Instrumentation for a gas path through host rock and along sealing experiment

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ABSTRACT*:* A key issue in the field of underground waste storage is the investigation of the barrier function of the host rock and the sealing of the disposal tunnel. For the demonstration of gas escape, a large scale "gas path through host rock and along sealing experiment" is currently being conducted at the Mont Terri Rock Laboratory in Switzerland. The experiment is focused on the gas paths along an excavation damaged zone (EDZ) developed around a sealed microtunnel section and the gas paths through the excavation undisturbed host rock. The instrumentation of the test site comprises suitable sensors to assess the hydraulic and geo-mechanic characteristics and the coupled hydromechanical processes around the tunnel. The first test data show a good response of the sensors to the induced pressures and stresses.

INTRODUCTION

The migration of the gas along a sealed microtunnel and through the host rock is being studied in a large scale experiment (HG-A experiment) by three members of the Mont Terri Consortium: the Swiss National Cooperative for the Disposal of Radioactive Waste (NAGRA), the French National Agency of Radioactive Waste Management (ANDRA) and the German Federal Institute for Geosciences and National Resources (BGR). A consortium consisting of Solexperts, Switzerland, Golder Associates, Germany, and SJ Geotech, Switzerland, was contracted for the instrumentation, test performance and numerical modeling of experiment parameters.

The experiment is focused on the gas paths along an excavation damaged zone (EDZ) developed around a sealed microtunnel section and the gas paths through the excavation undisturbed host rock. After the sealing of a nuclear waste repository, corrosion of the steel components and radiolysis of bitumen in the packaging generates gas (hydrogen). Therefore the gas pressure increases within the nuclear waste deposit. However, the gas should be able to escape without altering the hydraulic characteristics of sealing rock formations.

An additional aspect is the sealing of the excavation damaged zone, which is also a main topic in the radioactive waste disposal and the objective of a series of current research projects. During the operational phase of such a repository, the rock formations around the access tunnels will de-saturate and EDZ fractures develop. However, with the closure of these tunnels the re-saturation of the EDZ begins and the EDZ fractures tend to close. These "self-sealing" and "self-healing" effects were shown during previous experiments (Bossart et. al., 2002).

The HG-A experiment is being carried out in the Mont Terri Rock laboratory in Switzerland (see Figure 1, left side). The laboratory is located in Opalinus clay rocks and comprises multiple niches and galleries which are accessed through the security gallery of the highway tunnel (see Figure 1, right side). A large series of experiments have been carried out since the opening of the rock laboratory in 1996. The HG-A experiment site is placed within a gallery which was excavated in 2004 (Gallery 04 in Figure 1, right side).

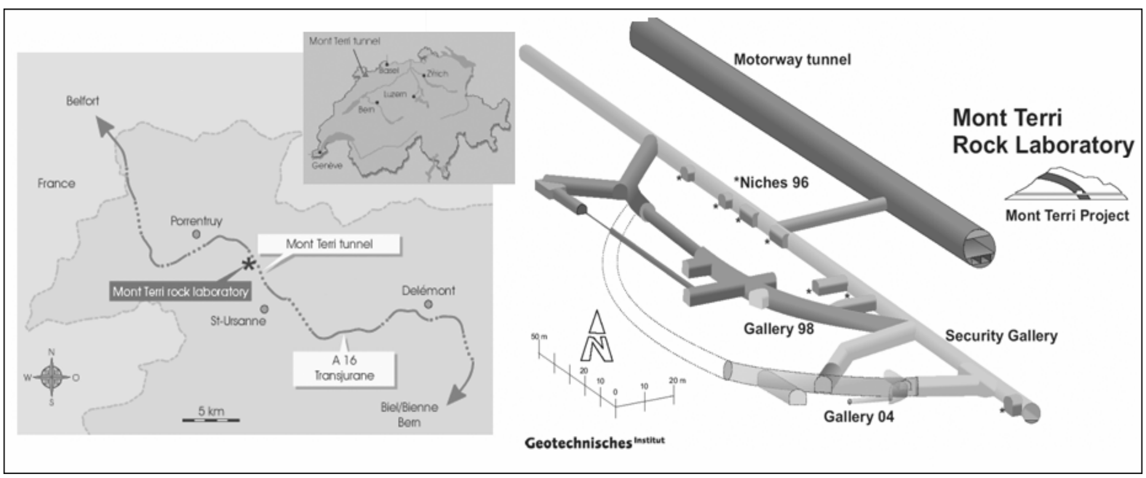

Figure 1: Location map (left) and layout (right) of the Mont Terri Rock Laboratory in NW Switzerland within the Opalinus clay; source: Mont Terri Consortium by Geotechnisches Institut.

