Instrumentation and Data Management for the Zurich Zimmerberg Railway Tunnel Construction
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1. Introduction

The 9.4 km Zimmerberg base tunnel is an important part of the Swiss Railway system. In the southern 700 m section, from Kollerwiese to the Lochergut portal, the 12.4 m-diameter tunnel passes directly under or very close to houses and existing structures. This section of the tunnel lies in lacustrian sediments and fluvial deposits from the Sihl river coming from the Alps east of Zurich.

The Herrenknecht mixshield TBM is specially designed to drill through rock and soil and within groundwater. The groundwater level in this part of Zurich is approximately 12m below the surface. The crown of the tunnel ranges from 12m to about 5m depth.

Instrumentation (mainly for monitoring settlement) located underground, on the surface and in buildings, in combination with an internet-based data management system, provides valuable, instantaneous information to all engineers involved. The system has proven to be a very powerful tool for immediate decision-making in critical situations, and for monitoring the effects of measures like grouting and jacking before and during tunnelling.

Instrumentation and data management via the internet is described below, and some results are shown. Solexperts thanks the SBB, the joint venture AZT, the project engineers IG BBPS (Basler & Hofmann, Balestra, Preisig and SNZ) and other companies involved for the fruitful cooperation in this very interesting and challenging project.

2. Project overview

2.1 The Zimmerberg Base Tunnel

The Zimmerberg railway tunnel between the city of Zurich and Thalwil is part of the Swiss AlpTransit project and the Bahn2000 project.

At present, all railway traffic from Zurich in the direction of Chur and Austria, from Zurich to Italy via the Gotthard tunnel and all local public transport along the left side of Zurich Lake travels over the old 2-track railway line. This results in extremely heavy traffic and a high frequency of trains. This railway line with many stations and frequent stops for local public transport is not able to meet the ever-increasing demands for greater capacity. Large railway expansion projects now underway will provide a much-needed increase in capacity.
Construction of the new Zimmerberg base tunnel began in 1997 and will be completed in the year 2003. The link to the Gotthard line will be completed by the year 2008 together with the Gotthard base tunnel.

From one of the two shafts at Brunau, the 12.3m diameter mixshield TBM is being used to construct the most difficult 2.7km-long section to the Lochergut portal. The first 2 km from Brunau was drilled through intact rock. After 2 km, the TBM was switched to closed-face mode. It will drill the last 700m under very shallow cover and will pass near existing structures. In this section, excavation will take place in lacustrian sediments of sand and silt and in coarse-grained fluvial sediments. The groundwater level in this section is at about 12m depth from the surface, practically at the level of the crown of the tunnel. The sand and especially the gravel are highly permeable with groundwater flow velocities of 10 to 30m per day. It is also anticipated that remains of structural elements (steel piles and parts of sheet piles) will be encountered within the excavation cross section.

From a 3.5 m diameter pilot tunnel, which is parallel to the main tunnel and above the groundwater level, extensive grouting above the tunnel took place. This grouting was almost entirely completed by the end of the year 2000, before the excavation of the main tunnel began at this particular section. The grouting created a covering layer about 3m thick. Additionally, below foundations of some of the houses above and very close to the new tunnel, and at certain pre-selected locations, grouting was performed over the whole tunnel cross section as well as above the tunnel. The purpose of grouting at pre-selected locations was to allow service of the TBM and long-term TBM-excavation stops (e.g. over Christmas). These measures are intended to prevent settlement (a maximum of about 20mm of settlements is allowed) and reduce the risk of blowout of the bentonite water slurry.
During drilling for grouting, some of the steel drill pipes (diameter 150m, length 1m) broke off and remained in the soil. These pipes as well as some large blocks (one as big as 60m³) affected progress and required special measures.

A section of the three-story underground garage of the SSF-building lies directly in the axis of the tunnel. With a series of micro-piles and a frame of pre-stressed concrete beams, the foundation of this office building was reinforced and a part of the garage was dismantled to prepare for TBM penetration through the old location of the structure.

In the last 150m of the southern part of the tunnel, until the Lochergut portal, grouting from the pilot tunnel was not possible. There the tunnel is excavated under a pipejacked umbrella. Each of the pipes has a diameter of 1.2m and is jacked over 130m to 150m practically horizontally at a vertical distance from the tunnel of about 1.5m.

