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Instrumented test shaft in soft ground

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Abstract

A large underground structure is planned under the existing main railway station of Lucerne (Switzerland) to expand the capacity of the station. An instrumented test shaft was built to study the proposed construction technique. The test shaft was 5.6 m wide and 13.6 m long consisting of reinforced diaphragm wall with a thickness of 80 cm and a depth of 24.0 m.

Three levels of struts were planned to support of the excavation to a depth of 18.0 m. Prior to excavation of the test shaft jet grouting columns were built between 18.0 and 23.5 m to support the lower part of the wall and provide a seal against piping.

The instrumentation used to monitor the test shaft included four TRIVEC systems (high precision measurements of the three displacement vectors), fixed to the reinforcement cage and imbedded in the concrete, inclinometers installed in the soil 1.5 m from the shaft, and strain gauges to measure forces on the struts during excavation. The effect of jet grouting at the base of the narrow excavation in soft soil led to high lateral pressures acting outward on the walls pushing the diaphragm wall against the soil outside of the shaft. The TRIVEC system indicated bending of the wall with maximum displacement of 130 mm at a depth of 12.0 m. Horizontal displacements of the same order of magnitude were observed in the upper soil layers. Increases in the measured forces in the struts during excavation showed that the buckling load on the struts would have been exceeded by the final level so additional struts were added. The results and interpretation of the measurements are presented and discussed in the paper.

1 Introduction

Lucerne railway station is one of the most frequented railway stations in Switzerland. In the recent decades, the efficiency of the railway traffic could be improved. The railway station and number of tracks are already at maximum capacity. A plan was developed to extend the station downward below the existing station. In order to study the geology and the proposed construction technique a test shaft was built. A large number of sensors and instruments were placed in and around the shaft for investigating the structural and hydrogeological behaviour of the structure and its surrounding. Geological in situ and laboratory investigations were carried out before and during the construction of the shaft (IG TiBLU 2013). These results were used to predict and verify the mechanical behaviour of the test shaft during construction (Rabaiotti et al. 2015). During the jet grouting of the shaft slab large displacements of the diaphragm walls towards the outer external soil were measured. During excavation of the shaft the loads in the struts exceeded the allowable maximum so additional struts were installed to prevent the collapse of the shaft.

In the first part of the paper a project overview is given, the instrumentation is described with a focus on the high accurate displacement measurements of the Solexperts TRIVEC system. Next, a short introduction to the observational method is made. Finally, the behaviour of the shaft during excavation is shown and discussed.

2 Soil investigation

2.1 Geology

The soil beneath the main railway station in Lucerne consists of a series of glacial and postglacial soft alluvial strata. Clay, silt, sand and gravel layers from different sedimentation processes are dominant. Figure 1 shows the main soil layers and their very heterogeneous composition.