EXPERIMENT LAYOUT

In the Gallery 04, a 13 m long and about 1 m diameter microtunnel was drilled in February 2005. Boreholes were drilled parallel and oblique to the microtunnel axis and equipped with multipacker piezometer systems, inclinometer chains, chain-deflectometers and stress cells to monitor the correspondent parameters in the host rock around the microtunnel (Figure 2).

The instrumentation of the 3 m long test section at the end of the microtunnel consists of surface extensometers, strain gages, time domain reflectometers (TDRs), piezometers and geophones. The test section is sealed by a large scale packer (megapacker). The rubber element of the packer is equipped with piezometers and the correspondent tunnel wall surface with TDRs and total pressure cells.

The megapacker design and emplacement was a major task during the instrumentation phase. The megapacker was built for a sealing length of 3 meters and an upper testing pressure limit of 40 bar. During the emplacement special consideration had to be given to potential damage of the rubber element, the tunnel instrumentation and artificial gas flow paths.

The acquired data is recorded in two data acquisition systems; one for long-term monitoring and the other for fast data sampling of key test parameters during active testing phases. The data is available for authorized persons through internet access and is quality checked on regular time base.

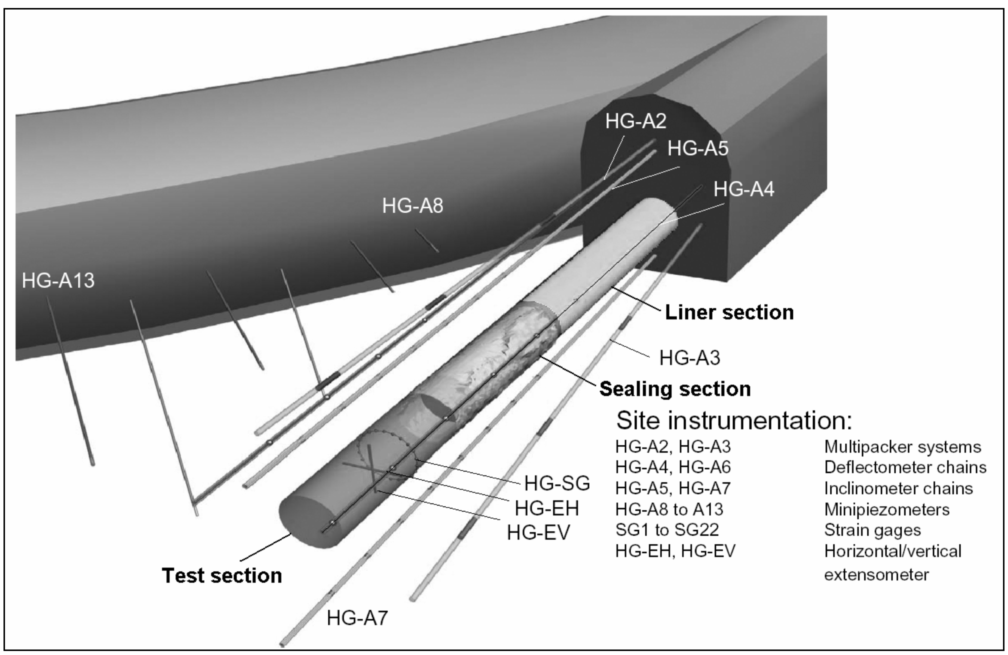

Figure 2: HG-A site with instrumentation of the microtunnel and of the axial boreholes.

The test plan comprises the following 6 phases (Figure 3): Phase 0 started in January 2005 with the drilling and instrumentation of the boreholes parallel to the microtunnel axis. The microtunnel was excavated in February 2005 with an auger rig of 1 meter diameter. The instrumentation, backfilling and sealing of the microtunnel (Phase 1) was carried out between April and May 2006. During Phase 2, between June and November 2006, the megapacker was emplaced and inflated, and the backfill saturated with water.

Subsequently, Phase 3 was started, which consists of a large series of hydraulic constant pressure and constant rate injection tests and which was still ongoing while this paper was submitted in March 2007. Gas injection tests will be performed in Phase 4. A second hydraulic test series during Phase 5 will complete the HG-A experiment.

INSTRUMENTATION OF THE BOREHOLES

The boreholes located axially to the microtunnel (see Figure 2) were drilled prior to the excavation of the microtunnel and were equipped with inclinometer chains, chain deflectometers and triple packer systems to observe the deformation and the pore pressures in the rock formations around the microtunnel during and after its excavation.

