Zurich Zimmerbergtunnel: Continuous Geotechnical and Geodetical Monitoring during the Construction Phase

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Abstract. The Zimmerberg Base Tunnel is part of the new 10.7 km long Zurich Central Station – Thalwil line and forms the core of the Swiss Federal Railways “Bahn 2000” project. The northern 780m long tunnel section passes through lake bed deposits and river gravel below the groundwater level. A mix-shield TBM (Herrenknecht) that was converted to hydro-shield mode tunnelled beneath a densely built-up part of the City of Zurich that was shallow overburden. Due to risk of failure (cave-in, excessive settlements) comprehensive measurements were an important part in the safety system. Manually taken measurements such as sliding-deformeter, inclinometers and precise levelling were combined with automatic measurements in terms of robotic digital levels, robotic total stations and hydrostatic levels for boreholes. Data visualisation of all measurements including the TBM position was provided via Internet. The high data measurement rate was combined with alarms that used GSM, E-Mail and Fax. All engineers who were involved in or responsible for the project were supported by quasi real time data that were used to evaluate the situation and make decisions in time.

Keywords: Motorized Digital Level, Robotic Total Station, Hydrostatic Levelling, GeoMonitor, DAVIS Data Visualisation, Sliding-Deformeter, Inclinometer

1 Introduction

Today urban areas are in need of increasing development and the shortage and cost of space lead to a high density of buildings and to larger structures as well as to underground construction work such as deep excavations and tunnelling. New construction with multi-storey basements for parking and storage facilities calls for deep open excavation accompanied by the risk of damage to adjacent buildings. The drilling of the tiebacks supporting the structure, large displacement of the supporting wall due to unexpected high loads or driving of piles in the excavation and piping might create settlement and tilting of neighbouring structures. Increasing transportation needs the enlargement of existing railway or subway stations, underpinning and new construction works. In urban areas new public or private roads can only be built underground, and heterogeneous soils and nearby foundations of existing buildings may be encountered. The excavation of tunnels will inevitably be followed by ground movements due to the transfer of stress. Grouting, jet grouting or freezing is frequently applied for the improvement of poor soil conditions for the underpinning of foundations or to create an artificial arch to facilitate the excavation of galleries. The drilling procedure itself might cause substantial settlements and the subsequent grouting or freezing creates ground heave. Concerning ground conditions there is always an element of uncertainty; the ground is a natural product and can be investigated only in a limited number of drill-holes. On the one
hand, the engineer must take into account these risks considering the characteristics of the subsoil and, on the other, he is obliged to obtain a cost saving design. To optimise the design already at an early stage, the engineer establishes a risk plan for the construction phases, which lists the potential events and is followed by a monitoring project to survey the critical zones and parts of the structure. The monitoring of displacements, strains and pore water pressures in the subsoil and for adjacent buildings, as well as in the structure itself, follows the constructional measures. The comparison of the measured and the predicted values is an important tool to check the behaviour of the structure and its surroundings and to intervene with additional reinforcement or corrections in the construction phases to prevent damage. For instrumentation the engineer has nowadays a large variety of instruments at his disposal to investigate the underground, the structures and neighbouring buildings, Thut [1]. Depending on the nature of the instrument and on the scale of the constructional measures the measurements are executed manually, semi-automatically or completely automatically. In most cases a combination of these procedures is applied. Automatic permanent monitoring exhibits - in contrast to manual monitoring - the following advantages:

- Measurement around the clock
- Immediate access to the data
- Fast reporting
- Transfer of the data by modem and/or internet to the decision maker
- Setting of alarm functions

In the case of damage to the structures, continuous, automatic measurements of the parameters such as settlement, tilting, deflection etc., the correlation of the data versus time with the measurements on the structures versus time allows conclusions to be drawn concerning the cause of damage.

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 that comes 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 depths.

Instrumentation (mainly for monitoring settlement) is located underground, on the surface and in buildings. The data from there measurements are used an internet-based data management system to provide 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 their fruitful cooperation in this very interesting and challenging project.
2 Project overview

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 of the tunnel to the Lochergut portal. The first 2 km from Brunau was drilled through intact rock by the TBM. After 2 km, the TBM was then changed to closed-face mode. It will drill the last 700m under very shallow cover and will pass near existing structures. The 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 depths 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.

3 Risk management

The risk management includes the determination and evaluation of risk, and the specification of measures, to limit risks to an acceptable level. Risk evaluation includes evaluating the possible amount of damage and the probability of occurrence. Although numerical values are missing for an arithmetical operation the combination is considered a product of both factors. In urban tunnelling failure extending up to the ground surface and large settlements are strongly undesired events with a high amount of damage. To limit the risk to an acceptable level measures are specified. Monitoring is a methodical execution of observations that aims to limit the amount of damage or the probability of the occurrence, or both.

