

GEOTECHNICAL AND HYDROGEOLOGICAL MEASUREMENTS, SAFETY AND RISK IN SLOVAKIA AND SWITZERLAND

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SWITZERLAND

Introduction

In the last two decades the importance of measurements accompanying construction work has increased enormously. For engineers and geologists it has become a standard procedure to monitor structural behaviour in each phase of construction as well as the interaction between the structure and the ground. The assumptions made with regard to the ground and the dimensioning of the structure could be confirmed with the aid of measurements. If necessary, in the case of critical occurrences that could endanger the structure corrective measures could be implemented.

The big increase in the use of monitoring is also due to the development of new measuring instruments and new measuring methods. This requires reliable and exact measuring instruments. They also have to be adapted to local requirements.

With the automatic recording of the measured values and the visualisation of the results a breakthrough was achieved in the field of geotechnical measurement and the monitoring of structures. Solexperts AG was the first firm to use large measuring systems, i.e. in 1995 and 1996 in the centre of Berlin and for the sluice gate Gabčíkovo.

1. Geotechnical Measurements, Structural Monitoring – Risk and Safety

Here an in-depth discussion of the terms risk and safety is not given, but instead reference can be made to the publication – «Risks in Tunnelling: Analysis and Procedures relating to the Zimmerberg Base Tunnel» (K. Kovári, M. Bosshard [1]).

Performing measurements is an integral part of risk management: «Use of measures and methods with the aim of achieving the required safety, [2]». The expression is frequently used in the same sense as risk analysis, risk control, system safety, etc.

In the planning and design of a structure, risk evaluations are carried out at an early stage. Such evaluations consist of at least three steps [1]:

- Assessment of the possible amount of damage
- Assessment of the probability of occurrence
- Assessment of the combined effect of amount of damage and probability of occurrence

1.1 Field Tests in the Risk Evaluation Analysis

Carefully executed field tests carried out in the design phase provide an important basis for risk evaluation during the construction of the future structure. This includes, e.g.:

In Tunnelling:

- In situ hydrogeological tests carried out for example in deep boreholes (up to 2000 m) as in the case of the alpine transversals AlpTransit Gotthard, Löttschberg, Brenner, Lyon-Turin, etc. They provide information on the permeability (water ingress into the tunnel), piezometric heads [3].
- Multiple packer systems for the long-term monitoring of the formation's water pressures and for taking water samples. Such systems have already been installed successfully with depths of more than 1000 m.
- Measurement of the primary stresses in the rock using Hydro-Frac tests down to depths of 4000 m [3]. In an interval of approx. 1.0 m, sealed with packers inflated under high pressure, the water pressure is rapidly increased to form a crack in the formation (Fig. 1). In the ideal case the crack forms normal to the minor principal stress. With a renewed application of the pressure only the rock stress has to be overcome and is determined together with the closing pressure the minimum primary stress.
- Determination of the deformation moduli in boreholes using the dilatometer up to depths of 1300 m [3]. The probe is sketched in Fig. 2. Essentially it consists of a steel cylinder with 3 openings, in which the displacement transducers are installed at an angle of 120° to one another. By means of a reinforced rubber packer the wall of the borehole is loaded in steps and the increase in diameter of the borehole is measured. When installing the probe it is important that the displacement transducer is in direct contact with the rock. This is ensured by means of the steel rods inserted in the sleeve.

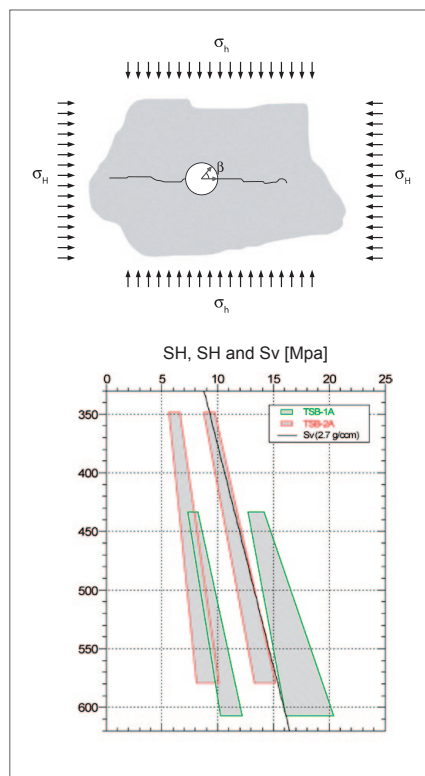


Fig. 1 Stress measurement, Hydro-Frac tests

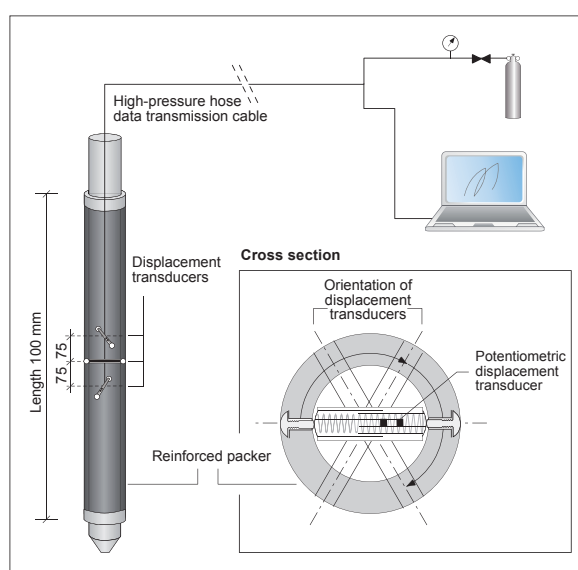


Fig. 2 E-Modulus of rock, Dilatometer probe

Special Foundations, Earthworks

- Pile loading tests to determine bearing capacity or serviceability. The strains are determined over the whole length of the pile (Fig. 3 Example: Stadium Hardturm, Zurich). With the help of these measurements the mode of action or the soil-pile interaction is determined using high-precision measuring instruments, e.g. sliding micrometer [4]. The pile, of diameter 1.20 m and length 15.0 m, is loaded up to 1200 tons. The small decrease in strain from the top to the base of the pile indicates a small influence of friction. Most of the load is transferred to the base of the pile. The Sliding Micrometer tube was installed in the ground below the pile where a settlement of approximately 30 mm over 3.0 m was observed.
- Loading tests (consolidation tests) on compressible soil using test fill and determination of settlements using the Sliding Deformometer in boreholes, Example: Bocca di Lido Venezia, Italy, and Barcelona, Spain [5]. Fig. 4 shows the profile of settlement due to a test embankment of height 5.0 m and base area of 80 by 80 m. Unexpected displacements of 90 mm were observed at depths between 12.0 and 20.0 m showing an argillaceous layer not observed in the cores from the drillhole.
- Determination of pore water pressures, permeability coefficients, deformation moduli and, in some cases, shear strength in boreholes.