Instrumentation includes various elements which are manually, semi-automatically, and automatically read and processed. All data and information from the instruments, together with the position of the TBM has to be available to all engineers in charge with the following criteria:

- Data are available around the clock and can be obtained quickly
- Processed data must be provided
- The data management system must be easy to operate
- All engineers in charge must have the same information and a complete overview
- Automatic alarms must provide immediate alerts in critical situations

3. Instrumentation

3.1 Settlement measurement from the pilot-tunnel

The pilot tunnel provided a good opportunity for instrumentation. To measure subsurface settlement and heave during tunnel construction (including all preparatory work and TBM excavation) an automatic system which combined hydraulic and geodetic levelling was installed. This system had to monitor a section approximately 50m ahead and 50m behind the TBM. In the end, the monitored section was about twice as long as originally specified by the client.
For hydraulic levelling, a specially designed system for borehole installation was used. This system includes a borehole probe (length 250mm, diameter 50mm) with a very precise pressure transducer. The probe is pushed into the borehole with fibreglass rods. Outside the borehole a small hydraulic reservoir is installed. The reservoir connects to the borehole probe with a hydraulic line and a pneumatic line to compensate for changes in atmospheric pressure. The sensor line connects to the interface outside of the boreholes. These sensors measure changes in level between the reservoir located at the borehole top and the sensor located at about 1.5 m above the crown of the tunnel. The distance between the sensor and the top of the borehole ranges from 6.5 to 8 m. The pilot gallery is very close to the tunnel and will also be affected by excavation. To measure total settlement, the readings of the hydraulic levels were combined with settlement readings at the top of the borehole (reservoir). For this purpose, two automatic Total Stations (theodolites with electronic distance meters) are employed. At every reservoir, an optical prism is installed as a measurement target for the Total Stations. At the opposite end from these instruments, reference points are installed and measured which are outside the influence of tunnel construction.

3.2 Automatic measurements of settlement in basements of houses

In the basement of two buildings, one of them being the SSF office building described above, settlement and heave had to be measured automatically over several months. This period covered the preparations before excavation and the period when the TBM passed under or near each building. A series of motion-controlled digital levels with bar-coded staffs was installed on the ceiling and walls in these basements. Reference points outside the influence of tunnelling activities compensate for settlements of the instruments (levels) themselves. Often the best location for installing a level is in
the centre of the influenced zone. This way visibility of the staffs (measuring points) is optimal. The levels are motorized to move and focus the optical axis on the bar code staffs, and include a spotlight for illuminating staffs.

Vertical deformations were observed which were mainly due to grouting activities (heave of up to 15 mm by the end of October, 2000). When the TBM passed beneath the basements of the instrumented buildings, settlements in the range of 2 to 4 mm were observed (beginning of January 2001).

3.3 Deformation measurements in vertical Boreholes

A total of 20 boreholes along the tunnel line have been instrumented to enable linewise deformation readings with the Sliding Deformeter (a high-precision probe extensometer) and with the borehole inclinometer. The boreholes above the tunnel crown reach to a depth of about 12m and the boreholes alongside the tunnel reach to a depth of about 30m. Combination measurement casing which enables readings with both instruments within the same borehole is installed and grouted to the soil. The soft grout (a mixture of cement, water and bentonite) and telescopic couplings every 1m guarantee that the measurement casing also moves in very soft soil without acting as a pile.
The readings from the Sliding Deformeter and borehole inclinometer are stored on a portable palmtop PC, and are processed using calibration readings to provide deformation profiles. To present, only very small settlements have been observed due to tunnel excavation. These results show clearly that the quality of the grouting is good, and that the selected tunnel excavation method is optimal, since no or only slight settlement has occurred.

3.4 Deformation measurements in the horizontal pipejacked umbrella

Two of the approximately 150 m-long pipejacked horizontal piles have been equipped with inclinometer casing. This casing was installed within 120 mm diameter steel protective casing and firmly cemented inside the piles with grout. Readings are taken with a standard horizontal borehole inclinometer probe. The probe is pushed into the casing to the end, and retracting the probe meter by meter, inclinometer readings are taken in two directions. These readings are stored on a portable palmtop PC, and are processed using calibration readings to provide deformation profiles.

