

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).

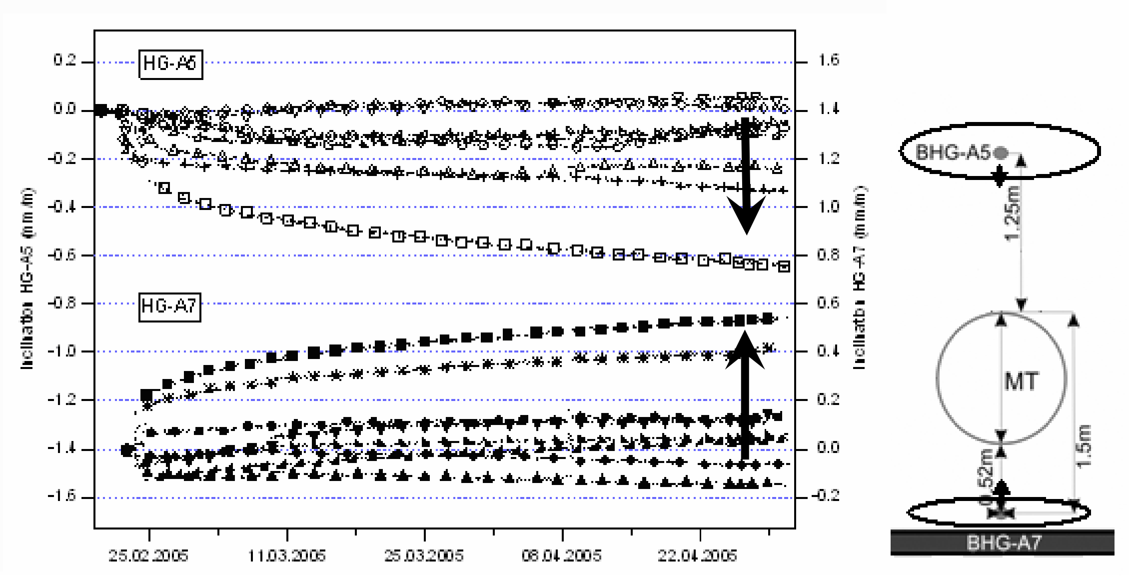

Figure 7: Data plot of the inclinometer chains installed in the boreholes BHG-A5 and BHG-A7 (right side). Location of the axial boreholes BHG-A5 and BHG-A7 in relation to the microtunnel (MT) and the displacement directions (arrows); source: Mont Terri Consortium.

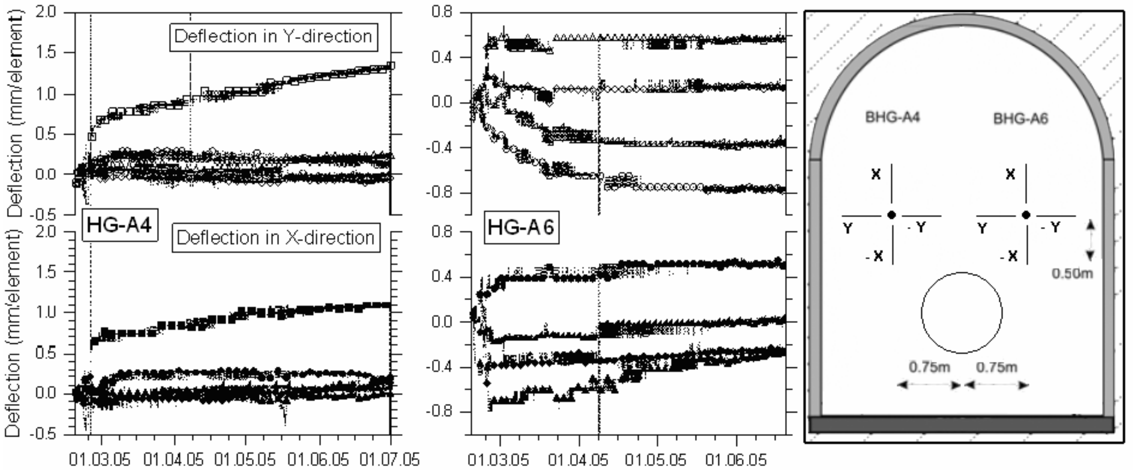

Figure 8: Deflections measured by the chain deflectometers the boreholes BHG-A4 (left) and BHG-A6 (center) and their position relative to the microtunnel (right).

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.