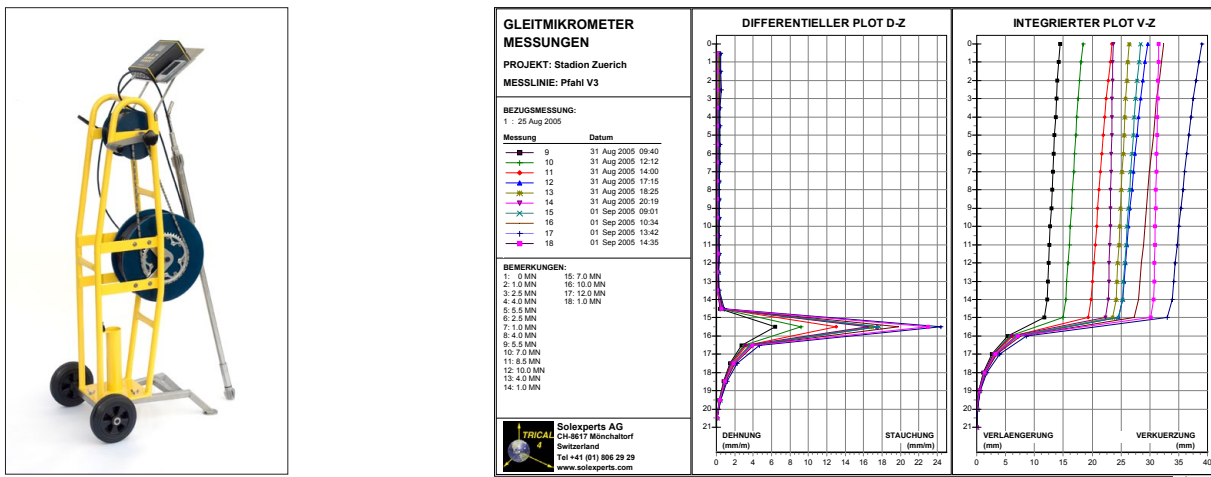


Fig. 3 Sliding Micrometer with cable reel / pile load test stadium Hardturm, strain distribution

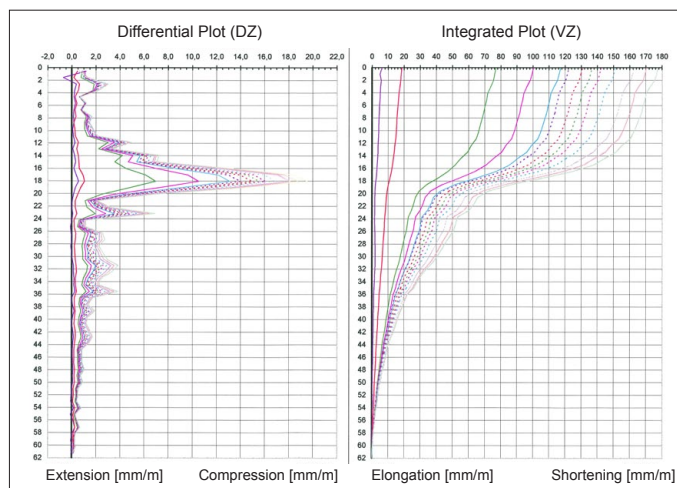


Fig. 4 Instrumented loading test on soft deltaic clays

1.2 Measurements during Construction

Advance exploration in front of the working face during the tunnel drive

The tests mentioned above for the design phase are applied in difficult hydrogeological and geotechnical conditions even during tunnel excavation, e.g. in squeezing rock or in soil. For this purpose, boreholes are drilled from the tunnel face or from niches.

- For the hydrogeological explorations horizontal boreholes are drilled from niches or the tunnel face using blowout preventers. The hydrogeological parameters are determined using the Pump Down Packer System (PDPS) [6]. Examples are la Réunion, AlpTransit, Löttschberg, etc. [7].
- To explore the deformation behaviour ahead of the tunnel face extrusion measurements are performed using the Sliding Deformeter in depths of borehole up to 30 m or in boreholes up to 100 m extrusion measurements are performed using the Reverse Head® Extensometer. They give information in advance on the expected displacements of the tunnel face and empirically on the convergences. They form the basis for stabilizing the tunnel face using anchors.

Geotechnical Measurements and Structural Monitoring

Erecting a structure causes stress redistributions in the ground, due to loading or unloading and due to changes in the pore water pressure, especially in the case of groundwater lowering. The load applied by the structure can be calculated fairly accurately. However, as soon as the interaction of the structure with the ground is taken into account for assessing the behaviour of the structure, uncertainties arise due to inaccuracies in the geotechnical evaluation of the ground. This applies to practically all projects, such as:

- Tunnelling in soil especially in urban areas
- Excavations in soil and below the groundwater level
- Retaining measures in the case of cuts in slopes
- Foundations of tall structures in soil
- Dams and embankments
- Monitoring of unstable slopes

Here too the risk assessment is the basis for the measuring and monitoring concept, for the method of measurement as also for:

- Types of instrument: displacement, inclination, pressure, etc.
- Required range of measurement and measuring accuracy depending on the size of the expected changes, long-term stability, etc.
- Arrangement of the instruments on the structure, in the ground and on neighbouring buildings, depending on the hazard scenario
- Sequence for the recording of measurements (measuring intervals)
- Storage of values and transmission with visualisation via the Internet
- Data access rights of the involved engineers, geologists and contractors
- Setting off an alarm if specified limit values are exceeded
- Defining measures to be implemented if unforeseen events take place, such as structural measures, and if necessary an evacuation plan for endangered persons

The following case studies give a detailed insight into the above mentioned measuring methods.