The inclinometer chain (CLINO-Chain, Figure 4) is used to monitor displacements in the structure or along the axis of a borehole by measuring the transversal displacements at multiple points along a borehole axis.

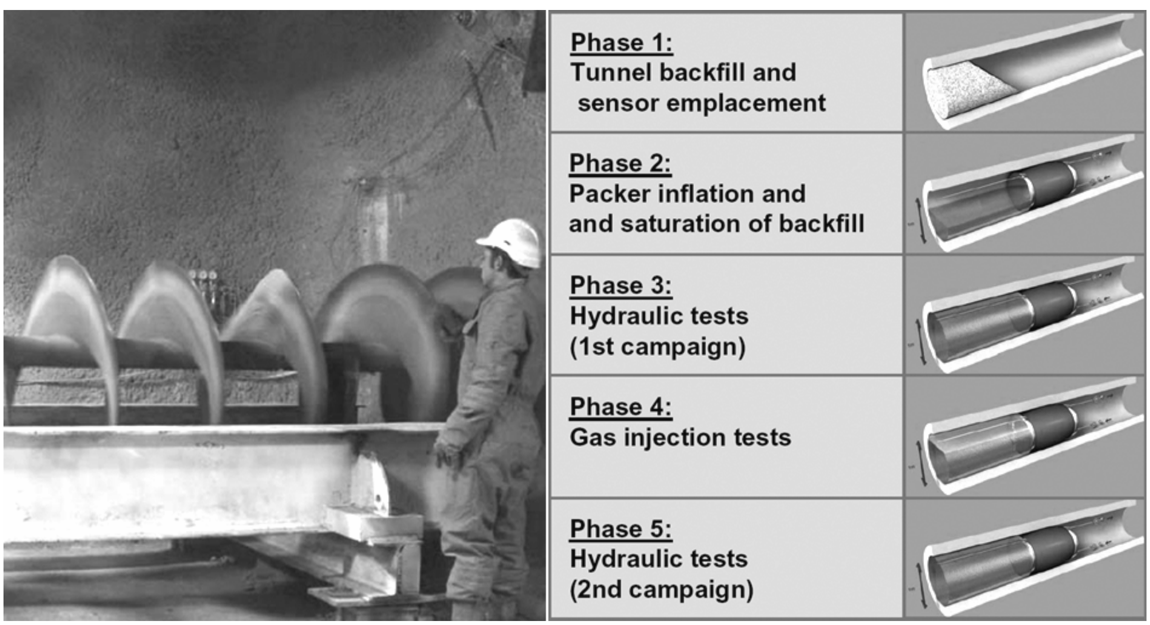

Figure 3: Excavation of the microtunnel with an auger rig (Phase 0) and general test plan of the HG-A experiment; source: Mont Terri Consortium.

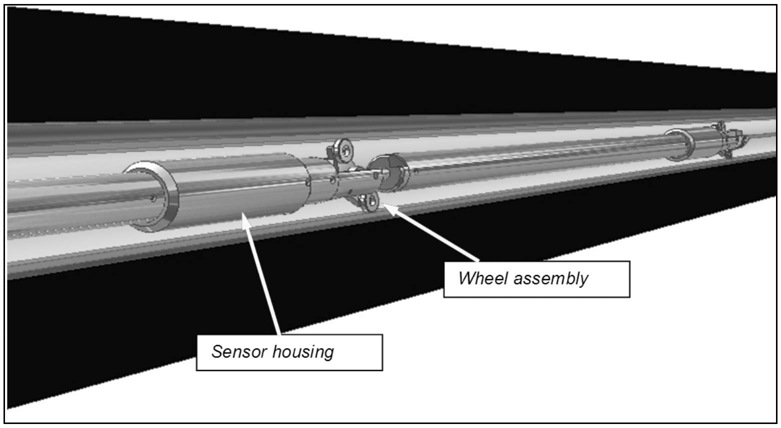

Figure 4: Drawing of the CLINO-chain; source: Solexperts AG.

CLINO-Chains were installed in the boreholes BHG-A5 and BHG-A7, which are downwards inclined by 1 deg (1/360) and 6 deg (1/360), respectively. The instrument is composed of sequentially mounted probes of a length of 1 m which are connected together by swivel heads with spring-loaded wheels that guide the probe in the centre of the grooved casing and fix the chain at the desired position. Each probe includes a high-precision and highly stable uniaxial inclinometer sensor. The 8 elements are installed at borehole depths between 5.8 to 13.8 m.

The Chain Deflectometer (Figure 5) is a multiple deflectometer used for the automatic monitoring of subsurface deformations, such as in slopes, around excavations or beneath dams. It was developed by the Swiss Federal Institute of Technology, Zürich (ETHZ) and is produced by Solexperts AG. Chain Deflectometers were installed in the boreholes BHG-A4 and BHG-A6.