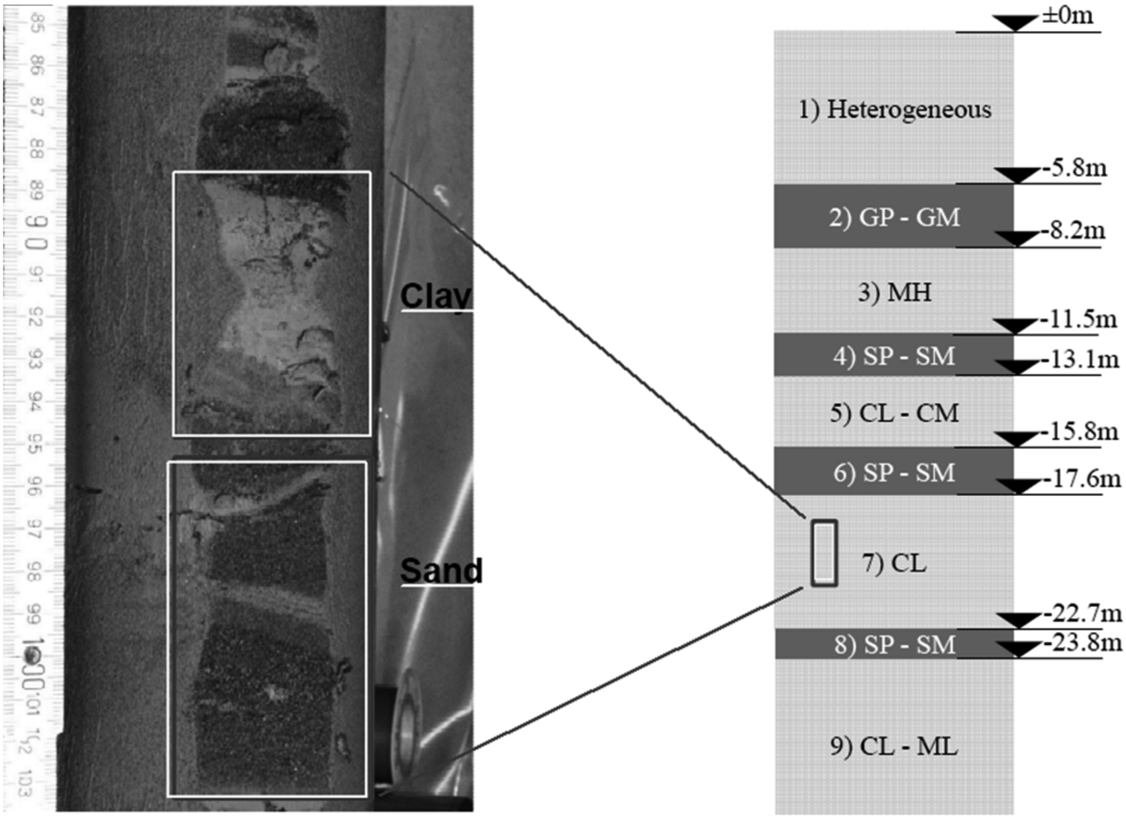

Figure 1 Soil layers and their composition

2.2 Laboratory and in situ tests

A large number of laboratory and in situ tests were carried out prior to excavation of the test shaft. Triaxial, oedometer and soil classification tests were carried out on undisturbed soil samples.

The soil conditions at the test shaft were also investigated by means of in situ tests. Cone penetration tests with piezometer (Piezocone tests) (CPTU), flat dilatometer tests (DMT) and self-boring pressuremeter (SBP). The results for the soil stiffness obtained with the carried out laboratory and in situ tests are shown in Figure 2.

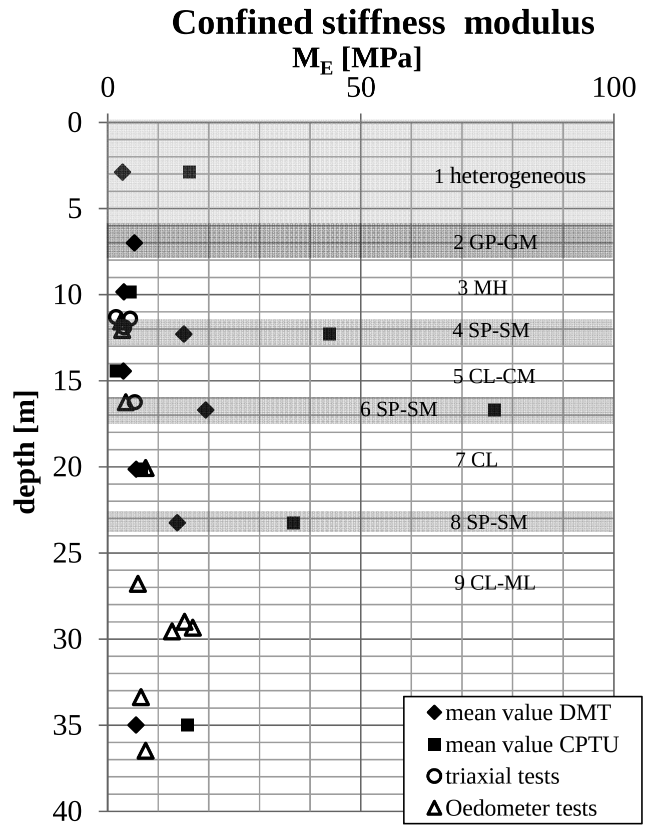

Figure 2 Mean values of soil stiffness for each layer as measured by the carried out tests

The soil properties show a very high spatial variability, as shown in Figure 3 based on the results of the DMT. This test allowed a large amount of information within a very detailed spatial resolution to be obtained, which is then suitable for a statistical investigation.