2. Projects and Measuring Methods

2.1 Tunnelling, Hydraulics, Rock Mechanics and Borehole Tests

The so-called Lugeon test has been around since the 1930s. It was introduced by the geologist Lugeon for a quick assessment of the permeability of the rock foundations of dams with a view to sealing by means of grouting [8]. In an interval sealed between double packers, water is forced into the rock in pressure steps of up to about 15 bar. The measurement of the pressures and of the injection rates is usually carried out manually at the ground surface. This type of test only gives qualitative information regarding the permeability values of the rock formation. A Lugeon corresponds to 1l/m/min at 10 bar.

Following from application in the field of oil exploration over the last 40 years, a method has been developed that permits obtaining far-ranging information on the hydrogeological conditions in rock. The method has proved successful in all base tunnels, e.g. in the Lötschberg, Gotthard, Brenner, and Lyon-Turin Ferroviaire tunnels, but also for investigating potential sites for nuclear waste repositories and hazardous waste landfills.

Basically (Fig. 5), the system possesses the following main components:

- Robust double packer system
- 3-fold pressure probe, measurement of the groundwater pressure, determination of possible bypassing of the packers, unaffected by friction losses in the testing tube
- Valve in the borehole to enclose the interval, which allows measurement of groundwater pressure and carrying out pulse and slug tests
- Data acquisition online and control of the test from the ground surface

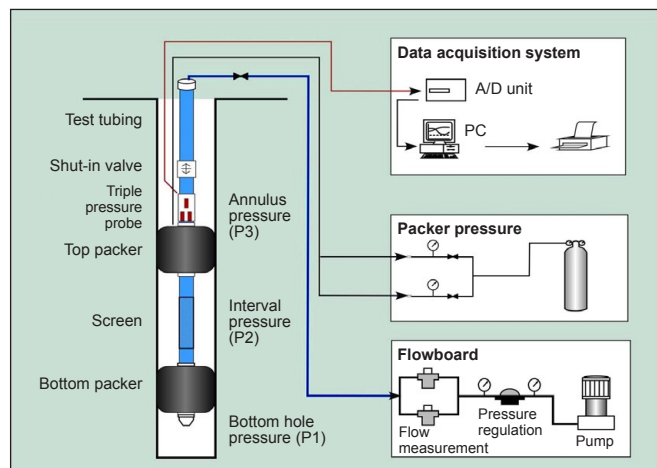


Fig. 5 Hydro testing device

Fig. 6 shows the distribution of the permeability values and the water pressures in the formation measured in a borehole in the exploratory investigation phase for the AlpTransit Lötschberg. Due to jointing and faults the values obtained are very heterogeneous, and only in a few cases can one speak of hydrostatic conditions [9].

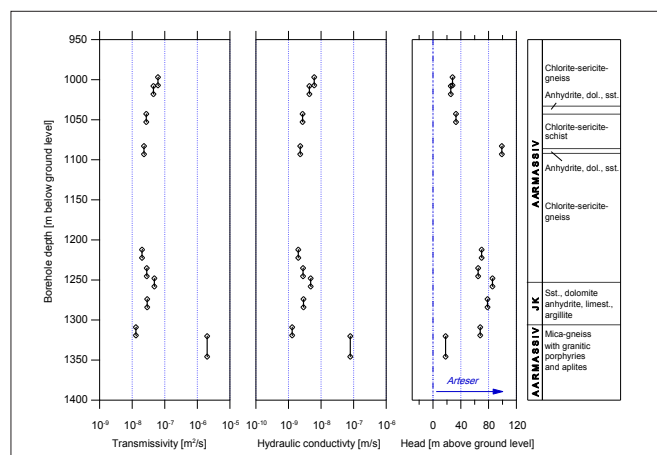


Fig. 6 AlpTransit Lötschberg, Bärsol (Jungfrau) profile of hydraulic parameters

2.2 Advance Tunnelling Explorations

Hydrogeological Explorations

In highly jointed rock and in karst formations, during excavation large water inflow endangering the safety can occur. To clarify these risks, in advance of the excavation boreholes are drilled with distances of up to 300 m and in the extreme case up to 600m with accompanying hydrogeological tests. Generally, wireline boreholes with preventers are employed. With the specially developed Pump Down Packer System PDPS, hydrogeological tests are carried out during the drilling of the borehole. If large water inflows are expected, the rock is sealed using a cement grout.

In the project AlpTransit Lötschberg the preliminary explorations along the proposed route of the tunnel in the calcitic allochthon zone of the Doldenhorn south of Mitholz revealed karst formations exhibiting high water pressures and potentially large water inflow were detected. To ensure the safety of the workers and of the structure and to implement sealing measures using grouting during the tunnel drive investigations were carried out systematically ahead of the tunnel face in horizontal boreholes.

The first investigations were carried out in a 500 m long borehole from a niche. Later, 300 m long boreholes from the tunnel face were used. In these boreholes the geology was mapped and both radar and hydrogeological tests were carried out.