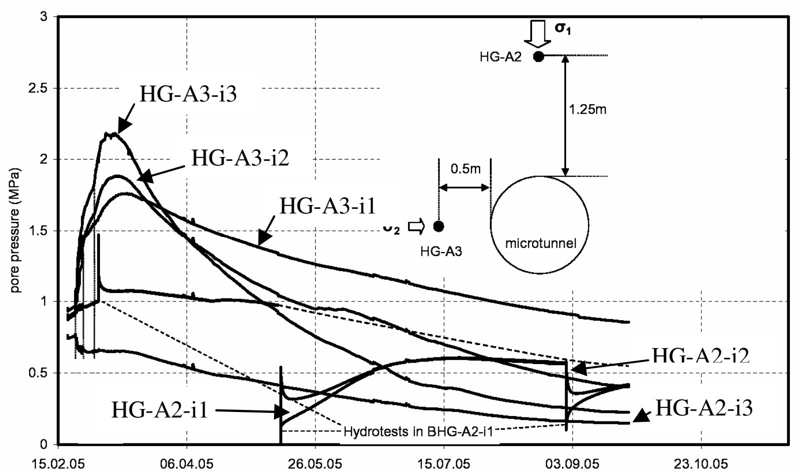

Figure 9: Pore pressure observations during and after the excavation of the microtunnel; source: Mt. Terri Consortium.

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.

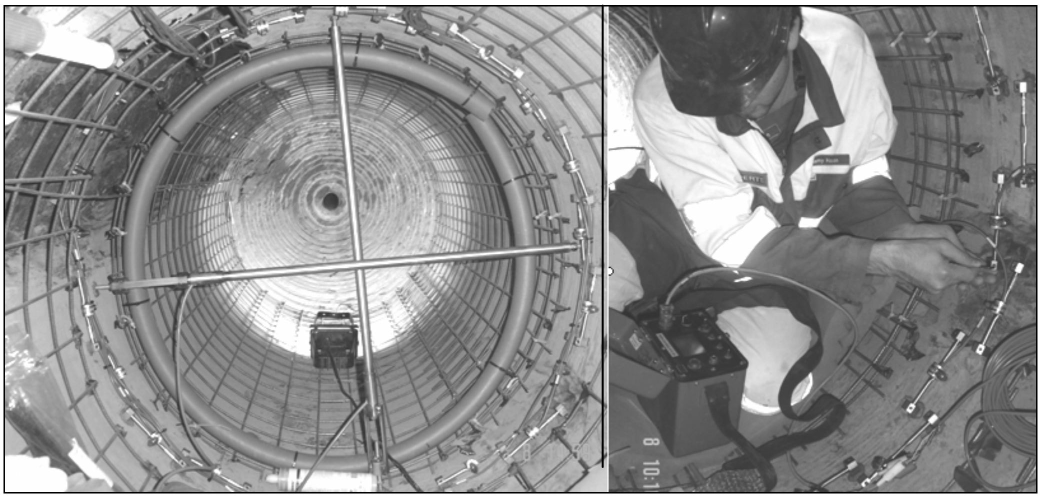

Figure 10: Microtunnel test section with strain gage ring at the tunnel wall and the two surface extensometers (left side), close-up of the strain gage ring and performance of control measurements after the installation (right side); source: Solexperts AG.

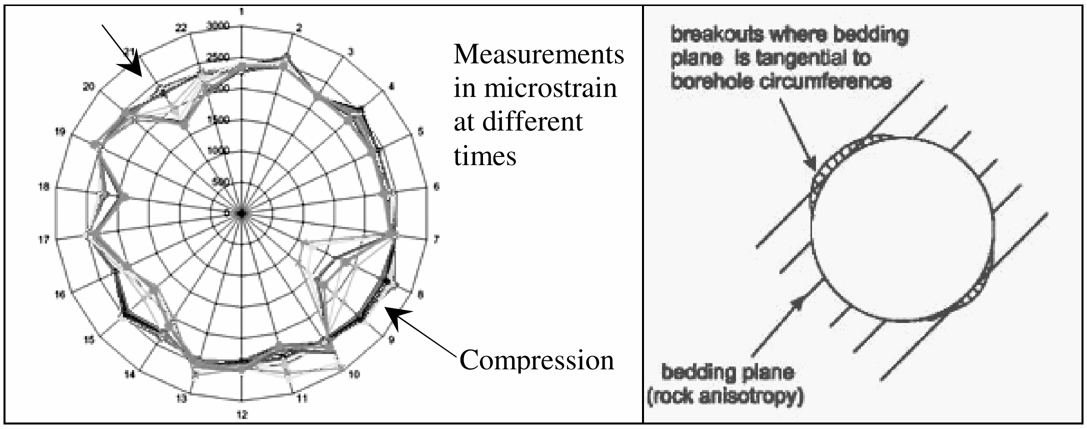

Figure 11: Deformations in the microtunnel measured by the strain gages (left), expected deformations in anisotropic rock (right); source: Mont Terri Consortium.