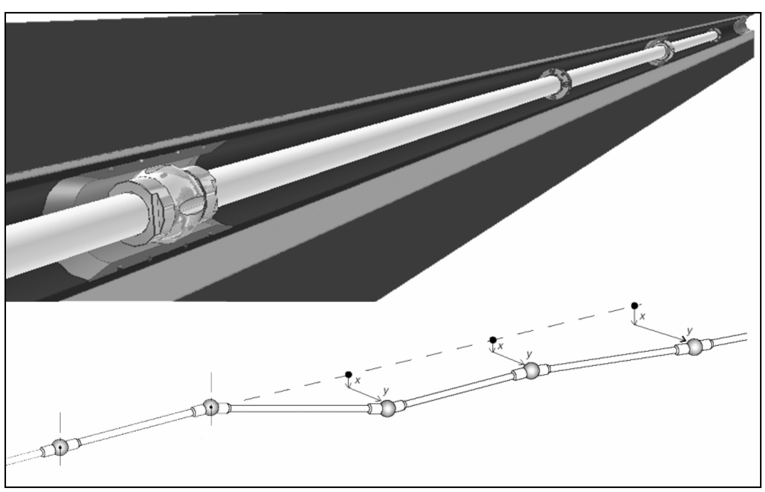

Figure 5: Drawing of the Chain Deflectometer; source: Solexperts AG.

The Chain Deflectometer consists of heads with electronic joints, connecting rods and heads at each end of the chain. Each head with an electronic joint holds the element which measures deflections in the x and y directions between two connecting rods. This element also includes the amplifier, the signal conditioner and the multiplexer. This arrangement enables readings of all elements of the Chain Deflectometer over one cable. The heads are connected to each other with connecting rods. The connecting rods, with a length of 1.5 m, also serve as the lead-through for the signal cable.

The pore pressures in two axial boreholes are measured with triple packer systems (Figure 6). The boreholes BHG-A2 and BHG-A3 are instrumented with 80 mm diameter hydraulic triple packer systems of 0.5 meter packer sealing length. Each test interval is equipped with 2 stainless steel (3 mm inner diameter) water lines; one for pressure observation and one flow line. The packer and the interval pressures can be controlled through a surface control unit which consists of manometers and pressure transducers for the interval and packer pressure monitoring.

EFFECTS OF THE MICROTUNNEL EXCAVATION

During the second half of February 2005 the microtunnel was excavated. Thus, the stress field in the surrounding rock, which was monitored with the above described instrumentation, was changed.

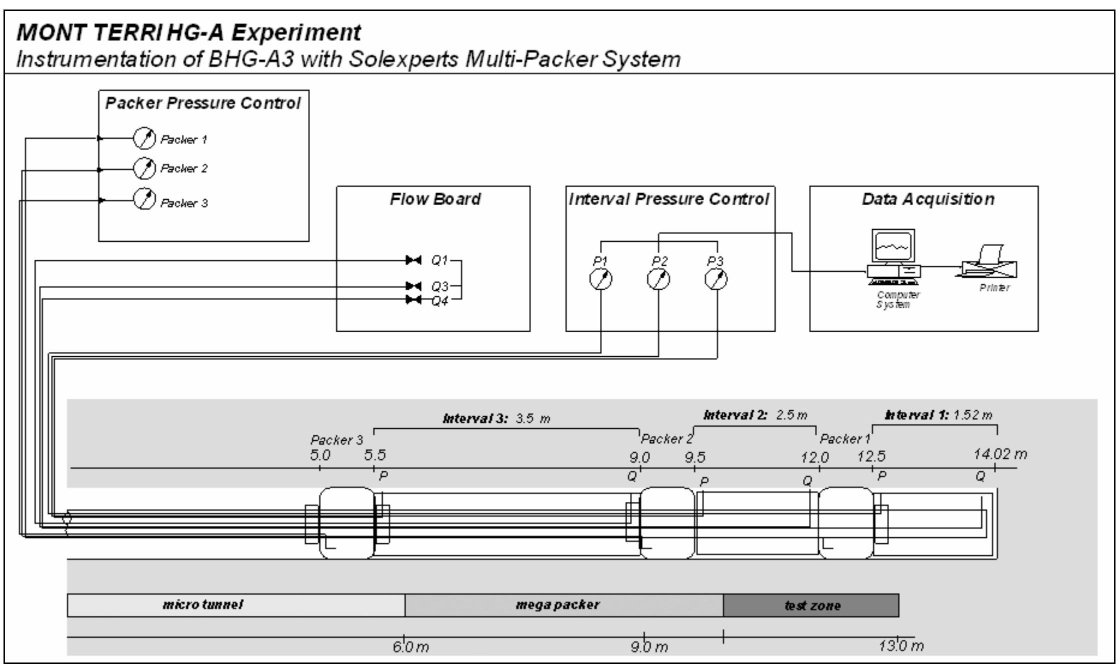

Figure 6: Schematic drawing of the triple packer system installed in borehole BHG-A3 (bottom) and the correspondent surface control units; source: Solexperts AG.

