ABSTRACT: Construction as well as deep excavation and tunnelling in urban areas have to be executed with the utmost care to avoid damage to persons and structures. The monitoring of displacements in the soil and at the adjacent buildings is an important tool for the project engineer to minimise risks and to optimise the constructional measures. Examples of automatic and visualised monitoring in Zurich and Berlin are reported.

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.

2 INSTRUMENTATION

For instrumentation the engineer has nowadays a large variety of instruments at his disposal to investigate the underground, the structures and neighbouring buildings, Thut [01]. 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.
3. ZIMMERBERG RAILWAY TUNNEL, ZURICH INSTRUMENTATION AND DATA MANAGEMENT

3.1 General overview

The Zimmerberg Tunnel is a project of the Swiss Federal Railways. The total length of the first part from Zurich to Thalwil is 10,726 m, of which 9,422 m is excavated as a tunnel. For the detailed description of the project and for the risk management see Bosshard [01], Gürtner [01], Kovári [01].

The major part of the tunnel (5.5 km) has been mechanically driven by a hard-rock TBM in the upper fresh water Molasse, from a starting shaft at Brunau southwards. The northern part also starting from Brunau 1900 m in rock and 700 m in soil was driven with a mixed shield, in soil the face supported by pressurised bentonite slurry.

The grouted cover had the aim of minimising settlement (20 mm was allowed) and preventing a collapse in the case of an unstable tunnel face. The design specified a cohesion \( c = 0.1 \) MPa and for unconfined compression a strength of \( d_c = 0.4 \) MPa. Complete zones around the tunnel section were grouted at pre-selected locations when the TBM had to be overhauled. Additional grouting was executed under the foundation of some nearby buildings (Oil tank Bremgartenstrasse) and to better encapsulate the erratic blocks encountered.

A section of the three-storey underground car park of the SSF building (Fig. 1) lies directly on the axis of the tunnel. The underpinning of the building was carried out using pre-stressed concrete beams supported by micro-piles (Fig. 3). The foundation of this building was reinforced and a part of the basement removed to prepare for excavation with the TBM.

Near the SSF building the TBM ends in a deep excavation supported by an arch-shaped diaphragm wall. In this part of the tunnel grouting from the pilot gallery was not possible. Therefore the tunnel is excavated under the protection of a pipe-jacked umbrella consisting of 10 sub-horizontal and slightly curved reinforced concrete piles (Fig. 4). The length is 150 m and the diameter 125 cm internally and 155 cm externally.
3.3 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 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.

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).

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 estimate 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 to large.

3.4 Instrumentation, monitoring, data sources

To verify the effect and the success of the constructional measures like shaft, grouting, underpinning and excavation of the tunnel by TBM, a comprehensive measuring and monitoring programme was developed in co-operation with the project leader. This instrumentation includes various elements, which are manually, semi-automatically and fully automatically read and processed (Naterop) [01]. All data and information on the instruments, together with the location of the TBM have to be available to all supervisory engineers with the following criteria:

- Data is available and can be accessed around the clock
- Processed data must be made available
• The data management system must be easy to operate
• All engineers in charge must be on the same information level and have a complete overview
• Automatic alarm must provide immediate alert in critical situations.

3.5 Data Management

The number of companies and engineers (12 persons had to have simultaneous access) involved as well as the amount of data (up to 1000 channels) called for a powerful tool for data handling. The DAVIS, Data Visualisation Software combined with the data management over the Internet offered an optimal solution for these needs.

The following companies and groups had access:
• Project manager, Swiss Federal Railway Company.
• Project engineers: Engineering group (leader Basler + Hofmann AG, Balestra, F. Preisig and SNZ). Engineers on site, project engineers.
• The contractor: Joint venture AZT (leader Zschokke Locher).
• Solexperts AG, together with Basler + Hofmann IT-Communication responsible for operating the system.

The automatic readings processed with GeoMonitor were transferred automatically every hour to a file server, while the processed manual readings were sent by e-mail to the same server.

The types of instrument are described in chapters 3.6 to 3.10.

The GeoMonitor was applied for automatic data acquisition. Up to 500 sensors are automatically read via a bus-line connecting the interfaces of these sensors. The interfaces are adapted to the signal of the sensors. Therefore all types, like analogue, digital and total stations, motorized digital levels etc. can be connected.

The raw data is processed by the remote computers and this data was compared with the predefined alarm values. Alarms were sent by FAX and SMS.

The processing includes:
• Hydraulic level: Calculation of settlement in relation to the reservoir and to the reference point.
• Total station subsurface and at ground surface: Calculation of settlement including Helmert transformation.
• Motion-controlled digital level: Calculation of settlement of the individual points in relation to the reference point.
• TBM position: Processed into a table, with a graphical presentation.

