Monitoring long-term hydromechanical processes in swellable Opalinus Clay shale of the new Belchen tunnel (Switzerland)

Martin Ziegler
Department of Earth Sciences, ETH Zurich, Zurich, Switzerland

Simon Loew
Department of Earth Sciences, ETH Zurich, Zurich, Switzerland

Arash Alimardani Lavasan
Faculty of Civil and Environmental Engineering, Ruhr-Universität Bochum, Bochum, Germany

Ernando Saraiva
Swiss Federal Nuclear Safety Inspectorate, Brugg, Switzerland

ABSTRACT: High swelling pressures and heaves of anhydrite-rich marls and Opalinus Clay shale (OPA) caused substantial damage to the Belchen highway tunnels between Basel and Lucerne in Switzerland, excavated with drill-and-blast technique in the 1960s. The tubes have to be refurbished and a new tunnel tube was constructed with a tunnel boring machine between 2016 and 2018. We have installed a monitoring system in a section of OPA to explore the evolution of radial pressures on the tunnel lining and the local hydro-mechanical conditions with the aim to characterize swelling processes of OPA in-situ. For the interpretation of radial pressures, the mechanical properties of the annular gap grout were explored and the impact of thermal strains on measured radial stresses was investigated with numerical simulations. Here we discuss key results obtained from the new Belchen tunnel that can be also relevant for design considerations of nuclear waste repositories in clay rocks.

Keywords: Rock swelling, In-situ experiment, Swiss Jura mountains, THM coupled processes.

1 INTRODUCTION

Rock swelling is a hydromechanical-chemical process that leads to volume or pressure increase in the ground caused by reduction of confining stresses, absorption and adsorption of water (i.e., inner crystalline and osmotic swelling; e.g., Madsen & Müller-Vonmoos 1989), or by a combination of these processes (e.g., Einstein & Bischoff 1975). Swelling of clay, clay rocks (e.g., Madsen & Müller-Vonmoos 1989), and anhydrite-rich rocks (e.g. Rauh & Thuro 2007 and Amann et al. 2013) can damage underground infrastructures. Rock swelling is considered a potential hazard to the built infrastructure and requires good design solutions for the construction process and the lining systems.

In the Swiss high-level waste (HLW) repository concept the great length of repository drifts and tunnels to be excavated in swellable Opalinus Clay shale (OPA) in the order of 24 km, together with the constraint to limit the damage of the geological barrier surrounding the emplacement drifts for HLW, among other factors, may suggest the use of tunnel boring machines (TBMs) for repository drifts (e.g., NAGRA 2016). Most in-situ observations of swelling phenomena come from conventional excavations (e.g., using drill-and-blast or road header technique) and less from excavations that use TBMs and segmental linings (tubbing stones) as part of the lining system. Thus, there is a need to better understand in-situ swelling around tunnels drilled with TBMs as such excavations do not require drilling fluids for blast holes and may cause smaller excavation damage zones (EDZs) with increased rock mass permeability, which should have an impact on the evolution of swelling processes, compared to conventionally excavated tunnels.

The construction of the new Belchen A2 highway tunnel tube *(Sanierungstunnel Belchen, STB)* between 2016 and 2018 offered a unique opportunity to explore fundamental and practical aspects of TBM excavation in OPA, despite its considerably larger diameter of 13.97 m compared to future repository drifts of 3.2 m (NAGRA 2016). The STB has a total length of 3.2 km and passes through the folded Jura mountains with 570 m of Opalinus Clay shale in two separate sections between tunnel meter (TM) 3180–3330 and 2200–2720 given from North. The tunnel lining consists of an outer segmental and an inner cast-in-place concrete lining. The main objectives of our studies in the STB are related to the in-situ processes, temporal and spatial evolution of potential rock swelling of the OPA. Here, we focus on the key results of monitoring data and thermo-mechanical simulations.