The inclinometer chains respond instantaneously on the tunnel excavation (Figure 7, left side). In the boreholes BHG-A5 and BHG-7 located above and below the microtunnel, the displacements were pronounced during the excavation and the daily excavation steps are clearly visible. The displacements slowed down after the borehole completion. Downward and upward displacements were recorded (Figure 7, right side). These displacements seem to agree with the changes in general stress due to excavation. In general, the lowermost borehole sections show the smallest displacements that increase up to a borehole depth between 7 and 9 m and slightly decrease towards the uppermost element at a borehole depth of 5.8 m. Until 1st of June, 2005, the maximum downward displacements measured in borehole BHG-A5 reached about 1.5 mm for the element between 6.8 and 7.8 m. During the same period the maximum upward displacement in borehole BHG-A7 was about 1.4 mm for the element between 8.8 and 9.8 m. The stabilisation of the uppermost elements might be due to the installation of the liner up to a borehole depth of 6 m immediately after the completion of the excavation.

Also the Chain Deflectometer elements react immediately on the excavation of the microtunnel (Figure 8). The main movements in the two boreholes are opposite to each other. The Chain Deflectometer in borehole BHG-A4 shows a trend in deflection towards the microtunnel, whereas the Chain Deflectometer in borehole BHG-A6 seems to indicate movements away from the microtunnel. These movements correspond to the stress redistribution in the surrounding rock (see also Figure 11).

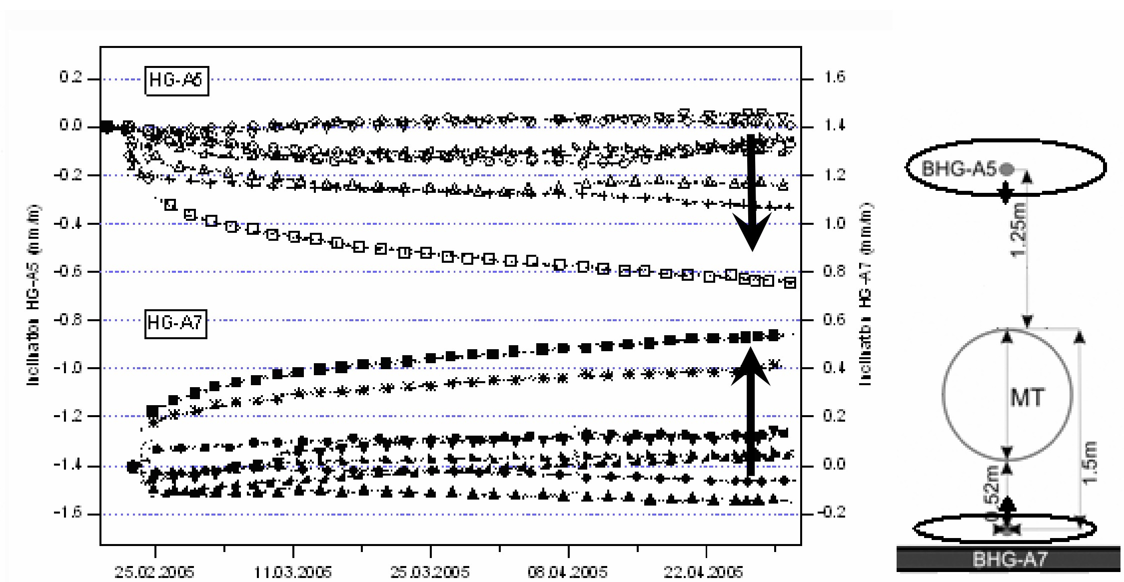

Figure 7: Data plot of the inclinometer chains installed in the boreholes BHG-A5 and BHG-A7 (right side). Location of the axial boreholes BHG-A5 and BHG-A7 in relation to the microtunnel (MT) and the displacement directions (arrows); source: Mont Terri Consortium.