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.

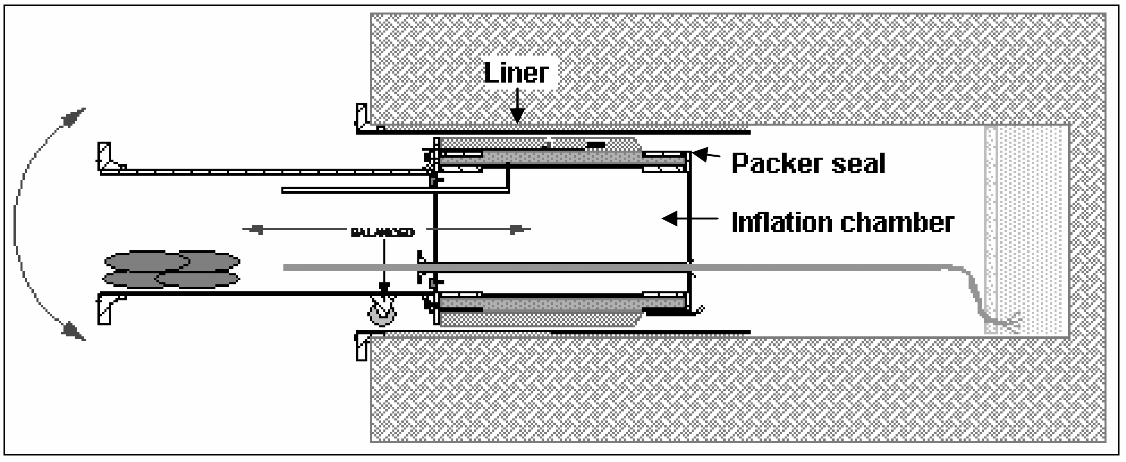

Figure 13: Schematic drawing of the Megapacker emplacement: The Megapacker was rolled through the steel liner and then shifted towards the final position. After leaving the steel liner the Megapacker needed to be balanced. Source: Baski, Inc.

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.

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Displacement measurements ahead of a tunnel face using the RH Extensometer

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ABSTRACT:

The RH-Extensometer (*Reverse Head Extensometer*) was developed to carry out continuous displacement measurements ahead of the tunnel face. Readings are made despite successively removing parts of the measuring rods in the course of the excavation procedure. This is possible because the head of the extensometer, containing the sensors and a data logger, is placed at the base of the borehole (i.e. it is the furthest away from the tunnel face and the last element to be reached). The recorded measurement data are transferred to the operator at the face of the tunnel by radio transmission. RH-Extensometer monitoring has a great advantage over commonly used Sliding Micrometer measurements because the monitoring does not interfere with the excavation procedure and provides continuous measurements. Practical experience using this new device in highly squeezing rock comes from the 57 km long Gotthard Base Tunnel in Switzerland, where convergence from 0.5 up to 0.7m regularly occurs in a controlled manner during excavation of the 13m diameter twin tunnel.

INTRODUCTION:

Nowadays tunnels frequently have to be driven at considerable depths and through weaker and more complex rock formations than ever before. To work efficiently and safely under these conditions, tunnel driving is often successfully managed using a sort of "observation method". This requires the excavation of the tunnel to be continuously monitored and the tunnel support system possibly adjusted (Lunardi P. 1998). The elements that may be modified based on this process include: rock bolting, distance between steel ribs, thickness of the primary shotcrete lining, length of attack, etc. Monitoring of the "extrusion", i.e. the axial displacement ahead of the face is a very important quantity for understanding the rock behaviour. Classical instrumentation includes the *Sliding Deformeter* for monitoring in soft ground and the *Sliding Micrometer* (Kovári, at al. 1979) for monitoring in rock. These instruments require installing measurement casings in boreholes in front of the tunnel face. Readings have to be taken manually by sliding the probe along the borehole to carrying readings at successive measurement points.