Therefore, it was decided to carry out a Monte Carlo Simulation, based in particular on the DMT results, in order to obtain the relevant parameter for the design.

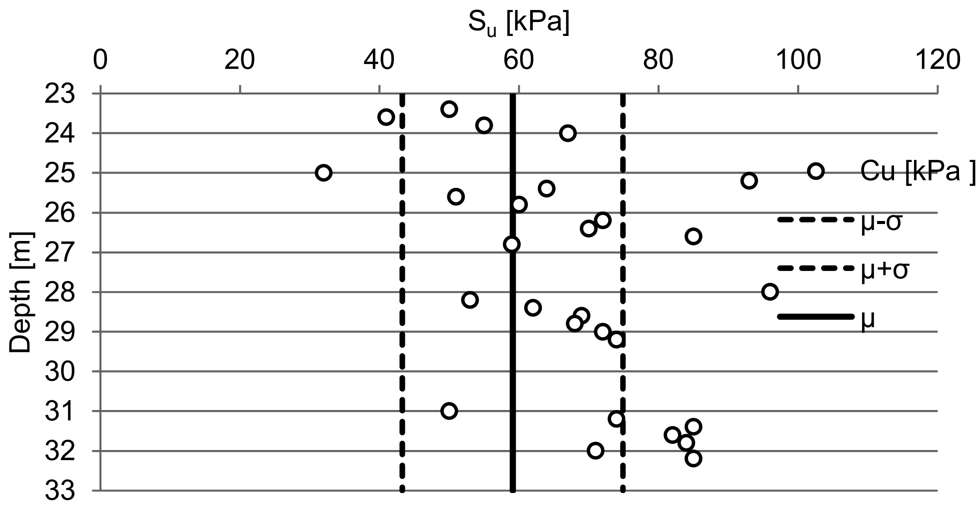

Figure 3 Distribution of the soil properties in layer 9 (undrained shear strength) as measured by the DMT. The vertical continuous line in the plot represents the mean value for the layers, the dotted ones the mean value plus or minus the standard deviation

2.3 Determination of soil parameters

The characteristic parameter values for the design were determined using a Monte Carlo simulation.

Equivalent layers (e.g. Layer D in Figure 4) were defined and their parameter determined based on the measured distribution of the soil properties and thicknesses of single layers across the site. Figure 5 shows the results of the simulation and particularly the distribution of the undrained shear strength for unit D.

More details on the simulation carried out can be found in Rabaiotti et al. (2015).

The parameters for the geotechnical units which have been used for the design are described in Table 1. For unit A and B it was not possible to obtain the fractile values (not enough data for determining a statistic distribution), therefore the mean values have been adopted.

Table 1 Mean and fractile values of the parameters for the geotechnical units

Unit	μM_{Eh} (MPa)	M_{Eh} (5%) (MPa)	μS_u (kPa)	S_u (5%) (MPa)
A	3.9		23.4	
B	5.3		4.8	
C	3.3	2.3	33.7	24.0
D	9.4	4.2	39.6	27.2
E	7.2	1.8	59.1	33.0