The overview and for every data source a specific graphical user interface were generated. Fig. 8 shows this overview with the tunnel divided into 5 sections and dots indicating hydraulic levelling (automatic), Sliding Deformeter/Inclinometer (manually) total stations (automatic and manually) etc. By mouse-click the windows with the layout of the instruments or targets are shown. These results are presented in several prepared graphics, one sensor versus time, several sensors versus time, or settlement in relation to the distance to the excavation face. Typical results are presented in the following sections.

By exceeding pre-set alarm values the alert is sent by SMS on mobile telephones.

For emergencies, portable-cases were equipped with a laptop, mobile phone, maps and a list of measures to be taken to react in case of danger. In the case of an alarm with the laptop the responsible engineers could access the server.
3.6 Settlement above the tunnel roof

To measure the subsurface settlement approximately 1.5 m above the tunnel roof during grouting and tunnel construction, an automatic monitoring system was installed, which combined hydraulic and geodetic levelling, (Fig. 2). In the tube with a diameter of 55 mm installed in boreholes from the pilot gallery the hydraulic levelling system was placed at distances of 6.0 to 8.0 m from the gallery.

The hydraulic level system consists of a borehole probe (length 250 mm, diameter 50 mm) (Fig. 9) with a precise pressure transducer, which is connected through a liquid filled hydraulic tube to the reservoir outside of the borehole. An additional hose equalises the barometric pressure. The sensor measures the relative vertical displacements with respect to the reservoir level. The signal from the pressure sensor is transferred via cable to the interface and read automatically with the GeoMonitor at the measuring station over a bus-line connecting all sensors.

The pilot gallery and the reservoir are close to the tunnel and are therefore also in the zone of settlement induced by the excavation. The evaluation of the total settlement above the tunnel roof was guaranteed with two automatic total stations (theodolites with electronic distance meter and automatic target recognition) and optical prisms at each reservoir point installed. The reference points were installed in zones with no movements.

These measuring sections along the pilot gallery were installed every 5.0 m. Fig. 10 shows the DAVIS window with the layout of the measuring sections. One had to monitor approximately 100 m ahead and 100 m behind the TBM. A typical plot with the settlement of 1 to 2.5 mm versus the TBM advance is shown in Fig. 11. The results correspond to the hydraulic levelling alone. The TCA in the pilot gallery showed no displacements.

The total displacement above the tunnel roof, with the TCA measurements superimposed on the hydraulic levelling is shown graphically in Fig. 13. In this zone the lower half of the tunnel face is located in fine grained glacial near-lake deposits. The settlement of 10 mm of N3302 before grouting may be due to the grout drilling in this formation below the ground water table. The maximum heave of 15 mm induced by grouting is of the same order of magnitude as that of the basement of the "Brengartenstrasse" see Fig. 15. The TBM excavation showed settlements of between 5 and 8 mm.
3.8 Deformation measurements in vertical boreholes

To monitor the deformations in the soil in the vicinity of the tunnel excavation 20 boreholes were equipped with special measuring tubes, which allow Sliding Deformeter and Inclinometer measurements in the same tube. The HPVC tube with longitudinal grooves for the inclinometer is fitted every metre with couplings, which can displace telescopically. The seat for the Sliding Deformeter is located in these couplings. The high precision of this instrument is due to the seating principle, the measuring head being spherical and the seat being conical. The Sliding Deformeter belongs to a family of instruments for the measurement of deformation in a profile and is described in detail elsewhere, Kovári [83] and Thut [99].

3.7 Automatic reading with motorized digital level

The tunnel excavation passes near the building "Bremgartenstrasse". In order to survey the settlement of this building a motorized digital level system (Fig. 14) and 11 bar-coded staffs were installed. For the description of the measuring system see Naterop [98]. The orientation, the focus and the reading are controlled via a PC and the GeoMonitor software. The main deformation with a maximum of 15 mm heave was due to the grouting below the basement. The settlement produced by the excavation is only 1 to 2 mm (Fig. 15).

With this type of measurement the vertical deformation $\Delta z$ and the horizontal deformations $\Delta x$ and $\Delta y$ in soil are checked metre-by-metre.

3.9 Deformation measurements in the horizontal pipe-jacked umbrella

Two of the approximately 150 m long pipe-jacked horizontal piles have been equipped with inclinometer casings. The casing was installed inside a 120 mm diameter steel protective casing and is 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 on retracting the probe metre-by-metre, 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 and are also transferred by e-mail to the file server.
• Grouting below the old building and jet grouting under the foundations to improve soil conditions.
• Construction of a 3-storey low building north, east and south, adjacent to the old building
• Braced excavation, 15 m deep with the dimensions 18.4 x 57.0 m at a distance of 19 m from the old building. The supporting wall was a sheet pile wall 21 m deep, placed in a bentonite-cement slurry trench with a depth of 42 m reaching a clay layer of low permeability.
• Drilling of 140 m piles with diameters 0.9 m and 1.2 m for the construction of a 22-storey building.

Already in the design submission, the client required stringent monitoring of settlement and tilting of the old building. The admissible settlement was fixed at 40 mm, while the tilting of the basement may not exceed 1/750 during construction and the tilt after completion of the work 1/1500. The contractor had to inform the client immediately when the tilt exceeds 1/2500.