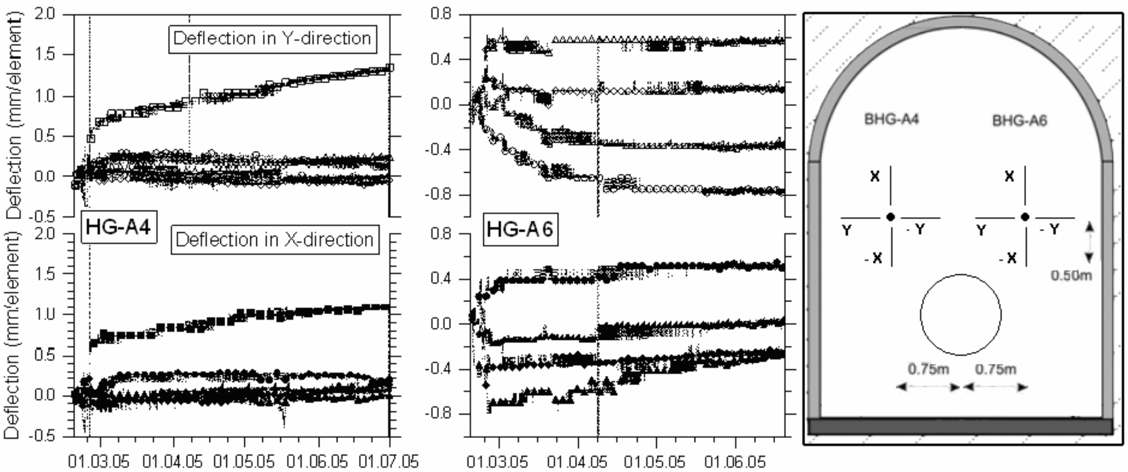

Figure 8: Deflections measured by the chain deflectometers the boreholes BHG-A4 (left) and BHG-A6 (center) and their position relative to the microtunnel (right).

The pore pressure records measured with the triple packer systems show a strong increasing trend which started immediately after the drilling of the microtunnel. This trend is caused by the deformation of the borehole due to the change of the stress field in the rock around the microtunnel (Figure 9) and is therefore considered as a poroelastic effect. The pressure increase in borehole BHG-A3 is stronger compared with the increase in borehole BHG-A2. The distance between the tunnel wall and borehole BHG-A3 is about 0.5 m and 1.25 m between the tunnel wall and borehole BHG-A2. Therefore the pressure plot seems to provide indications on decreasing stress field changes around the microtunnel with increasing distance.

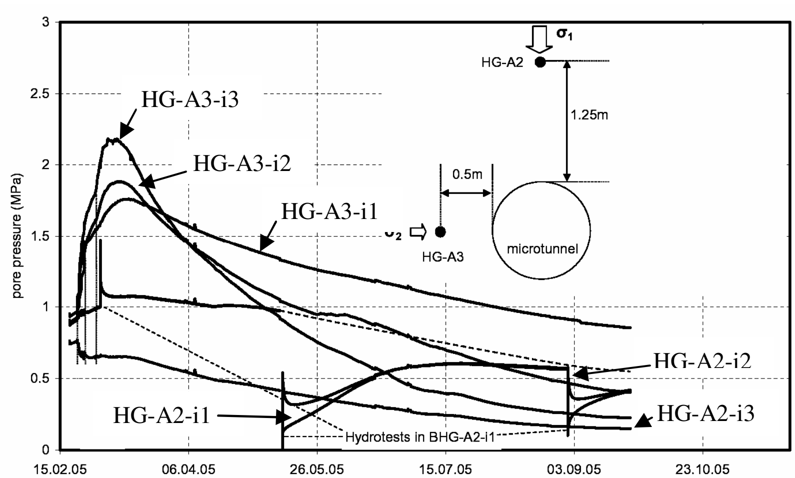

Figure 9: Pore pressure observations during and after the excavation of the microtunnel; source: Mt. Terri Consortium.

INSTRUMENTATION OF THE MICROTUNNEL

In the microtunnel test section a ring of 22 strain gages of the type Geokon, 4000B-2, with rebar mounting blocks were installed to measure the tangential deformations on the surface of the microtunnel (Figure 10). Every strain gage includes also a thermistor to measure temperature and to distinguish thermal induced strain from load induced strains. The strain gage consists of a length of steel wire tensioned between two mounting blocks that are arc welded to the surface of a structural steel member. Deformation of the structure under the load produces relative movement between the two mounting blocks causing a change in the wire tension and a corresponding change in its frequency of vibration. The strain in the wire is displayed directly in microstrain.