From the beginning of the project the owner was aware of the difficult tunnelling conditions and was looking for measures to decrease risk. Some of these measures are described in the following.

4 Injection, Grouting body

Extensive grouting above the tunnel was done from a 3.5 m diameter pilot tunnel drilled parallel to the main tunnel and above the groundwater level. This grouting was almost entirely completed by the end of the year 2000, before the excavation of the main tunnel.
began in the 700m section. The grouting created a covering layer about 3m thick. Additionally, below the foundations of some of the houses 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 excessive settlements (a maximum of about 20mm of settlements is allowed) and reduce the risk of blow-out 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 boulders (one as big as 60m³) affected progress and required special measures.

4.1 Slurry support

Experiences with highly permeable river gravel in the Zurich region suggested the use of a special slurry that consist of bentonite, sand, polymer material and vermiculite. This mixture ensures that the large pores near the surface of the working face are filled. Due to operational difficulties (transport, separation) this slurry composition was only used in exceptional circumstances. For this reason the injection was improved.

4.2 SSF building

A section of the three-story underground garage of the SSF-building lies directly in the axis of the tunnel. The foundation was reinforced with a series of micro-piles and a frame of pre-stressed concrete beams and a part of the garage was dismantled to prepare for TBM penetration through this building. During the TBM advance hydraulic jacks were used between the concrete beams and the building to compensate for settlements. Spaces between ground and the new structure were filled with aeroconcrete.

4.3 Piped jacked umbrella

In the last 150m of the tunnel before the Lochergut portal grouting from the pilot tunnel was not possible. There the tunnel will be excavated under a pipejacked umbrella consisting of 10 pipes. Each of the pipes has a diameter of 1.2m and is jacked over 130m to 150m almost horizontally at a vertical distance above the tunnel of about 1.5m.
4.4 In Situ Tests in Grouted Soil

The improvement of the ground is one of the main measures to minimise settlements and to prevent collapse.

The highly heterogeneity heterogeneous soil, the grain size distribution varying from fine sand to gravel with cobbles, made the extraction of intact cores by drilling and therefore laboratory tests impossible. The mechanical characterisation of the grouted soil was determined in situ by means of plate load tests and the dilatometer test in situ.

Five plate loading tests in an excavated niche from the grouting gallery and three plate load tests in shafts with an internal diameter of 130 cm were executed (Fig. 5).

![Fig. 5 Plate loading test in the shaft](image)

The test device was specially designed for tests in the narrow shaft. The device (Fig. 6) was assembled at the surface and lowered into the shaft by crane. The final installation and the preparation of the loading surface were done by one technician only.

![Fig. 6 Plate loading test device](image)

Performing the plate loading test, loading and displacement was remote-controlled from the surface and saved on a PC. The tests were run carried out up to failure (Fig. 7) to evaluate the bearing capacity.
The mean deformation modulus determined (with 16 tests, 8 tests with two opposite plates) amounted to approximately 700 MPa. The mean value of the bearing capacity was higher than 15 MPa. A rough estimation leads to the values of 0.2 MPa for $c$ and 0.8 MPa for the unconfined compression strength.

The dilatometer tests were not successful, as with the strong roughness of the borehole walls the values were underestimated or in some cases the diameter of the borehole was too large.

### 4.5 Monitoring

Instrumentation includes various elements that are manually and automatically measured. All data and information from the instruments, together with the position of the TBM has to be available to the 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 project overview
- Automatic alarms must provide immediate alerts in critical situations

### 5 Instrumentation

#### 5.1 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 that combined hydraulic and geodetic levelling was installed. This system had to monitor a section of the tunnel that is approximately 50 m ahead and 50 m 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 uses a borehole probe (length 250 mm, diameter 50 mm) with a very precise pressure transducer. The probe is pushed into the borehole with fiberglass rods. Outside the borehole a small hydraulic reservoir is installed. The reservoir connects to the borehole probe via 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 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.

5.2 Automatic measurements of settlement in basements of houses

In the basement of two buildings, one of them being the SSF building described above, settlement and heave had to be measured automatically over several months. This time range covered the period for 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 the basements of these buildings. Reference points outside the influence of tunnelling activities compensate for settlements of the instruments 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 on the bar code staffs, and include a spotlight for illuminating staffs.

Vertical deformations were observed that 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).