2 METHODOLOGY

2.1 In-situ monitoring systems

We conducted the main in-situ works in a cross-section at TM 2315–2317 near the cross-passage 5a (CP 5a), which connects the new tube with the western tube of the existing Belchen tunnel (Figure 1a). At the monitoring site, we explored the rock mass structures, especially tectonic faults, and installed a broad range of sensors that measure essential rock mass states and deformation using: i) seven radial Total Pressure Cells (TPCs) with temperature sensors installed at the end of 2016 in the outer lining system facing the annular gap grout, ii) three radial boreholes equipped with Sliding Micrometer tubes, iii) a vertical borehole into the invert with two Time-Domain Reflectometry (TDR) sensors for in-situ volumetric water content (VWC) measurements of the OPA (Figure 1b), and iv) four boreholes in CP 5a, of which two have double-packer systems, for hydraulic and pneumatic testing and long-term pore pressure monitoring. The technical details of sensors and installations are given by Ziegler & Loew (2017, 2018). In this paper, we describe and discuss in-situ data of total radial pressures, radial displacements and in-situ volumetric water contents.

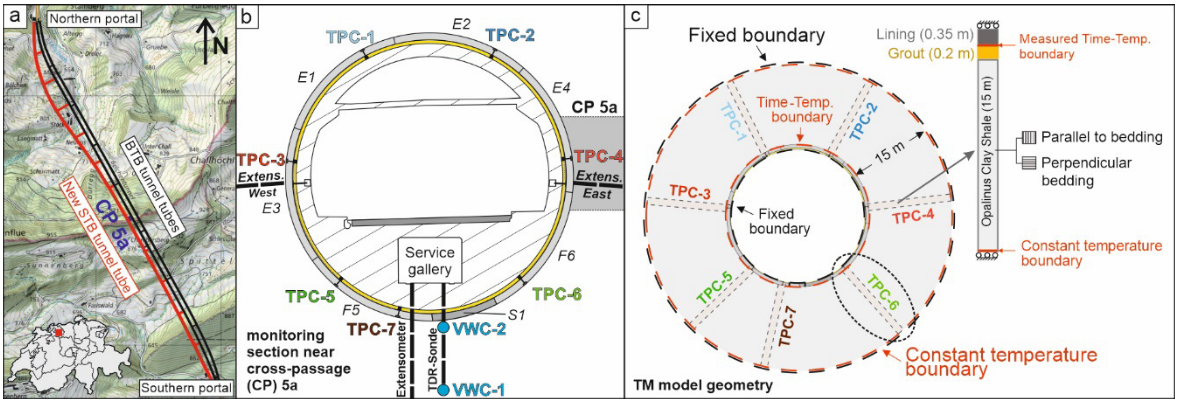

Figure 1. (a) Project location. (b) Cross section of the TPC-equipped tubbing ring at TM 2315–2317 together with TDR and extensometer boreholes near CP 5a. (c) TM model setup. Modified after Ziegler et al. (2022a).

The 13–15 m long extensometer boreholes were drilled into the tunnel invert and sides and equipped with grouted measuring tubes to survey radial deformations with Solexpert's sliding micrometer sonde (Figure 1b). The shallowest measuring intervals locate 1 m (invert) and 0.2 m (west and east sides) inside the rock mass. The TDR borehole probe measures changes of the water content inside the rock mass at 3.1–3.3 m (VWC-1) and 0.2–0.4 m (VWC-2) vertical distance from the interface between rock and annular gap grout. The VWC sensors were calibrated for clay-rich rock and data were offset-corrected using laboratory values from rock cores at the sensor positions.

2.2 *Thermomechanical simulation*

Many processes can contribute to the evolution of total pressures at the contact between the tubbing and grout, including temperature variation, excavation-induced stress redistributions, swelling, creep and relaxation. In this work, we carried out numerical simulations to assess and quantify the mechanical influence of temperature on the total radial pressure in order to enable qualitative evaluation of other processes causing changes in pressure at each TPC position.