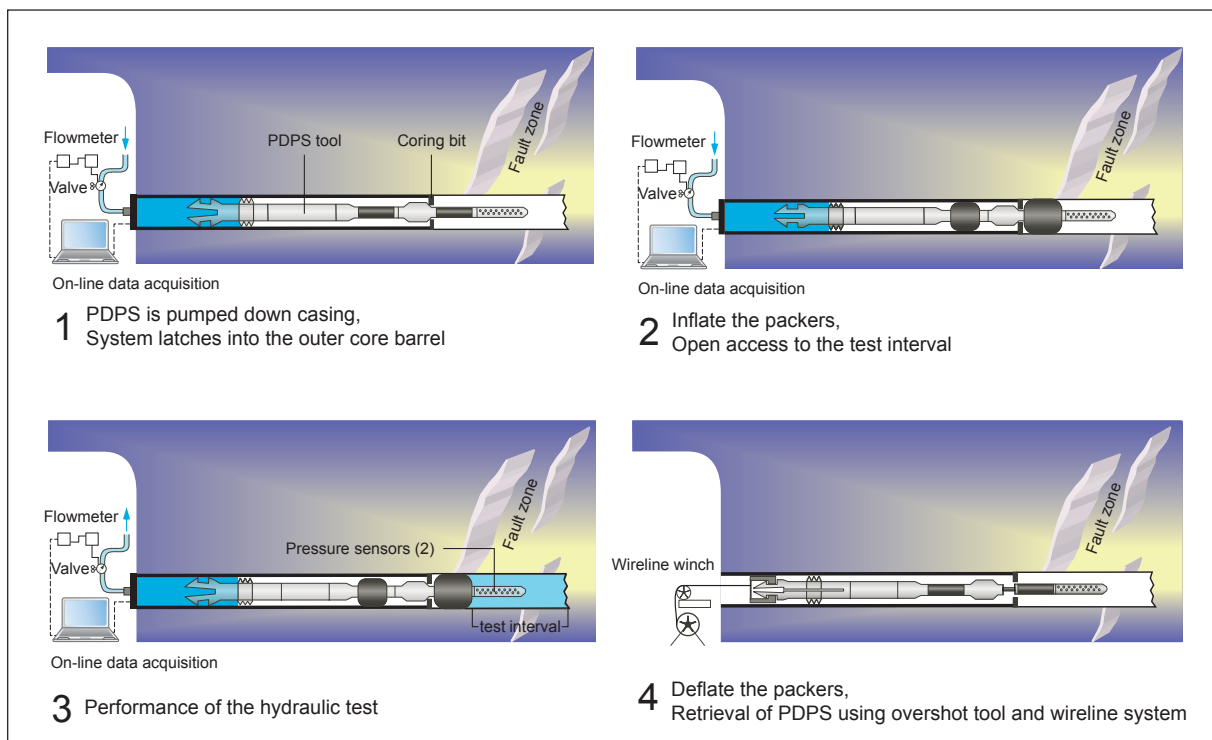


Fig. 7 Pump Down Packer System (PDPS) for hydrogeological testing ahead of the excavation face

For the hydrogeological tests the PDPS system developed especially for this type of test was employed. For the test carried out while the borehole was drilled, the borehole casing is withdrawn about 50 m. Then the system was installed in the preventer and pumped into the borehole. After coming to rest in the landing ring, by increasing the pressure in the borehole the two packers are pressurized (Fig. 7).

The two packers, one below the crown in the rock and the other in the borehole casing, seal the test interval and prevent water penetration at the crown between the borehole casing and the rock. Normally the permeability values were determined using the discharge tests and the water pressure in the formation by sealing off. The evaluation of the tests was performed online on site.

After completing the tests the packers were deflated by pulling on the casing (activation of a shear pin) and are removed using an overshot.

In total 15 tests were carried out in 13 boreholes. They provided the basis for the decision to seal the zones where large water inflow would occur by means of grouting. The highest values of transmissivity were $5 \cdot 10^{-5} \text{ m}^2/\text{sec}^2$ with a flow rate of 1500l/min [6], [7].

Tunnelling and Rock Mechanics Explorations

In squeezing rock formations, especially in the case of large overburdens, the rock mechanics investigations ahead of the tunnel face provide important information regarding the stabilizing of the tunnel face but also for the design of the temporary tunnel lining.

For the measurement of rock displacements in boreholes with a length of up to 100 m the «Modular Reverse Head» (MRHX®) (Fig. 8) has been developed. Its first application was in the construction of the AlpTransit Gotthard. At the intermediate attack Sedrun, for the tunnel advance in the north direction the intermediate Tavetscher massif, a completely disintegrated and fissured formation with a tunnel overburden of 1800 m and correspondingly high water pressures, was traversed.

The instrument comprises a chain of simple extensometers (10 to 20 elements). At the bottom of the borehole is the logger, which permanently saves the measuring values in intervals of, for instance, 1 hour.

The read-out of the measuring values can be performed at any time by means of a transmission cable and a hand help PC. The information gained is not local in character, but provides a continuous distribution of the displacements. Thus for example, (Fig. 9), immediately after excavating a portion of the tunnel face the deformation rate increases and after some time slows down. Also the drilling of anchors in the tunnel face accelerates the displacements by the process of loosening. After installing the anchors the displacements cease completely [10].

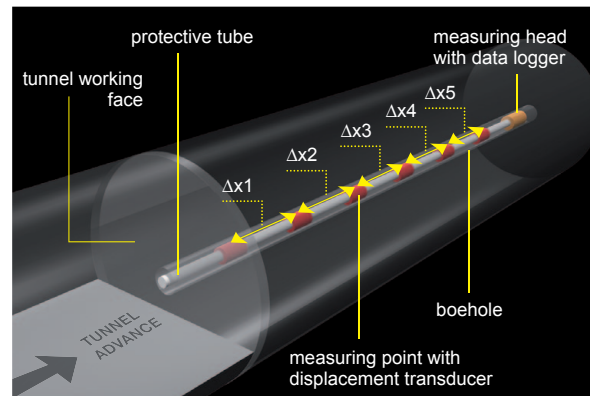


Fig. 8 Reverse Head Extensometer (M-RHX), permanent measurement of displacements during excavation

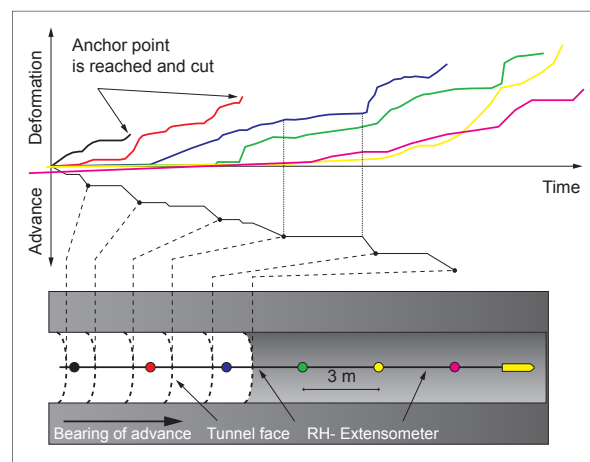


Fig. 9 M-RHX Extensometer measuring results

2.3 Geotechnical Measurements and Monitoring of Structures

The Northern Bypass in Basle is part of the Swiss motorway network. It connects the French motorway A35 with the Swiss motorway A2. The underground connection was constructed below the groundwater and in the gravel terraces of the Rhine, which consist of very compact gravel and gravel-sand without fines.

To control the dewatering operation, i.e to keep the amount of discharged water in the 6 wells to a minimum, the construction site was enclosed over a wide area by sheetpile walls.