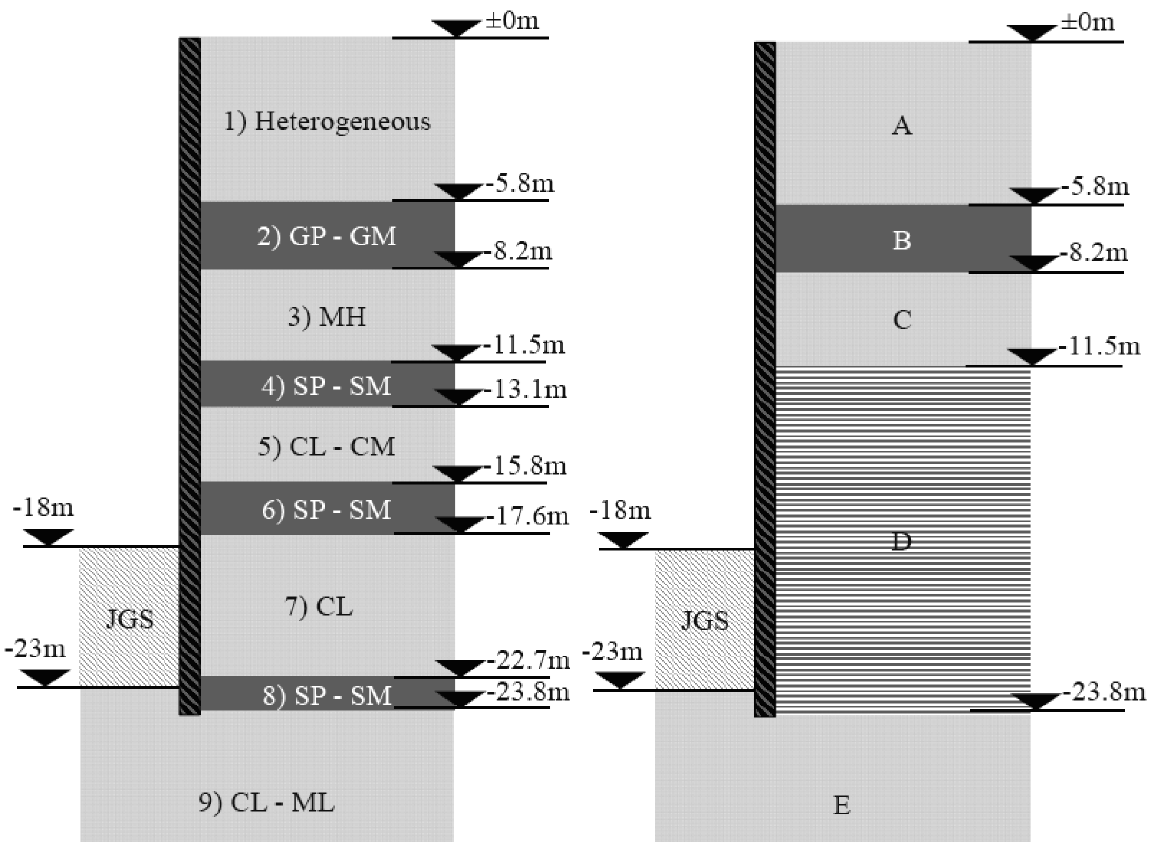

Figure 4 Comparison between soil layers and geotechnical units

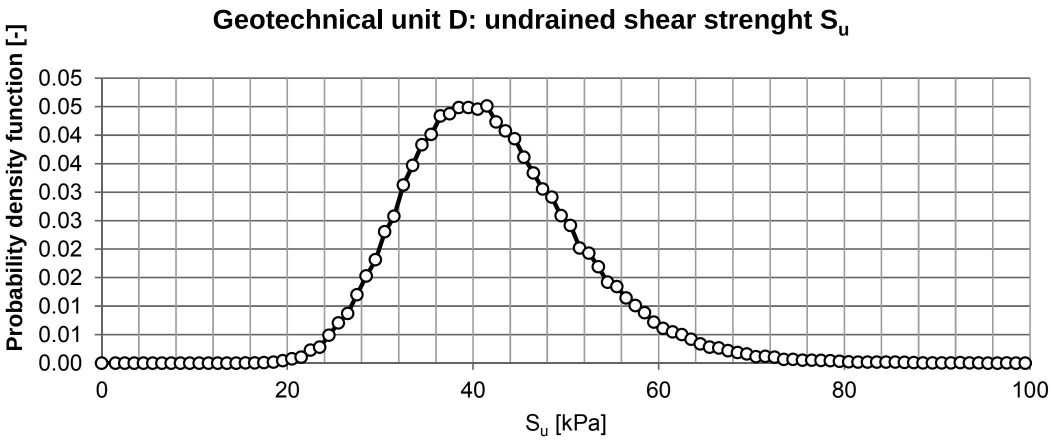

Figure 5 Probability density function of the undrained shear strength Su for geotechnical Unit D