### 3.10 Automatic and manual settlement measurements at the surface

Four Total Stations were employed to automatically measure settlement on buildings and on the pavement. They are operated in a similar way to those used in the pilot tunnel. The Total Stations were 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 very accessible, classical manual levelling was performed.

The measured settlement was redundant with respect to the other measurement and was in the range of 2 to 4 mm.

### 4. GSW BERLIN, GROUTING, EXCAVATION, PILE FOUNDATION

#### 4.1 Constructional measures

GSW stands for "non-profit-marketing building company". Beside the existing shallow-founded 16-storey building (in the following referred to as the "old building"). The following constructional measures (Fig. 18) were carried out Sänger [96]. Thut [97].

Fig. 18 GSW Berlin, site plan, constructional measures, instrumentation

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

The measured settlement was redundant with respect to the other measurement and was in the range of 2 to 4 mm.

### 4.2 Monitoring

Also for the monitoring the following requirements were defined already in the tender documents.

- Monitoring until 6 months after completion of the entire construction work.
- Monitoring must start 1 month before starting construction work,
- Results must be transmitted within 24 hours
- During grouting monitoring at an hourly rate
- Accuracy: Displacement in soil, structure ±0.5mm

The measured settlement was redundant with respect to the other measurement and was in the range of 2 to 4 mm.

In view of these conditions the contractor decided to install an automatic measuring system consisting of:

- Two motorized digital levels (Leica Na 3003) installed at the old building at two opposite corners to monitor settlement and tilting, the reference point being installed on an adjacent building.
- Seven multi-rod extensometers to monitor soil displacement.
- Three piezometers
- One pressure gauge in the pumping well in the excavation of the underground car park.
- Inclinometer measurements in the support wall.

Fig. 19 shows the cross section with the geology and the measurements on the structure. By modern the
contractor and the supplier of the automatic system had access to the collected and processed data, the results of the measurements being followed by both parties.

**Settlement due to the constructional measures**

The settlement of the corner of the old building measured with the motorized digital level from July 95 to June 97 are summarised in the graph in Fig. 20. It is shown that at the end of construction in October 97 the original levels of July 95 were almost regained but in between several pronounced displacements were observed, which could be correlated with the constructional measures.

![Fig.20 Settlement and heaving due to the construction measures](image)

**Drilling, grouting 1st July to 15th October 95**

The drilling and jet grouting below the foundations and the drilling and grouting below the foundation slab induced settlement of the old building of 20 to 22 mm. The difference in time of the beginning of the settlements corresponds to the difference in grouting interventions starting at corner II-7 and ending on corner I-1.

**Deep excavation, leak of the slurry-cement wall 24th October to ~19th November 95.**

Small settlements of about 4 mm were observed on the building adjacent to the deep excavation. On 23rd October the excavation was still in the marl (Fig. 18) and for a short time the pore water pressure below the layer with small permeability exceeded the overburden pressure. This caused a fissure in the bentonite cement slurry trench. Locally beneath the tip of the sheet pile wall, settlement of approximately 38 mm were observed. The excavation was flooded in order to repair the slurry wall with jet grouting.

**Piling for the 22-storey building, January 96 to May 96**

Soon after starting of the piling works the leveling showed large displacements at the corner measuring point Niv. I-1, which starting at approximately 25 mm reached 65 mm. In the fine-grained sand and with the ground water table near the surface, even with the utmost care in extracting sand with the bucket, displacement could not be prevented. The partial vacuum led to a kind of piping and induced the settlement.

**C grouting, June 96, October 96**

In view of the large settlements and the tilting of 1/860 and also to avoid further displacements and damage, already at an early stage in March 96 compensation grouting to reverse the settlements and to rectify the building was executed and was intensified from July to October 96. Fig. 19 shows that this measure succeeded, the maximum settlement reaching only 10 mm with almost no tilting. The costs for this unforeseen intervention amounted to approximately 3 Mio. DEM.

**5. CONCLUSIONS**

At the Zimmerberg Tunnel in Zurich and the GSW site in Berlin extensive automatic and manual geotechnical measurements were carried out to monitor the construction procedures. At both sites drilling, grouting and piling works were adopted as constructional measures to improve the soil conditions. The latter, however, are completely different at the two sites. In Zurich the soil consists of gravel, moraine and sand, with the water table at a depth of approximately 8.0 m, whereas in Berlin the water table is near the surface and the soil is a uniform sand. With the site conditions in Berlin the constructional measures, primarily the drilling, caused local piping leading to considerable, though unavoidable, ground settlements. At the Zurich site, by contrast, the drilling did not cause settlements at the building, but ground surface heave was observed due to the grouting. In Zurich the tunnel was excavated using a Hydro-TBM using a special pressurised bentonite slurry which, together with the grouting, proved very successful and practically no settlements were observed.