From a starting shaft of diameter 25 m with an excavation support consisting of a pile wall the tunnel tubes were driven in the direction A2 protected by a jacked pipe umbrella and in the direction France by a normal pipe umbrella. Fig. 10 shows schematically a cross section with the installed measuring instruments.

Most of the measurements were carried out automatically using the software GEOMONITOR II (Fig. 11). The measured values are transmitted via a bus cable to the measuring control centre. The software converts the raw data online into project-specific values, e.g the displacements measured by the theodolites as settlements, heaves, horizontal displacements or water levels in the piezometers in m above mean sea level.

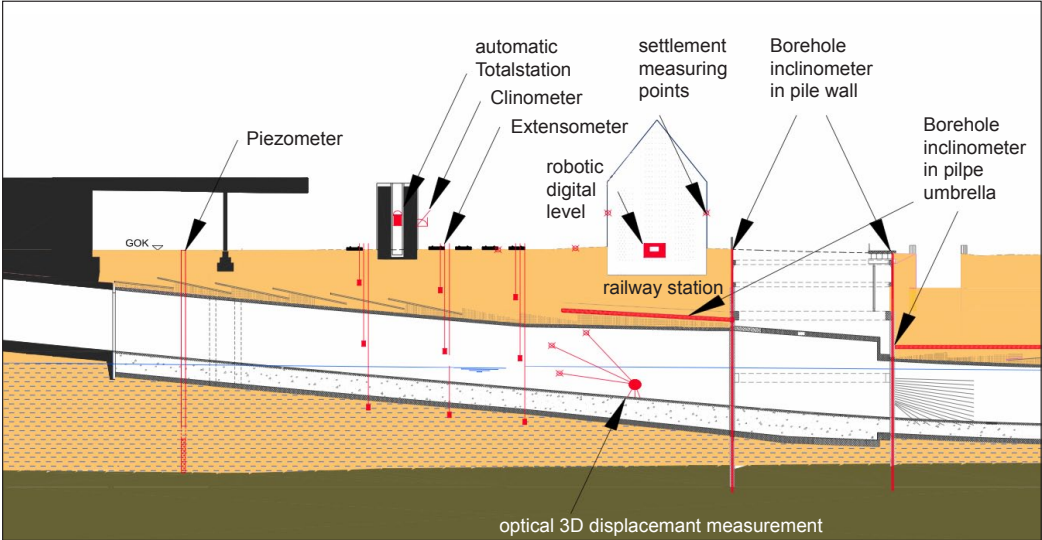


Fig. 10 Basel Luzernerring, schematic view of the tunnel and monitoring

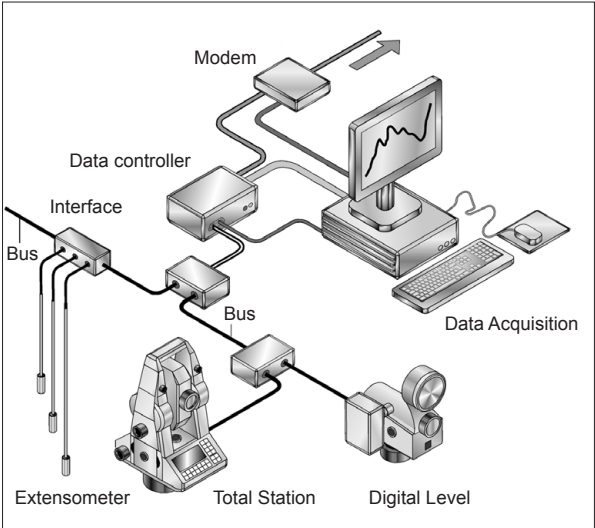


Fig. 11 GeoMonitor 2, automatic data acquisition system

Special attention given to settlements and differential settlements was required by the structures of the railway station St. Johann, the railway tracks, the bridge Luzernerring with a high density of traffic and the adjoining rows of houses in Hüning street. These measurements were mainly automatic. If specified limiting values were exceeded various alarms were triggered.

The displacement measurements for the pile wall and for jacked pipe umbrella were carried out manually using inclinometers.

The following measuring instruments were operated automatically:

- 2 theodolites monitoring the streets and pavement areas, the retaining walls and the piers of the bridge Luzernerring as well as the row of houses Hüning: measuring accuracy of 2 mm
- 1 motorized digital level to monitor settlements at the railway station St. Johann: measuring accuracy 0.3 mm
- 5 2-fold to 3-fold extensometers in the region of the railway tracks: measuring accuracy 0.2 mm
- 2 horizontal chain inclinometers for the pipe umbrellas for the tunnel direction France, measuring accuracy 0.2 mm/m
- 5 pressure sensors in the observation wells for monitoring the groundwater level: measuring accuracy 2 cm
- 2 vibration measuring devices

Data Visualisation

The software Web Davis was used for quick access to the large number of automatic and manual measurement values. With this software, via a codeword all those involved in the project could get an immediate picture of the structural behaviour by inspecting the displacements and pressures. In Fig. 12 a project overview is given with the layout of the measuring stations, as displayed on the PC screen. By clicking on any station the instrument's recorded time history, influence lines or any selected method of presentation of values can be displayed graphically.

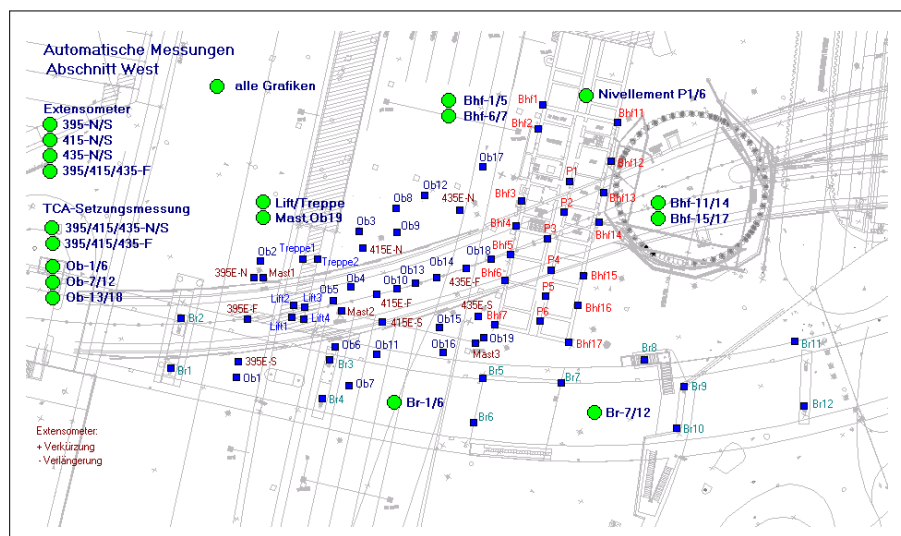


Fig. 12 Basel Luzernerring, project overview, WebDAVIS, presentation on the PC screen

Measurement Results

At the railway station St. Jakob, during the installation of the pipe umbrella settlements of up to 30 mm occurred. Fig. 13 shows the isolines and the variation of settlement along two selected axes A and B.