In this framework, simplified thermo-mechanically coupled numerical analyses were carried out for radial slices around the tunnel (Figure 1c). The initial stress and pore pressure were set in the models considering data originating from the Mont Terri URL. We defined different scenarios to study the influence of the elastic modulus of the grout (1 and 2 GPa) as we measured in our tests and direction of bedding planes (perpendicular and parallel to sensor plate) on the total pressure in the construction and operation periods (i.e., within 360 days from excavation and afterwards). The detailed model setup and parametrization are given in Ziegler et al. (2022b).

3 RESULTS

3.1 *Radial pressures on tunnel linings*

An annual air temperature variation of ΔT=10°C between summer and winter months can be seen in the tunnel (dotted line, Figure 2). A dependence of the pressure signal on the tunnel temperature is identified for sensors TPC-1−6 and may relate to thermomechanical (TM) deformation of the tunnel lining/rock mass system. The increase (decrease) in the tunnel's air temperature may lead to a considerable increase in the lining's temperature and expansion (shrinkage) of the lining system, causing a reversible rise (reduction) in total pressure of measured Δσ=0.25–0.4 MPa. In contrast, TPC-7 located below the concreted invert is much less influenced by the changing temperature than the other sensors and shows highest pressures (note that higher pressures at TPC-4 are caused by stress redistribution related to the excavation of CP 5a). TPC-7 is more isolated and its temperature fluctuates only by about Δ3°C/year, while it is between Δ4°C/year for TPC5 and TPC-6, and Δ10 °C/year for TPC-1 to TPC-4. The annual TM coupled total pressure cycles are superimposed on a long-term cooling trend of 4–5°C/year of the tunnel between 2017 and 2019. Nevertheless, we recorded long-term rising total pressures of all sensors to a maximum of 1.5 MPa.

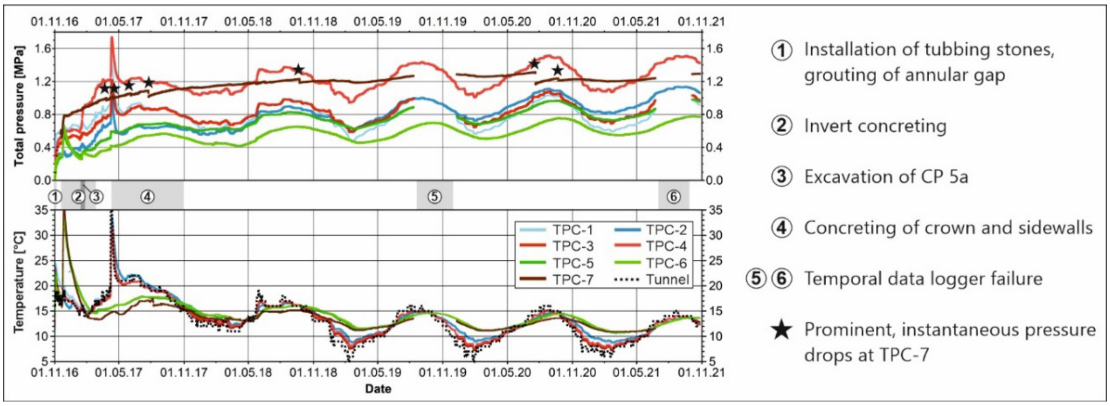

Figure 2. Evolution of radial total pressures and tunnel lining temperatures after Ziegler et al. (2022a).

3.2 *Volumetric water content*

After an equilibration phase of 3–4 months, VWC-1 increased slightly from 13.3 to 13.8 vol.-% until October 2021. In contrast, VWC-2 indicated higher water contents ranging from 14.0 to 15.2 vol.-% and a steeper trend (0.12 vs. 0.28 vol.-%/year) (not shown). VWC-2 clearly exceeds the reference in-situ water content of 13.2 ± 0.1 vol.-% obtained from laboratory tests (Naegeli 2018).

3.3 *Radial displacements*

Eight readings were made between December 2016 and April 2021. In this period, only minor total (i.e., cumulative) radial lengthening of 0.4 mm at the western tunnel side was recorded. In contrast, 1.8 mm lengthening at the invert and 2.8 mm lengthening at the eastern tunnel side were measured. Deformations in the invert occurred mainly in the shallowest 1-m interval. At the eastern tunnel side, the extensional deformations originate from four depths intervals of which three are clearly associated with tectonic fault zones and linked in time with the excavation of CP 5a. While the most recent measurements at the tunnel sides suggest negligible displacements, the shallowest interval at the invert recorded further, though minor extension (0.2 mm/m/year; Ziegler et al. 2022b).