3 Test shaft

3.1 Dimensions and design

Figure 6 shows the dimensions, the construction stages of the test shaft as well as the main installed instrumentation. The shaft including the walls has a length of 13.6 m and a width of 5.6 m. The diaphragm walls, 80 cm thick and 24 m deep, consist of eight diaphragm wall barrettes. The corners of the diaphragm walls are formed by monolithic barrettes. The walls are supported by three steel struts and waler braces at depths of 4.1, 9.2 and 12.2 m. The excavation took place in four stages. Jet grouting was carried out ahead of the excavation, to support the excavation and seal the shaft against groundwater. The jet grouting columns had a diameter of approximately 2 m and were built with cement–air suspension (double fluid).

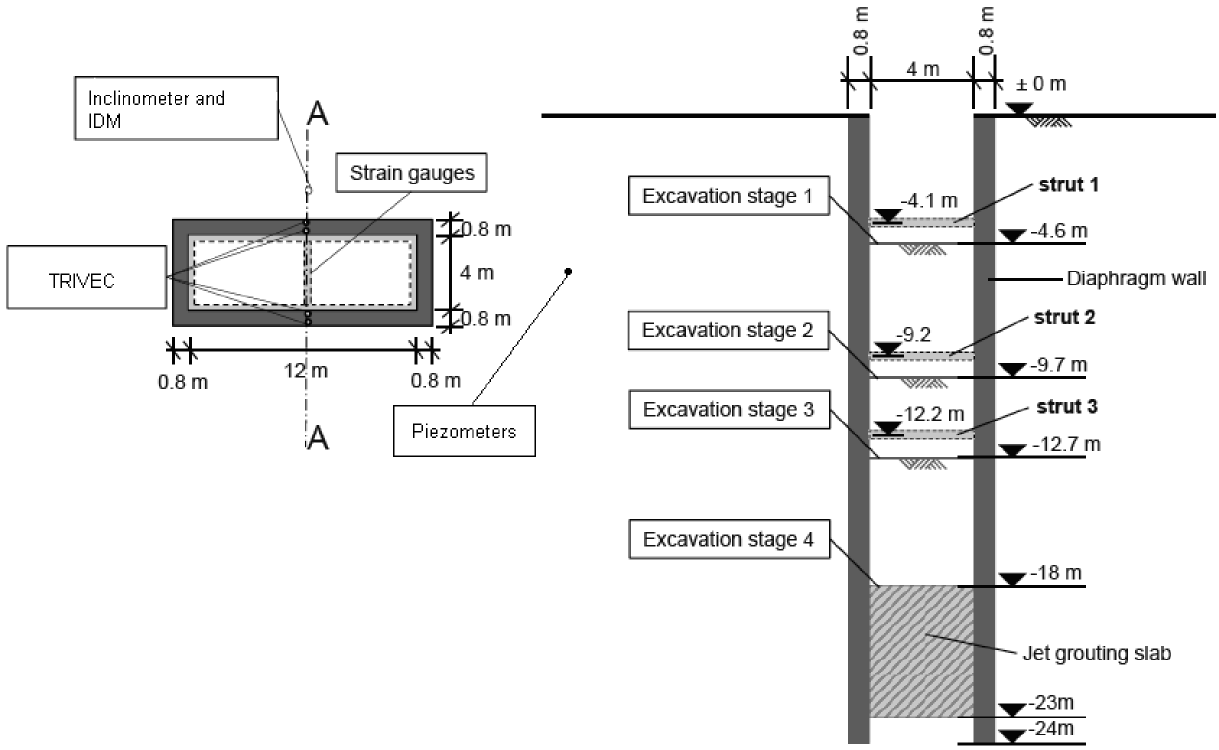

Figure 6 Plan view and cross-section of the test shaft indicating the depth of the struts and excavation stages as well as the installed instrumentation

3.2 Instrumentation

Several measuring devices were installed in the shaft and the surrounding soil (Figure 6).