Sliding micrometer measurements were planned for the Gotthard Base tunnel in Switzerland but high overburden pressure (2700m) and high water pressures (100bar) severely damaged the measurement casings after a short period of time. The Reverse Head (RH)-Extensometer was developed to resist these harsh conditions and automatically provide continuous measurements ahead of the tunnel face. Additionally, unlike the *Sliding Micrometer*, it allows readings to be taken without affecting the work in the tunnel.

DESIGN OF THE RH-EXTENSOMETER

The RH-Extensometer was developed to make automatic continuous measurements ahead of the tunnel face. The rods and measurement head are cemented into a borehole drilled into the face of the tunnel. Measurements are made even as the measuring rods are being successively destroyed during advancing excavation because the head of the extensometer, containing the sensors and a data unit, is placed at the base of the borehole (i.e. it is the furthest away from the tunnel face and the last to be destroyed). Currently RH-Extensometers are between 30 and 40m in length and monitor 6 measuring anchors.

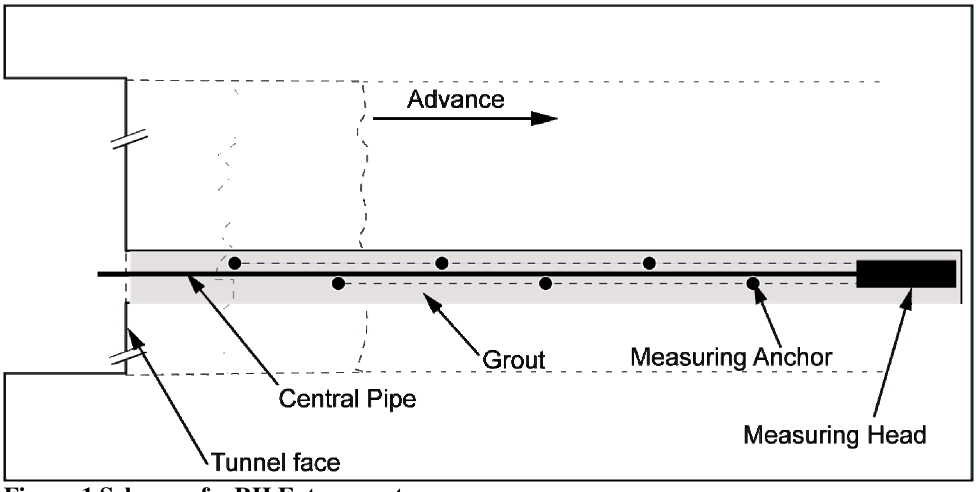

Figure 1 Scheme of a RH Extensometer

The measuring head (Figure 1 and 2) consists of two parts: 1) a measurement unit with six displacement transducers, a temperature and optionally a pore water pressure sensor and 2) a data unit which monitors, stores and transmits the data. The range of the displacement transducers is 500mm with an accuracy of +/- 0.1mm.

The data unit consists of a data logger, a radio transmission module with external antenna and a battery. The battery powers the system for three to four months depending on the surrounding temperature and data acquisition rate. The data logger can record at a rate between 1 measurement per second and 1 measurement per day. The sampling rate can be modified when communications with the instrument are