From the settlements, the calculated differential settlements gave an angular distortion of the structure of 1/333. In brick masonry this value has caused cracking.

Below the row of houses Hünig, before driving the tunnel grouting was carried out to improve the strength of the ground. This led to a measured heave of about 5 mm without causing any damage.

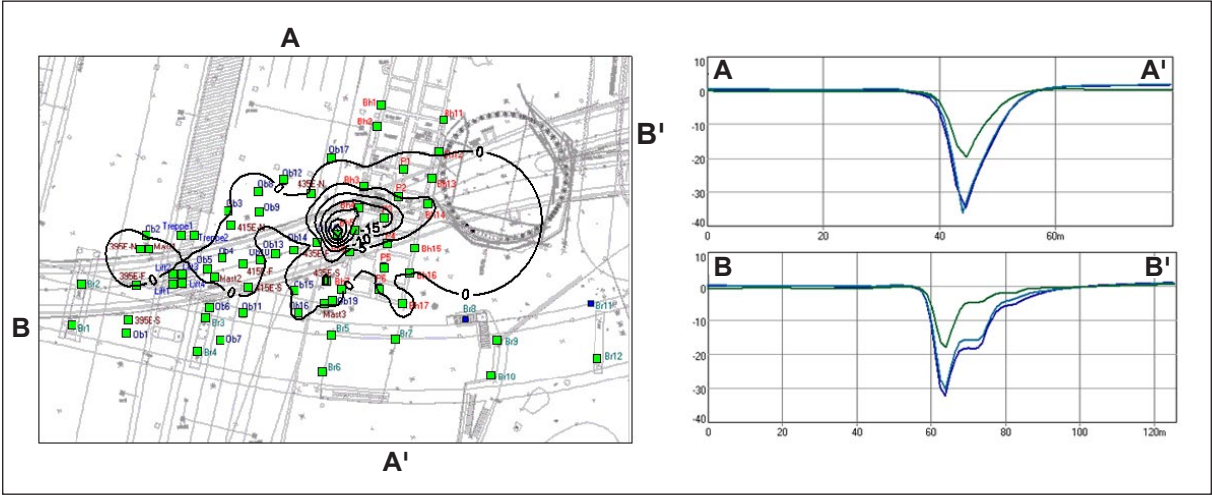


Fig. 13 Basel Luzernerring, settlements, ISO line and settlement profile near the railway Station St. Johann

Conclusions

Careful planning, extensive and goal-oriented preliminary field investigations in the design phase are indispensable measures if one is to obtain a good prediction of the behaviour of a future structure. They increase safety during execution by reducing the risk of unforeseen occurrences.

The measuring methods briefly described above together with the case studies show the importance of observations accompanying construction, with geotechnical measurements of displacements, pore water pressures as well as observing the behaviour of neighbouring structures. They demonstrate the soil-structure interaction on a scale 1:1 and provide an essential basis for an assessment of the assumptions made in the design of the structure and if necessary also for any required remedial measures.

SLOVAKIA

ABSTRACT: Removal of commercial barriers 20 years ago allowed construction activities in the Slovak Republic to expand. After a slow start for the first few years construction activities grew rapidly. The need for geotechnical monitoring grew in parallel with large constructions projects such as high-rise buildings in Bratislava, industrial structures, tunnels and cuttings in slopes for roads. Deep excavations, cuttings in slopes and tunnelling result in changes of stress and are accompanied by displacements, which can damage adjacent structures and even the construction projects themselves. In addition to minimizing damage, geotechnical measurements allow characterization of the ground and the interaction between the structure and the ground. Several projects in Slovakia and Switzerland that include geotechnical monitoring will be discussed.

3. Geotechnical risks in Slovakia

Geological risks in Slovakia reside mainly in a complicated geological structure of the West Carpathians. The range was formed in the same period as the Alps (ca. 64 million years ago), however the Carpathians exhibit a very varying geology and tectonics (External-, Central- and Internal West Carpathians).

The capital Bratislava and its eastern surroundings are located in Neogene to Quarternary basins. Geotechnical monitoring in the area is focused on the observation of deep excavations for high-rise buildings and on the system of waterworks on the river Danube. Geotechnical risks in Bratislava are due mainly to confined groundwater in Neogene strata. The permeability of Neogene is quite low. However, thin more permeable layers with high pore water pressure are present at depths of 17 to 25 m, with piezometric levels higher than the groundwater level in the permeable Quarternary layers (ca. 5 m below ground, while the Quarternary reaches down to 12 m or deeper). Although the Gabčíkovo waterworks is located not more than 60 km from Bratislava, the Quarternary strata reach down to 400 m. High permeability of gravel layers with a shallow ground water level greatly complicated the construction and operation of the power plant and the locks on the Danube.

There are a large number of landslide areas in Slovakia. The most important areas include the Carpathian flysch, Neogene depressions, Neogene volcanites and core mountain ranges. Building the transport infrastructure in such areas involves major geotechnical risks. Motorway (D1) and expressway (R1, R2) connections between Bratislava and Košice and modernization of the railway line on the route are currently under construction. Construction of the D3 motorway connecting Žilina with the border with Poland is about to be intensified within a short time. Flysch in the area are subjected to the erosion and slope erosion of deluvial sediments with a high content of clay components exhibits an intense development of sheet and stream erosion landslides after sudden changes in rock saturation.

In addition to the adverse geological conditions, the land relief itself, river network and high atmospheric precipitation are a source of geotechnical risks. The region of Upper Nitra suffers from highly active landslides threatening the inhabitants. Geotechnical risks in the region are also connected with mining activities that resulted in the loss of several human lives recently.