Four Solexperts TRIVEC systems were set inside the retaining walls of the shaft. The TRIVEC is a high-precision instrument for obtaining the continuous distribution of the three components of the displacement vector (axial and perpendicular to the vertical borehole axis). It is applied in special measurement casings which are fixed to the reinforcement or installed in boreholes. Unlike the conventional borehole inclinometer which is applied in grooved casing, the TRIVEC is applied in measurement casing which consists of a chain of reference points with cone-shaped measuring marks. This casing has probe seating marks at 1 m intervals. A measurement is taken after bracing the probe between two adjacent marks, and measurements are repeated along the length of the casing. The probes and marks use the 'ball and cone' seating principle to achieve highly precise placement within the measurement casing. The spherical heads on each end of the probe accurately locate themselves with high reproducibility within the cone-shaped seating collars built into the measuring tube. This approach enables detection of the slightest relative displacement or inclination change between two adjacent collars. The accuracy (1σ) of measurement is better ±0.04 mm/m in Δx and Δy and ±0.002 mm/m in Δz (Frodl et al. 2007).

An Invar calibration tool is regularly used to check the functioning of the probe and to determine a zero point. The calibration tool consists of two measuring marks with a precisely defined distance (Amstad et al. 1987) for the z-axis. A precisely defined inclination can be established with the help of end blocks. Long-term drift on the sensors' readout unit has practically no effect on the results obtained with linewise deformation measurements. Table 2 summarises the specifications of the instrument. Figure 7 illustrates the principles to the probe and the reading system.

The TRIVEC tubes were fixed at the reinforcement cage and, after setting in place, imbedded in the concrete. On each side of the shaft there were two parallel tubes separated by a distance of 50 cm (wall thickness 80 cm). Bending of the wall could be measured by the inclination measurements and also by comparison of the respective displacement measurements in the parallel tubes (Kovári et al. 1982).

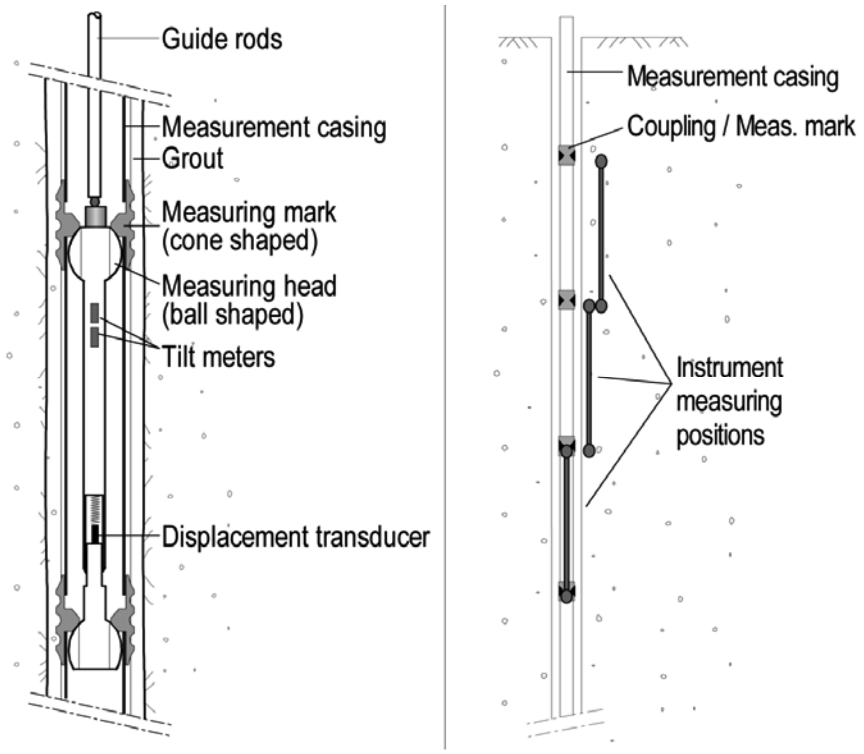

Figure 7 (a) TRIVEC instrument in measuring tube; (b) stepwise placing of the TRIVEC in the measurement tube