5.3 Deformation measurements in vertical boreholes

A total of 20 boreholes along the tunnel line have been instrumented to enable line wise deformation readings with a Sliding Deformeter (a high-precision extensometer) and a borehole inclinometer. The boreholes above the tunnel crown reach to a depth of about 12 m and the boreholes alongside the tunnel reach to a depth of about 30 m. Combination measurement casing that 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 each 1 m guarantee that the measurement casing also moves within very soft soil and does not act as a pile.
The readings from the Sliding Deformeter and borehole inclinometer are stored on a portable palmtop PC, and are processed using calibration data to provide deformation profiles. To present, only very small settlements have been observed due to tunnel excavation. These results suggest that the quality of the grouting is good, and that the selected tunnel excavation method is optimal.

5.4 Deformation measurements in the horizontal pipe-jacked umbrella

Two of the approximately 150 m-long pipe-jacked 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 to the end of the casing, and then retracted meter by meter while inclinometer readings are taken in two directions. These readings are stored on a portable palmtop PC, and are processed using calibration data to provide deformation profiles.

5.5 Automatic and manual settlement measurements on the surface

Four motorized 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 measuring points always covers the zone of influence.
Classical manual levelling is performed for long-term settlement monitoring and to supplement automatic settlement readings, especially for measuring points, which are not easily accessible.

Measured points at the surface in DAVIS window, heaves due to grouting.

Measurements with hydrostatic levelling from the pilot tunnel in the same interval.
6  Data Management

6.1  Data Sources

Data from diverse instrumentation and other various sources result in a large number of measuring points that necessitate a powerful tool for data handling. DAVIS (Data Visualisation Software from Solexperts) 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)

Solexperts AG, the company responsible for operating the system

The following table gives an overview of the various data sources:

<table>
<thead>
<tr>
<th>Type of instrument</th>
<th>Type reading</th>
<th>Measuring positions</th>
<th>Number of Instruments</th>
<th>Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrostatic Levelling</td>
<td>Automatic</td>
<td>98</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Total Stations, sub surface</td>
<td>Automatic</td>
<td>98</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Total Stations, surface</td>
<td>Automatic</td>
<td>700</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>Precise Levelling</td>
<td>Manually</td>
<td>380</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Motorized Digital Level</td>
<td>Automatic</td>
<td>37</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Sliding Deformer</td>
<td>Manually</td>
<td>390</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Borehole Inclinometer</td>
<td>Manually</td>
<td>430</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Horizontal Inclinometer</td>
<td>Manually</td>
<td>290</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>TBM Advance</td>
<td>Automatic</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Manually read instruments have an interval between readings of .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.

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

- Hydrostatic 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 measurements).
- 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.
- Motorized Digital 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 could be viewed on the Internet at www.los201.ch by anyone. This website also contains interesting information about the project.

7 Safety Concept

The term “safety concept” should be thought of as “totality of activities and precautions with the aim of limiting the risk in a system to the accepted risk” [Kovari, 2001]. For the realization of the safety concept the term “safety plan” is often used. It is a tool of risk analysis and risk management. To a clear-cut system or subsystem information are put together and were represented on a plan. Together with the determination of risk a plan with events is set up which specifies the measures for undesired events. In terms of an extended determination of risk a safety commission is establish and involves all concerned groups that are: municipal departments (electricity, water, telecommunication, waste disposal, underground construction), police department (traffic), owner, project planner, project manager and contractor. Public relation should include the residents into the project. A good information policy improves the acceptances for the project that usually provides some obstacles for the residents.

An important part of the safety concept is the alert in case of exceeding an alarm limit. Beside the realization of communication in a technical sense the behaviour in case of an alarm has to be specified in the safety plan. The scheme shows the facts: after the automatic measurements are made and processed, data from different 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 charts are automatically updated with new data. Via Internet a protected access is provided for the involved parties. In case of exceeding an limit, an alarm message is sent to the security service, which distributes the information following specified rules. It also exist a so called “Pikett-Koffer” which contains a laptop from which the data server could be accessed, a mobile phone (alert), also some information concerning the properties and objects. Four alert boxes were used by the SBB as the owner, the project planner, the project management and the contractor. All alerts were - of cause - passed to the engineers in charge of the measurements.
8 Conclusion

The construction of the tunnel for the two-track railway Zurich-Thalwil-line in soft ground required an efficient risk management. A measure to control the risk was the monitoring system. With various sensors the heaves and settlements were automatically measured and the information was provided to the engineers in charge through a comprehensive data management system. The alert was an important part of the safety concept that also contains specified measures for possible occurrences of different undesired events. The safety plan helps to face the risk in a rational way and plays an important role by formalizing the procedure and visualizing the information that concerns the project in totality. It is the interface for the collaboration of experts and other groups. The specified measures and the use of them helped to improve the safety. No remarkable damages occurred and the settlements were less than expected. This is an achievement of those who designed and realized this project - a remarkable success.

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