3.4 *Thermomechanical simulation*

Figure 3 shows a comparison between the numerical predictions for four scenarios (parallel and perpendicular bedding, E-moduli of 1 and 2 GPa) and measurements of TPC-6 as an example. The numerical results capture the overall trends of pressure variation reasonably well upon (1) rapid temperature fluctuation due to the hydration of the invert concrete about 25 days after tubbing ring installation (Figure 3a) and (2) the longer-term cyclic temperature evolution (Figure 3b). The deviation between measured and simulated pressures grows with time and could indicate the buildup of swelling pressure and/or rock mass convergence, e. g., through creep processes, not captured by the simulations. Rock bedding orientation had a negligible impact on total stress compared to the elastic stiffness of the gap grout. The entire analysis is given in Ziegler et al. (2022b).

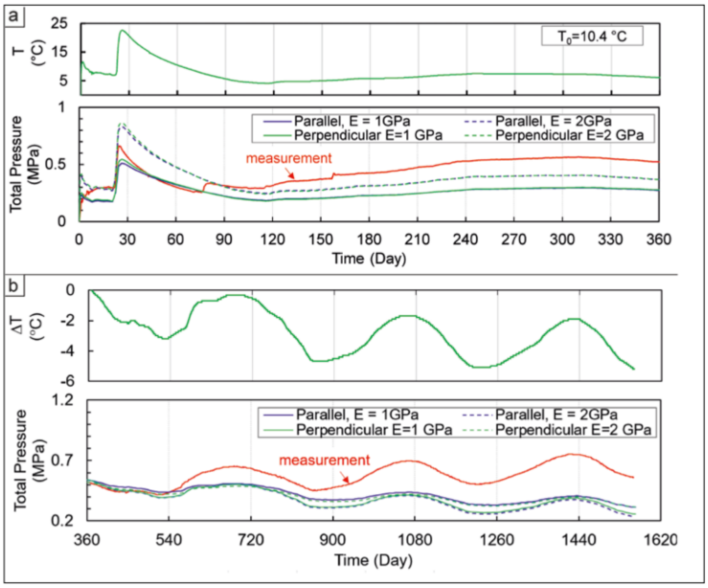

Figure 3. Measured input temperature and result of a TM simulation of TPC-6 (a: first 360 days; b: after 360 days) after Ziegler et al. (2022a). The deviation between the measurement (red) and modelled data (blue, green) at about day 75 relates to the excavation of the near-by cross-passage 5a, and later differences by, e.g., additional radial stresses from swelling or creep processes, which are not covered in the model.

4 DISCUSSION AND CONCLUSIONS

4.1 *Radial total pressures and radial strains*

Fast total pressure responses of 0.2–0.55 MPa within one week after tubbing ring installation suggest good coupling of sensors, gap grout, and rock formation in the STB monitoring site. Four years after TPC installation, we recorded total pressures of 0.5–1.5 MPa (Figure 2). Radial total pressures were also obtained from the interface between OPA and the concreted invert arch at a monitoring section in one of the old Belchen tunnels. But the recorded pressures were on average only 0.03 MPa within the first three weeks (max.0.1 MPa) after the concreting and gently increased to on average 0.15 MPa (max. 0.3 MPa) after four years. Huder & Amberg (1970) and Grob (1972) associated the measured total pressure evolution with rock swelling. The TPCs were installed in a refurbished invert and we conclude that the conditions of TPC installations have a substantial influence on the recorded pressure levels and the significance and comparability of measured data. Nevertheless, the obtained datasets from the old and new Belchen tunnel show also a similarity, i.e., a rapid pressure increase followed by a slower rise in pressure over many years.