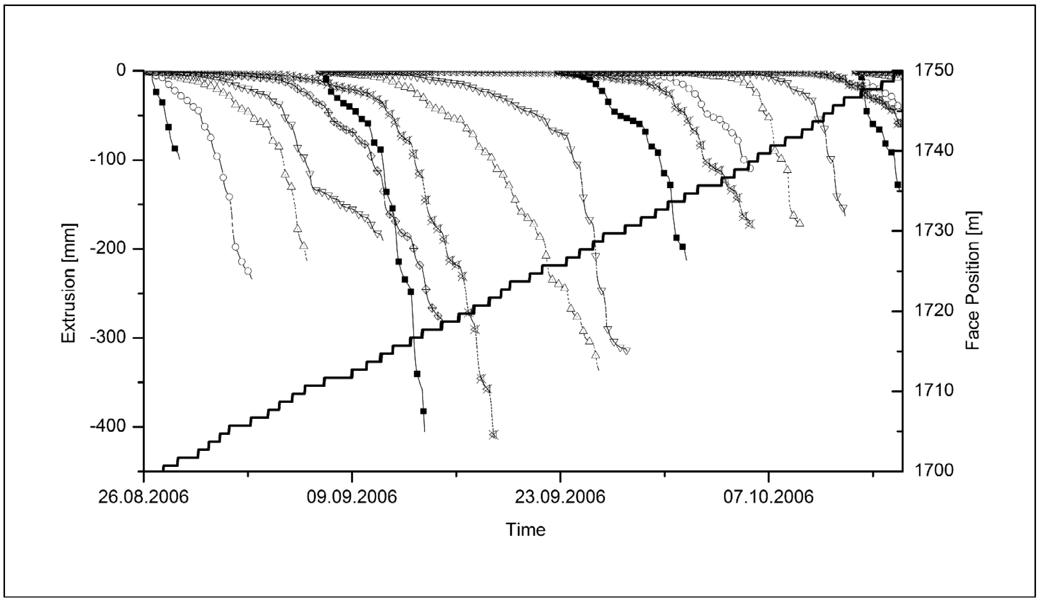

Figure 7 Measurements of overlapping installed RH-Extensometer (RHX1699 –RHX1747), Sedrun

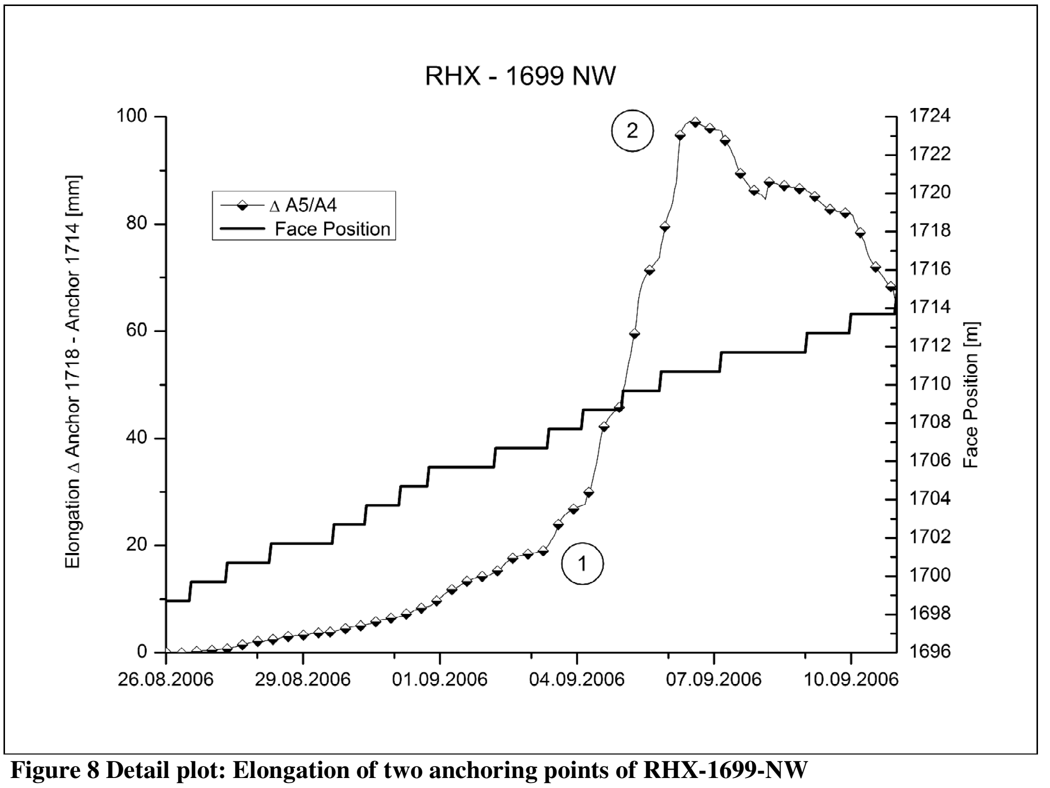

Figure 8 Detail plot: Elongation of two anchoring points of RHX-1699-NW

The effect of a new series of anchor bolts is shown in Figure 8. At point 1 the extrusion of the face is speeding up as the time between two excavation steps is very short (see the solid line in Figure 8) and end of the last anchoring layer is reached. At point 2, new rock bolts are installed, the extrusion of the face slows down and the section close to the face becomes consolidated because it is tied back by the shotcrete and the bolts.

The Reverse Head Extensometer is a new tool that offers advantages and can be easily employed in tunnelling projects with difficult geological lithologies and harsh conditions. The RH-Extensometer offer continuous monitoring of the tunnel face and is a valuable tool and another step toward obtaining a completely controlled excavation process. The next generation of a RH-Extensometer with wireless sub terrain data transmission and modular structure is on the way.

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