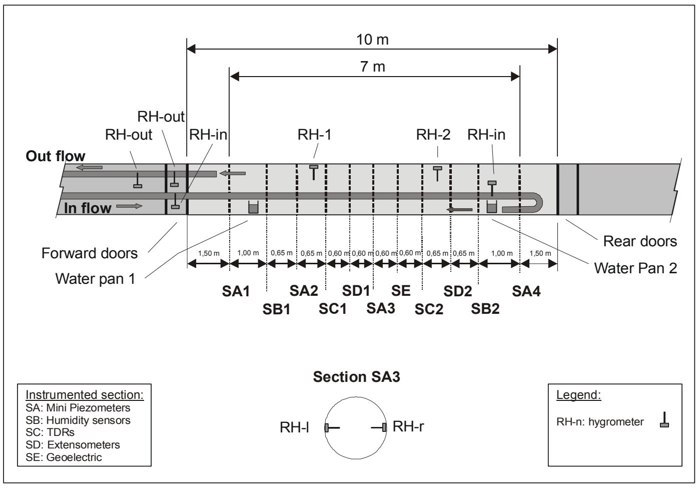

Figure 1: Layout of the ventilation test

The following phases of the test were performed:

- Phase 0 in which the tunnel was excavated and left open without controlled ventilation conditions for 41 months.
- Phase 1 in which the tunnel was subjected to controlled ventilation conditions. During the first stage of this phase, the RH in the tunnel was allowed to be close to 100% causing some resaturation of the clay. In the second stage ventilation with controlled RH was applied. Three RH steps were used: 80%, 30% and 2%. This Phase lasted about 19 months (11 months for the first stage and 8 months for the second).
- Phase 2 also consisted of two stages. In the first stage, the RH was again allowed to be close to 100 % causing again some resaturation of the host clay. Afterwards, a controlled ventilation stage was performed. In this stage, the RH of the incoming air was kept at the low value of 2 % to ensure the strongest possible ventilation effects

over the time available for the test. In total, this phase lasted 33 months, 12 months for the first stage and 21 months for the final strong ventilation stage.

The test was instrumented with hygrometers, piezometers and extensometers. Figure 2 shows the test tunnel during the installation of the instrumentation.

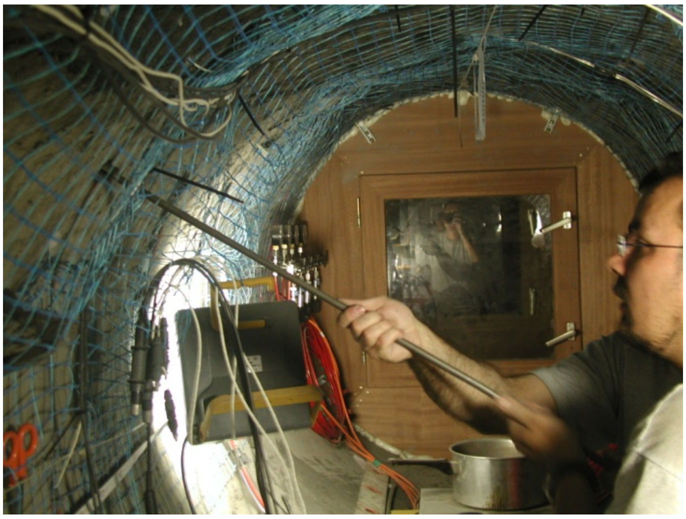

Figure 2: Installation of the instrumentation

3 FORMULATION

The hydromechanical formulation used is a particular case of a general THM formulation developed formerly [5]. The key equation in this particular case is the water mass balance [6] expressed as:

$$\frac{\partial}{\partial t}\left(\theta_l^w S_l \phi + \theta_g^w S_g \phi\right) + \nabla \cdot \left(\mathbf{j}_l^w + \mathbf{j}_g^w\right) = f^w \qquad (1)$$

where the first term reflects the change of water mass with time in a generic representative volume and the second term represents the divergence of water flow. The right hand side term is a sink/source term that is equal to 0 in the present case. θ_l^w and θ_g^w are the volumetric masses of water in the liquid and the gas phase, respectively. $\theta^w{}_l=\omega^w{}_l.\rho_l$, where $\omega^w{}_l=m_w/m_l$ is the mass fraction of water in the liquid. The same nomenclature is used for the gas phase. S_l and S_g are the degrees of saturation of liquid and gas phases, respectively. j_l^w and j_g^w are the fluxes of water (with respect to a fixed reference) in the liquid and gas phases, respectively.