To measure radial deformations two Solexperts surface extensometers were installed. Due to difficult rock conditions, it was not possible to install them exactly in the planed horizontal and vertical direction at an angle of 90° (see Figure 10). The surface extensometers consist of displacement transducers with measurement rods in stainless steel housings. The connection to the surrounding rock is ensured with threaded bolts which allow adjustment.

In the period between their installation in July 2005 and October 2005 (open tunnel conditions) the strain gages show compression in the sector between 4 and 5 o'clock (looking towards the rear end) and in the opposite sector between 11 and 12 o'clock (Figure 11). These movements indicate regions of high tangential stress and might be explained by the reactivation of bedding and fault planes which are parallel to the tunnel circumference.

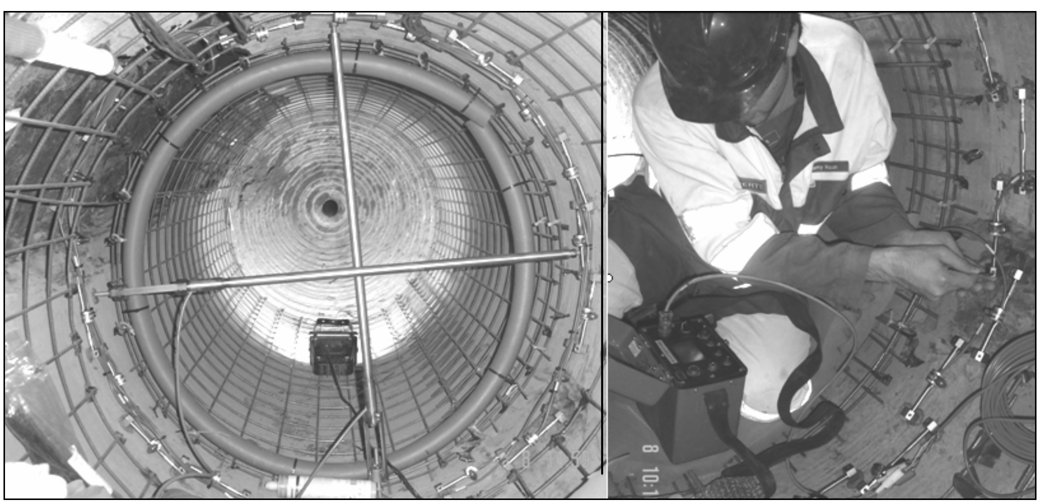

Figure 10: Microtunnel test section with strain gage ring at the tunnel wall and the two surface extensometers (left side), close-up of the strain gage ring and performance of control measurements after the installation (right side); source: Solexperts AG.

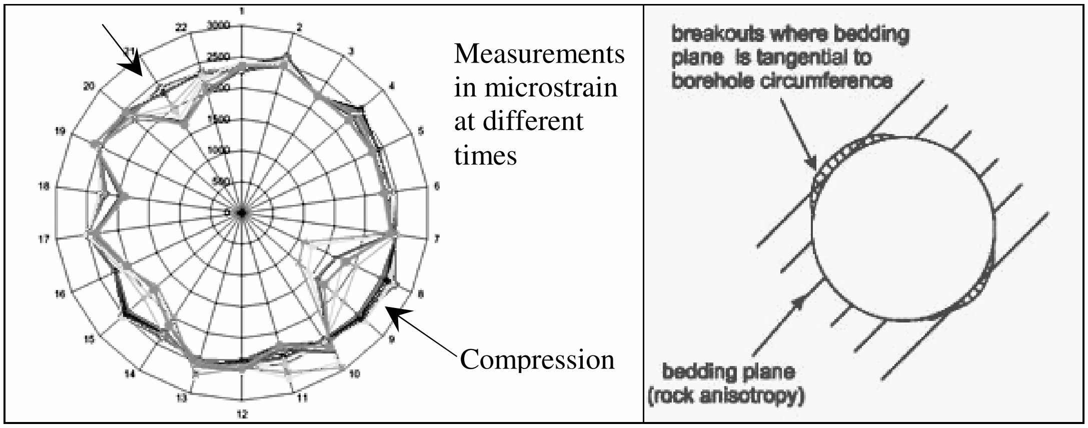

Figure 11: Deformations in the microtunnel measured by the strain gages (left), expected deformations in anisotropic rock (right); source: Mont Terri Consortium.

In the same period, the two perpendicular surface extensometers show a compression of the microtunnel in both directions.

SEALING OF THE MICROTUNNEL

The microtunnel is sealed with a large scale packer (megapacker) with a diameter of about 0.94 m, a total length of about 4.3 m and a weight of about 3.6 tons (Figure 12). The sealing element with a length of about 3 m consists of rubber with a maximum applicable differential pressure of 40 bar. The rubber element is equipped with 12 piezometers which are placed at inlets on the rubber surface.