Table 2 Technical specification for the TRIVEC

Parameter	Specification
Probe length	1,000 mm
Sensor	Digital displacement transducer
Measuring range	±10 m
Accuracy per position	±0.002 mm < 0.02 % FS
Sensor	Capacitance digital inclination sensor
Measuring range	±180 mm/m (±10°)
Accuracy per position	±0.04 mm/m <0.02 % FS
Pressure / watertightness	Up to 15 bar

Other instrumentation included multi depth piezometers (type piezopress) and a standard inclinometer in the soil at a distance of 1.5 m from the wall, in line with the struts. Inclinodeformeter (IDM) measurements were carried out in the inclinometer tubes. The analysis of the inclinometer and the IDM test results allows changes in the earth soil pressure or the soil stiffness to be estimated. The IDM does this by making very precise measurements of the induced change in the shape of the inclinometer pipe (Schwager 2013). The forces in the struts were measured during excavation of the shaft using strain gauges. Alarm values for the strut forces were set in the automated monitoring device.

3.3 Application of the observational method

The observational method in geotechnics was proposed by Karl Terzaghi and discussed in a paper by Ralph B. Peck (1969) as a basis to reduce the costs during construction incurred by designing earth structures based on the most-unfavourable assumptions. The method uses a design based on the most-probable conditions rather than the most-unfavourable. Gaps in the available information are filled by observations: geotechnical-instrumentation measurements and geotechnical site investigation (for example, borehole drilling and a CPT). These observations aid in assessing the behaviour of the structure during construction, which can then be modified in accordance with the findings.

The observational method is part of various geotechnical standards (e.g. Eurocode 7 2007) and its main attributes can be described as follows:

- Exploration sufficient to establish the general nature, pattern and properties of the deposits.
- Assessment of the most probable conditions, and the most unfavourable conceivable deviations from these conditions. Geology plays a major role.
- Creating the design, based on a working hypothesis of behaviour anticipated under the most probable conditions.
- Selection of quantities to be observed as construction proceeds, and calculation of their anticipated values based on the working hypothesis.
- Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning subsurface conditions.
- Selection (in advance) of a course of action or design modification for every foreseeable significant deviation of the observational findings from those predicted based on the working hypothesis.
- Measurement of quantities to be observed and evaluation of actual conditions.
- Design modification in accordance with actual conditions.

For the test shaft in Lucerne the description of the geology and soil parameters support the application of the observational method. A design based on unfavourable soil parameters for single soil layers, whose thicknesses vary considerably within the perimeter of the future underground station would be overly conservative. The geotechnical parameters are derived for the geotechnical units, which have a more uniform thickness over this region (Figure 4).

3.4 Shaft construction

After the instrumentation has been set and the diaphragm walls have been constructed, the slab of the shaft was jetted. This process consists of injecting and mixing cement into the soil mass. The cement is injected through a rotating nozzle at high pressure. The soil is eroded and mixed with the cement suspension, creating a column of cement-stabilised material. One well-known possible consequence of this technique is increase in earth pressure and deformation in the surrounding soil and adjacent structures.

In Lucerne, during the jet grouting, crack openings with a width of approximately 2 cm were observed at the corners of the shaft. The TRIVEC measurements showed that the walls were pushed into the soil, with a maximum horizontal displacement of 13 cm at 12 m depth, well above the level where the jet grouting slab was constructed (Figure 8).