Relative humidity is defined as the ratio of the partial pressure of water vapour in the mixture to the saturated vapour pressure of water at a given temperature. It can be related to $\theta^w{}_g$ through:

$$RH = \frac{p_v}{\left(p_v\right)_0}\cdot 100 = \frac{\theta_g^w}{\left(\theta_g^w\right)_0}\cdot 100 \qquad (2)$$

where p_v is the vapour pressure and subscript $()^0$ stands for the saturated state. Kelvin's law relates vapour concentration in the gas phase to water potential (suction).

An important observation of the test is the existence of a skin effect, i.e. the fact that the relative humidity measured in the air of the tunnel is quite different from the value observed just inside the clay. Accounting for the skin effect requires the modification of the boundary condition used in the analysis. The condition applied is:

$$j_g^w = \beta_g \left(\left(\rho_g \omega_g^w \right)^0 - \left(\rho_g \omega_g^w \right) \right) \tag{3}$$

where j^w_g *[kg/s/m²]* is the flux of water in the gas phase, the subscript $()_0$ stands for the prescribed values, ρ_g *[kg/m³]* is the gas density, ω^w_g is the mass fraction of water and gas and β_g *[m/s]* is a coefficient that controls the velocity at which the boundary values tend towards the prescribed values

The calculation domain, mesh discretization, initial and boundary conditions and material parameters of the hydromechanical analyses are presented in more detail in [7].

4 RESULTS AND DISCUSSION

Only selected test results are presented here. Measurements of relative humidity from the hygrometers close to the tunnel wall and of pore pressures in the Opalinus clay at the end of the experiment (Phase 2) are plotted in Figure 3. The results of the computations are also included showing a good agreement. It can be noted that several model results have been plotted corresponding to different line orientations. They are somewhat different because of assuming anisotropy in clay permeability.

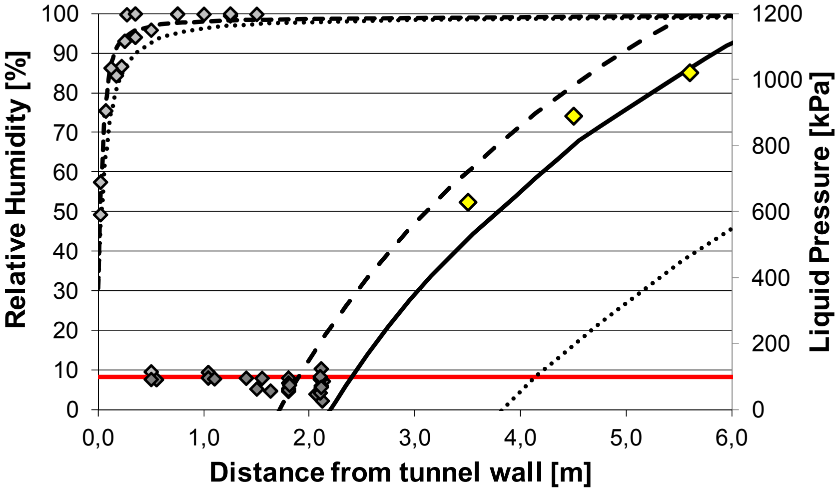

Figure 3: Distribution of relative humidity and pore pressures in the Opalinus clay at the end of Phase 2. Observations and model results (dashed lines: vertical direction, dotted lines: horizontal direction, full line: 45° direction).

It is interesting to compare those observations with the water content and, especially, degree of saturation profiles obtained from the samples retrieved form the boreholes drilled at the end of the test (Figure 4). It is apparent that whereas suction extends to about 2-3 m from the tunnel wall, the unsaturated material occupies only a zone of about 40-50 cm around the tunnel. These observations clearly disprove the association that is often made between suction and unsaturation. Incidentally, the size of the unsaturated zone computed in the analysis corresponds quite well to the test observations (Figure 5). The effect of the permeability anisotropy of the Opalinus clay on the computed contours is also readily apparent. Naturally, Opalinus clay, being a fine-grained material, can sustain significant suction values without becoming unsaturated.