Numerous volume-unstable rocks in the Trnava highlands, Nitra highlands, East Slovak lowland and the lowlands in the southern part of Slovakia constitute a potential for unpredictable behaviour, as they are formed by loess and by the rocks containing clay minerals of the smectite group. Due to changes in humidity or in stress conditions, such rocks exhibit changes in volume and mechanical properties, or they decompose. The largest geotechnical risk resides in tunnel excavation in swelling rocks. High pressures from swelling are anticipated in fault zones of the

Višňové tunnel, where the clay minerals from the smectite group were identified during the driving of the exploratory tunnel, resulting in the heave of rail tracks and convergences up to 44 cm. The Višňové tunnel has a high overburden (up to 800 m), while the rocks in unfavourable geotechnical sections exhibit only low strength. In addition to swelling, squeezing is also expected; the estimate of the extent of squeezing is based on the ratio of triaxial pressure strength and the overburden weight. Values up to 2 signify very high to high squeezing, while those from 2 to 4 signify medium to low squeezing. The solution lies in the application of the yielding lining from high-deformable concrete, providing a reduction of swelling and squeezing potential and decreasing the pressure acting in the lining.

The State Geological Institute of Dionýz Štúr is carrying out the monitoring of geological hazards within the project named Partial Monitoring System of Geological Factors of the Environment. Monitoring of geotechnical hazards forms a part of construction activities and is performed mainly by specialized private companies for the contractor. Recently, an effort has been made to separate the realization of geotechnical monitoring in motorway construction from the contractor, which means that the geotechnical monitoring will be carried out directly by the operator (National Motorway Company – Národná diaľničná spoločnosť).

4. Instrumentation used in geotechnical monitoring in Slovakia

Common awareness of the need for geotechnical monitoring has always existed in professional circles in Slovakia, coming from advanced science disciplines, such as engineering geology and soil mechanics. Systematic monitoring has been an integral part of the construction and operation of water resources structures. Inaccessibility of the instrumentation at an international level has hindered the complex advancement of methods in geotechnical monitoring; progressive methods were developed mainly in research institutes and universities during the socialist period. However, an important contribution was made by the companies performing the engineering-geological exploration and technical and safety supervision. An increased use of monitoring techniques has been brought about by developments since the formation of Slovak republic, due to the free market and the construction of challenging geotechnical structures, mainly tunnels and deep excavations.

Geodetic measurements represented the mostly used monitoring technique in geotechnical monitoring. Major advances featured the **application of geodetic robots for a continuous automated monitoring of surface deformation** at the lock chambers of the Gabčíkovo Waterworks in 1997. The GeoMonitor system, including the operation of two total stations Leica TCA 1800 (Fig. 14), has been an innovative product of the international level of knowledge and techniques, with its main application to complement knowledge of the behaviour of lock chambers for the design of their reconstruction, emphasizing the determination of the primary causes of the locks' seepage.

The monitoring concept resulted from the need to distinguish the short-term deformations of lock chambers due to filling and emptying from the long-term deformations due to settlement of the locks in time. The continuous operation of lock chambers formed non-stationary conditions, hence the comparison of the results of standard successive measurements led to an ambiguous interpretation of the actual situation and the settlement prediction of lock chambers. In addition to the determination of causes of seepage, the monitoring was designed to create an adequate database of input data for the localization of the seepage by mathematical modelling. The system of automated geotechnical monitoring also had to provide an operational observation of the effectiveness of realized reconstruction works. As the GeoMonitor system succeeded in fulfilling all the presented tasks, the question of modernization of the system emerged from the operator of Vodohospodárska výstavba, public enterprise, in order to create an operative tool for the safety control of deformational behaviour of lock chambers from any location. The

provided and successful upgrade – GeoMonitor II implemented primarily the progress in the field of data transfer and data processing. As with tacheometers, levelling instruments can also be robotized: the motorized instruments Zeiss DiNi 10 have been used since 1997 in Slovakia for continuous measurements of vertical displacements of a housing estate close to a large excavation.

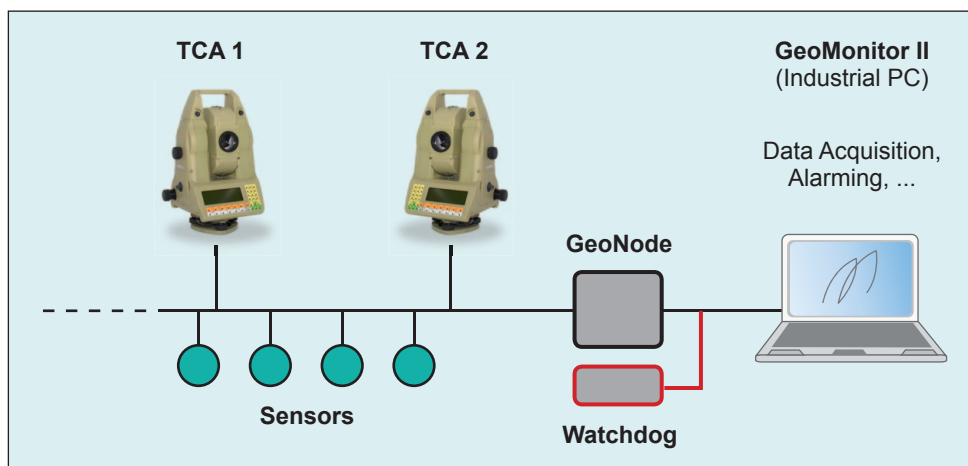


Fig. 14 Automated system GeoMonitor II in the lock chambers of Gabčíkovo waterworks

In the field of instrumentation for point measurements, **vibrating wire gauges** have been established in Slovakia in the last 10 years. Among the most commonly used devices, are piezometers measuring the pore water pressure, tensometers embedded in concrete and tensometers welded to steel constructions. Instrumentation of a transit gas pipeline in the landslide areas of Slovakia represents a significant application of vibrating wire strain gauges taking into account the geotechnical hazards. Three vibrating wire tensometers are installed in a cross section of the high-pressure piping and the values of relative deformations are transmitted remotely (Fig. 15). Automation of the measurements uses the tiltmeter sensors and dilatometers with pre-defined limit values, with an alarm activated after exceeding the limits resulting in sound or light signals or a short message service. The tiltmeter sensors were installed in 2009 and 2010 in the inclinometric boreholes in the Upper Nitra region, to ensure warning the inhabitants after the sudden activation of landslides. Dilatometers are installed usually to the houses in the neighbourhood of construction activities or to rock blocks (Castle of Spiš). Vertical Inclinometers have turned out to be widely used instruments in recent times, providing the subsurface deformations in landslide areas and in the timbering of excavations.