Our simplified numerical calculations support the assumption that the annual air temperature cycles lead to substantial radial pressure changes (Ziegler et al. 2022b). Our simplified model does not account for the anisotropy of field stresses, plastic deformations, creep, consolidation and swelling processes around the tunnel. Advanced models together with more sophisticated hydromechanical constitutive laws will be used in the future to investigate these aspects.

The annual thermal stress variations are superimposed on a general, long-term rise in radial pressures. The rate of this radial pressure increase is likely reduced but not compensated by a general cooling trend of the tunnel. Overall long-term radial pressure increases may be attributed to long-term creep processes of the rock formation against the relatively stiff lining system and/or to swelling of the rock mass. Considering radial deformation observations from the extensometer boreholes, we may argue that rock mass convergence is relatively small at the monitoring site.

The evolution of temperatures inside and around HLW emplacement drifts during construction and prior to waste emplacement will depend mainly on the repository depth below ground and the ventilation. The amplitude of possible annual thermal cycles will be strongly reduced if underground sites will be disconnected from the ambient ground surface air temperatures or if the ventilated air will be passively or actively heated or cooled. However, once HLW are emplaced and drifts are backfilled and sealed, the radioactive decay will produce heat over many 100s of years with peak temperatures at the excavated rock surface of up to about 90°C (Bossart et al. 2017). Such high temperatures will lead to additional thermal loads on support systems over long time spans.

4.2 Swelling pressures and water origins

Neglecting stress redistributions by the excavation of the cross-passage, strongly affecting TPC-4, would indicate that radial total pressures in the tunnel invert's center (TPC-7) are considerably larger (Δp=0.1–0.7 MPa) for most of the recorded time compared to the other locations (TPC-1–6). The mean value of radial pressure at TPC-7 since 2019 is 1.24 MPa. This is well within typical ranges of maximum swelling stresses for OPA of 1–2 MPa. In addition, increasing radial extension within the interval 1–2 m into the formation were recorded at the invert extensometer borehole. Evidence supporting rock swelling in the invert comes from the estimation of in-situ volumetric water contents. The VWC inferred from 0.2–0.4 m radial depth has increased continuously and its most recent value of about 15.2 Vol.-% exceeds laboratory measurements on specimen taken from the TDR borehole.

Origins of water required for swelling can be manifold. Inflows from permeable units can be hazardous and were inhibited by pumping pits in the STB. Intact, saturated OPA has a VWC of 12.9–13.6 Vol.-% and a liquid permeability of 10^{-21} to 10^{-23} m^2 (Bossart & Thury 2008). Thus, the flow of water through intact OPA is controlled by pore pressure diffusion. Natural groundwater flow is altered by damage and pore pressure disequilibrium induced by tunnel excavation and the permeability of excavation damaged zones can be many orders of magnitudes greater than the permeability of intact OPA. Rock mass hydraulic permeability inferred from borehole tests of tectonic fault zones in the nearfield of the STB were as low as 10^{-18} m^2 (Renz et al. 2019). Besides natural sources of water, swelling of clay shale is likely initiated during the tunnel construction by radial stress relief together with exposure of the rock to process and construction waters. We measured an in situ gravimetric water content of about 60 w.-% of the hardened gap grout, which may promote initial rock swelling and release water to the rock formation over longer time spans.

Radial total pressures showed sudden drops at about 0.9−1.3 MPa recorded by TPC-7 (Figure 2). The stress level at which such drops occurred are within the range of the crack initiation stress level (0.9–1.4 MPa; Antonioli 2018, Ziegler et al. 2022b) of saturated gap grout, which suggests that the grout is yielding under the current stress. Consequently, yielding of the gap grout may limit the buildup of greater radial total stresses at TPC-7.

Filling materials used in excavations with TBM required to close the annular space between the rock formation and precast, segmental lining systems allow long-term local swelling, rock mass deformation and potential damage evolution also after their installation and contribute to complex stress paths. Thus, the choice and homogeneity of gap grout materials, among other factors, can have measurable impacts on the deformation and stress evolution around tunnels drilled with TBM.

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