3.5 Automatic and manual settlement measurements on the surface

Four automatic Total Stations are used to automatically measure settlement on buildings and on the pavement. They are operated similarly to the ones used in the pilot tunnel. The Total Stations are moved with the progressing tunnel excavation, so that the zone of influence is always covered by measuring points.

For long-term settlement monitoring and to supplement automatic settlement readings, especially for measuring points which are not easily accessible, classical manual levelling is performed.

4. Data Management

4.1 Data Sources

Diverse instrumentation, data from various sources and a large number of measuring points necessitated a powerful tool for data handling. DAVIS Data Visualisation Software combined with data management over the internet offered an optimal solution for the needs of the various engineers and companies involved:
The project manager for the client, the Swiss Federal Railway Company (SBB)

The project engineers: Ingenieurgemeinschaft BBPS, Zürich (Basler & Hofmann AG, Balestra, F. Preisig and SNZ)

The contractor (joint venture AZT)

The following table gives an overview of the various data sources. Manually read instruments have an interval between readings of 0.5 days to 45 days. This interval is determined by the position of each point in relation to tunnel excavation and other construction work. Automatically read instruments are measured at intervals of about 0.5 to 1 hour.

<table>
<thead>
<tr>
<th>Type of Instrument</th>
<th>number of locations</th>
<th>type of reading</th>
<th>total number of measurement points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic levelling</td>
<td>4</td>
<td>automatic</td>
<td>98</td>
</tr>
<tr>
<td>Total Station subsurface</td>
<td>4</td>
<td>automatic</td>
<td>98</td>
</tr>
<tr>
<td>Total Station above surface</td>
<td>16</td>
<td>automatic</td>
<td>640</td>
</tr>
<tr>
<td>Manual levelling</td>
<td>manual</td>
<td></td>
<td>380</td>
</tr>
<tr>
<td>Motion-controlled levels</td>
<td>3</td>
<td>automatic</td>
<td>37</td>
</tr>
<tr>
<td>Sliding Deformeter</td>
<td>20</td>
<td>manual</td>
<td>390</td>
</tr>
<tr>
<td>Vert. Inclinometer</td>
<td>15</td>
<td>manual</td>
<td>430</td>
</tr>
<tr>
<td>Horiz. Inclinometer</td>
<td>2</td>
<td>manual</td>
<td>290</td>
</tr>
<tr>
<td>TBM-Position</td>
<td>1</td>
<td>automatic</td>
<td>1</td>
</tr>
</tbody>
</table>

Data from all automatically-read instruments are processed at the remote computers. Processing basically involves comparison of processed data with predefined alarm values, sending alarms via fax and SMS and:

- **Hydraulic levelling** Calculation of settlement of the sensor in relation to the reservoir at the borehole top and in relation to the reference (from Total Station reading).
- **Total Station subsurface and above surface**: Transformation (Helmert transformation) in relation to reference points, even if some of the reference points are not visible, settlement of each individual measuring point in relation to reference points is calculated.
- **Motion-controlled levels** Calculation of settlement of the individual measuring points in relation to reference points.
- **TBM Position** processed into a table and plotted to a graph which can be viewed on the internet at [www.los201.ch](http://www.los201.ch) by anyone (try it out). This website also contains interesting information about the project.

After these automatic measurements are made and processed, data from these sources are sent to an FTP server. All data are also stored in a backup file on a server. Operation of the data visualization is done on the DAVIS server where all the data files from the different sources are combined into one database. The graphics are automatically updated with new data.
Sensor positions and all graphs of data can be viewed over the internet. An overview of this part of the project includes symbols for the various instrumentation.

Some of the typical instrumentation layouts and graphs generated from measurement data which are available over the internet are shown below.

Locations and results from linewise deformation measurements with the Sliding Micrometer and the borehole inclinometer.
Measurement points at the surface and measurement results as displayed in DAVIS

DAVIS screen and measurement results of hydraulic levelling in the pilot tunnel

Settlement measured with hydrostatic levelling from the pilot tunnel as the TBM was passing directly below instruments:

Plotted against time

Plotted against TBM advancement