The innovation introduced in Slovakia in 1998, the **measurements of 3 components of subsurface deformation along the measured line in boreholes** by the combination of measurements by vertical Inclinometer and Sliding Deformeter were used in monitoring railway embankments in Devínska Nová Ves. The main goal of the monitoring was to investigate the cause of the vertical displacements of rail tracks, as it was not possible to determine the failure model just by visual observation. Evaluation of three-vector measurements enabled one to assess the nature of the problem, i.e. whether it is a stability problem (Δx , Δy) or a settlement problem (Δz), and thus to select the optimal method for the embankment reconstruction. Three-vector measurements of subsurface deformations have recently become a common part of geotechnical monitoring in portal areas of tunnels, in the determination of landslide mechanisms and in the construction of geotechnical objects in historic city centres. Fig. 16 shows an observation of the influence of pile installation for a cut-and-cover road tunnel causing deformations in the subsoil of the Church of St. Bartolomej in Prievidza.

Sliding Deformeter measurements (Δz) have been established mainly in the measurement of the unloading and overloading of the subsoil under high-rise buildings in Bratislava founded in deep excavations. Measurements of expansion and compression of the layers of thickness from 1 m to 25 – 35 m under the bottom of the excavation provide valuable information on real deformation modes of the subsoil. Such investigations of the modules at fullscale 1:1 allowed, apart from the laboratory oedometric tests, the recording of existing pore water pressure during actual changes in the stress conditions due to the excavation or to the construction of a high-rise building.

Approximately 30 such deformetric boreholes were realized in Bratislava and the synthesis of the knowledge from all of them enables us to describe the engineering-geological conditions of Bratislava very appropriately in relation to structural design for the serviceability limit state.

The paper of Hulla et al. provides more details on the issue. Regarding the measurements of the subsurface deformations along the measured line, determination of the subsoil settlement of high embankments by a horizontal Inclinator has become a standard in recent years, which replaced the less precise measurement by hydrostatic levelling.

Building of the motorway tunnel Branisko at the end of 20th century broke the decades-long stagnation in Slovak tunnelling. As the technology of shotcrete was admitted for **tunnel construction** for the Slovak motorway network, representing an **observational method of construction**, experienced foreign geodesists helped the Slovak geodesists in their training. 3D optical convergence measurements have become routine and essential measuring methods in tunnelling. Extensometric measurements in Slovak tunnels use only fibreglass rod extensometers fixed in the boreholes hydraulically.

Due to the absence of experience in tunnelling of a whole generation of Slovak geotechnical engineers, the measurements of contact stresses and stresses in shotcrete were used in the excavation of the tunnels Branisko, Horelica, Sitina and Bôrik.

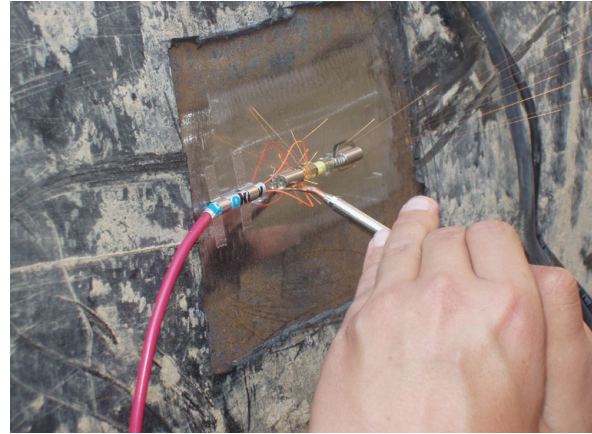


Fig. 15 Installation of vibrating wire gauges on a high-pressure gas pipeline in a landslide area

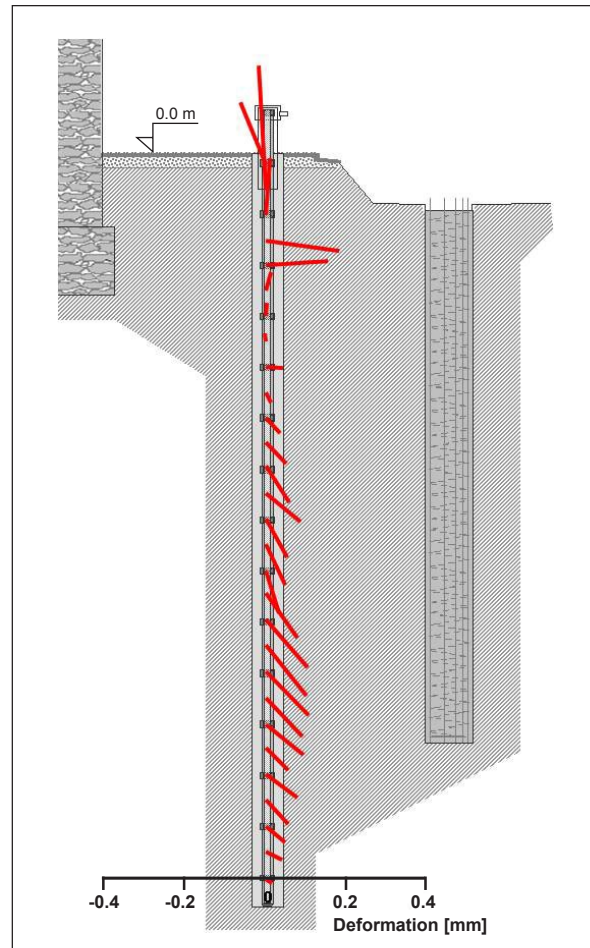


Fig. 16 Graphical presentation of differential subsurface displacements in the x - z plane

Based on the evaluation of the results it is obvious that such measurements are appropriate in squeezing rock formations and with shallow overburden, when it is not apparent whether the rock crown is formed. Measurements of contact stresses were approved as very valuable during tunnelling in Carpathian flysch.

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