Figure 12: Megapacker before the emplacement into the microtunnel. Cables and lines pass through the megapacker centre pipe; source: COMET Photoshopping GmbH.

The sealing section was fixed between tunnel meter 6 and 9. An extension tube was needed to be attached to the packer to emplace the megapacker to the designated position. The cables and lines of the sensors installed at the rear end (test) section of the microtunnel are routed through the pipe located in the centre of the megapacker. The line and cable passes were sealed at the well head.

The emplacement of the megapacker was demanding because of its large dimensions and weight compared to the small clearance between the packer and the tunnel wall. Therefore it was considered as a major task. During the preparatory work a slight kink of the tunnel axis was detected. Therefore a trial test with a dummy was performed which demonstrated the feasibility of the emplacement concept.

The emplacement procedure consisted of two main phases:

- During the first phase the packer advances within the steel liner and the weight is distributed on the front and rear end wheels. The packer is pushed into the mircotunnel using a forklift.
- During the second phase the megapacker rear end and the rubber element passes the steel liner rear end and advances through the sealing section of the tunnel. During this phase it was crucial that the packer (in particular the wheels) would not touch the tunnel wall. Hence all the Megapacker weight was distributed on 3 wheels which were in the liner. The weight was balanced outside the tunnel applying an additional weight on the extension pipe such that the major part of the packer was completely in the air (Figure 13). The balance and the movements of the packer were controlled through one forklift placed in front of the microtunnel entrance, by ultra-sound distance meters and a rear view camera.

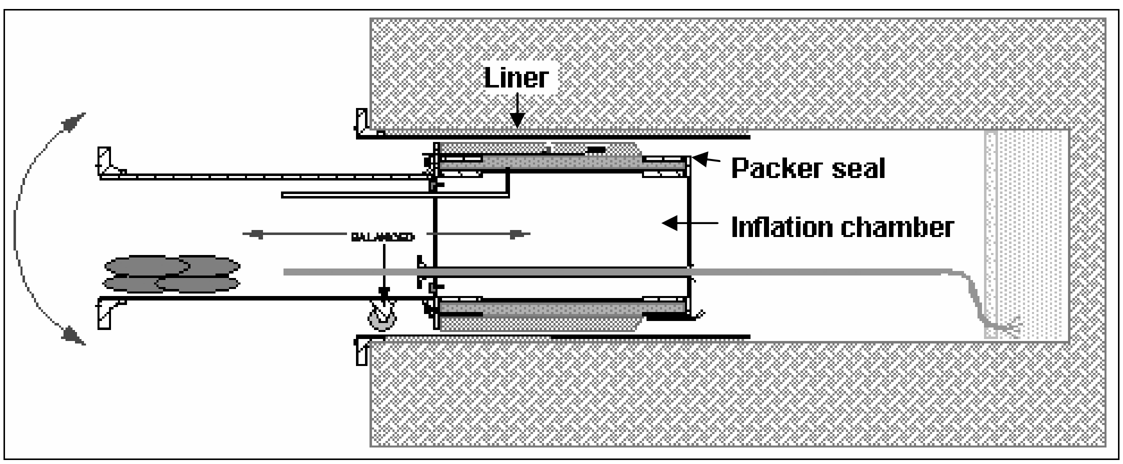

Figure 13: Schematic drawing of the Megapacker emplacement: The Megapacker was rolled through the steel liner and then shifted towards the final position. After leaving the steel liner the Megapacker needed to be balanced. Source: Baski, Inc.

The packer was inflated after the successful emplacement in June 2006. The mandrel was filled with grout to increase the collapse pressure of the packer steel tube.

CONCLUSIONS AND OUTLOOK

During the HG-A experiment the microtunnel as well as the surrounding bedrock were successfully equipped with different type of sensors to measure the adequate parameters for the characterization and observation of the area during excavation, sealing and subsequent saturation and testing of the microtunnel. The pronounced fabric and fault anisotropy and the high tangential stress due to stress redistributions is shown by the strain gages measuring the surface deformation in the microtunnel. The changes in the stress field caused additionally an increase in pore pressures indicating deformations in the bedrock, with a general tendency towards the microtunnel as shown by deformation measurements. The sealing of the microtunnel was accomplished by the emplacement of a megapacker. The ongoing experiment continues with three different testing phases: one with the performance of initial hydraulic tests, one with the main gas injection test and a further hydraulic test phase, which should provide more detail on the existence of gas paths around the microtunnel and on the behaviour of the bedrock.

ACKNOWLEDGEMENTS

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