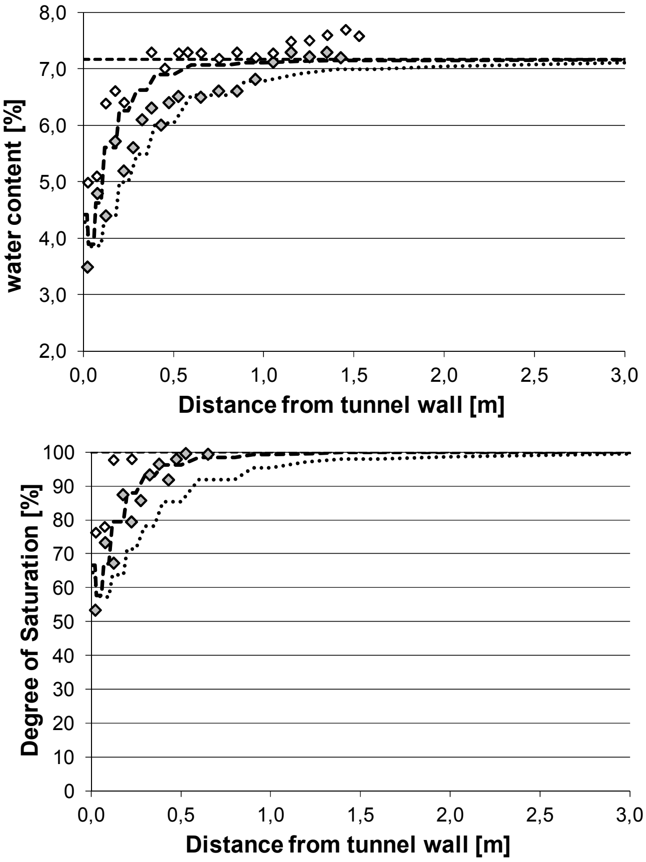

Figure 4: Distribution of water content and degree of saturation in the Opalinus clay at the end of Phase 2 desaturation. Observations and model results (dashed lines: vertical direction, dotted lines: horizontal direction).

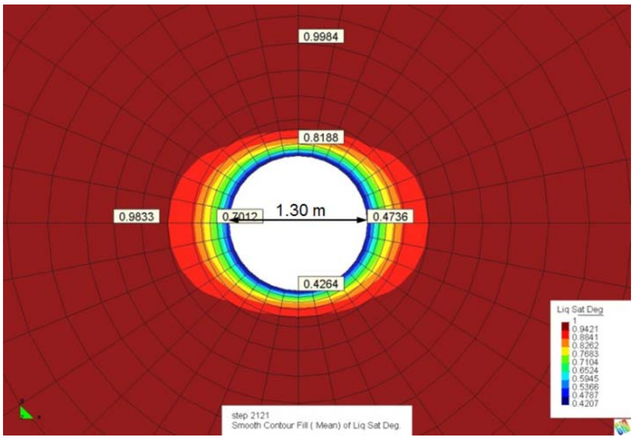

Figure 5: Computed contours of degree of saturation at the end of the test.

5 CONCLUSIONS

The effects of ventilation on a tunnel excavated in argillaceous material (Opalinus clay) have been evaluated by means of a full scale field test involving the introduction of air with controlled humidity, a comprehensive instrumentation system and a long test duration. Test observations have been interpreted with the assistance of a coupled hydromechanical analysis in which specific features of the problem such as the skin effect has been taken into account.

Two different zones around the tunnel have been identified: a small desaturation zone and a larger zone in which the Opalinus clay is under suction. The desaturation zone reaches only about 50 cm inside the rock in spite of the very low relative humidity applied during the long periods of ventilation. The suction zone extends to 2.5-3 m away from the tunnel wall but it appears that it has only been moderately enhanced by ventilation. It can therefore be concluded that, in spite of the very strong drying applied by means of air of very low humidity, the ventilation effects on Opalinus clay have been modest and limited to zones quite close to the tunnel.

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