The inclinometer at 1.5 m distance from the shaft walls showed displacements in the same order of magnitude in the upper soil levels, the different stiffness of the soil layers is clearly indicated by considering the differential displacement steps (Figure 9).

The crack openings partly closed during the excavation. Struts of type HEB300 were installed equipped with strain gauges. The strut forces that were measured by strain gauges during the stepwise excavation were far greater than those predicted by using active or even rest earth pressure. Therefore, an extra four struts were added in the last two excavation stages (Figure 10). The forces in the lowest strut level continued to increase after the final excavation was terminated.

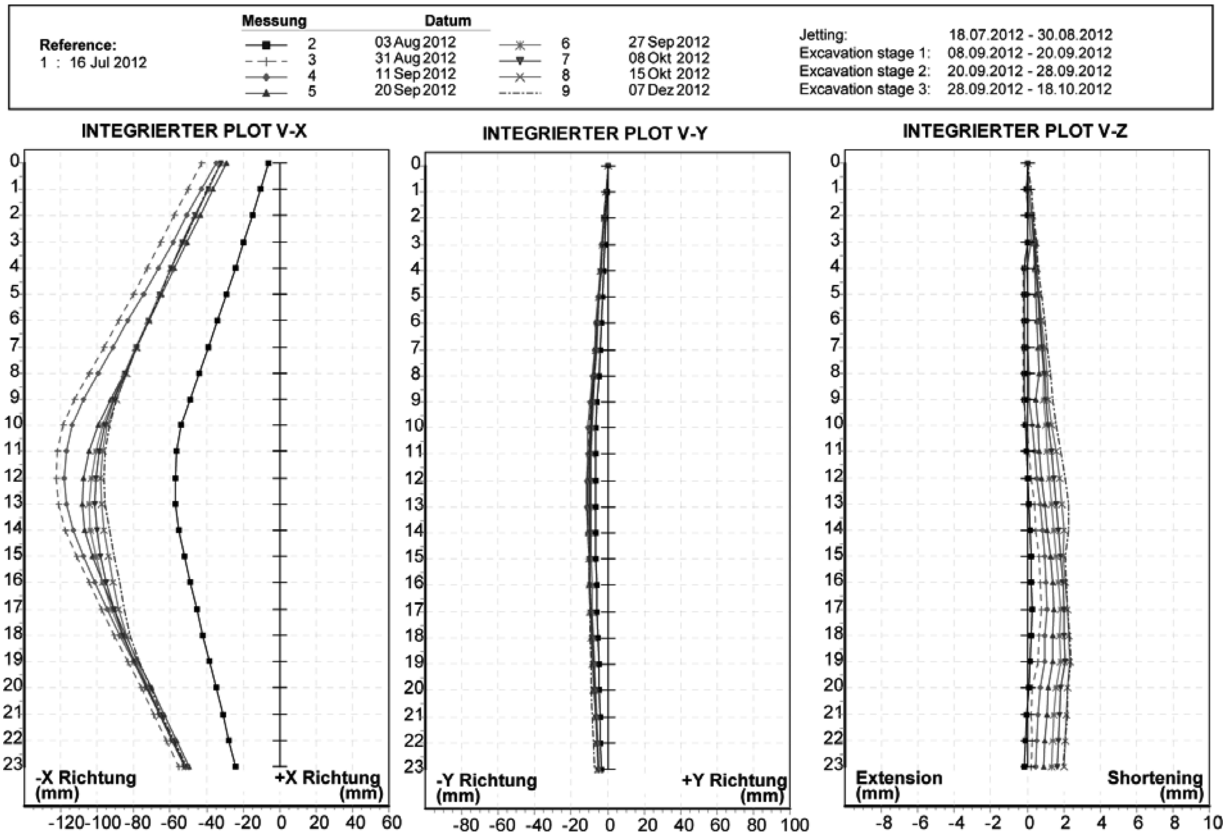

Figure 8 Integrated TRIVEC Measurements in the retaining wall (outer side); (a) horizontal displacements rectangular to the wall; (b) horizontal displacements in wall direction; (c) cumulated strain

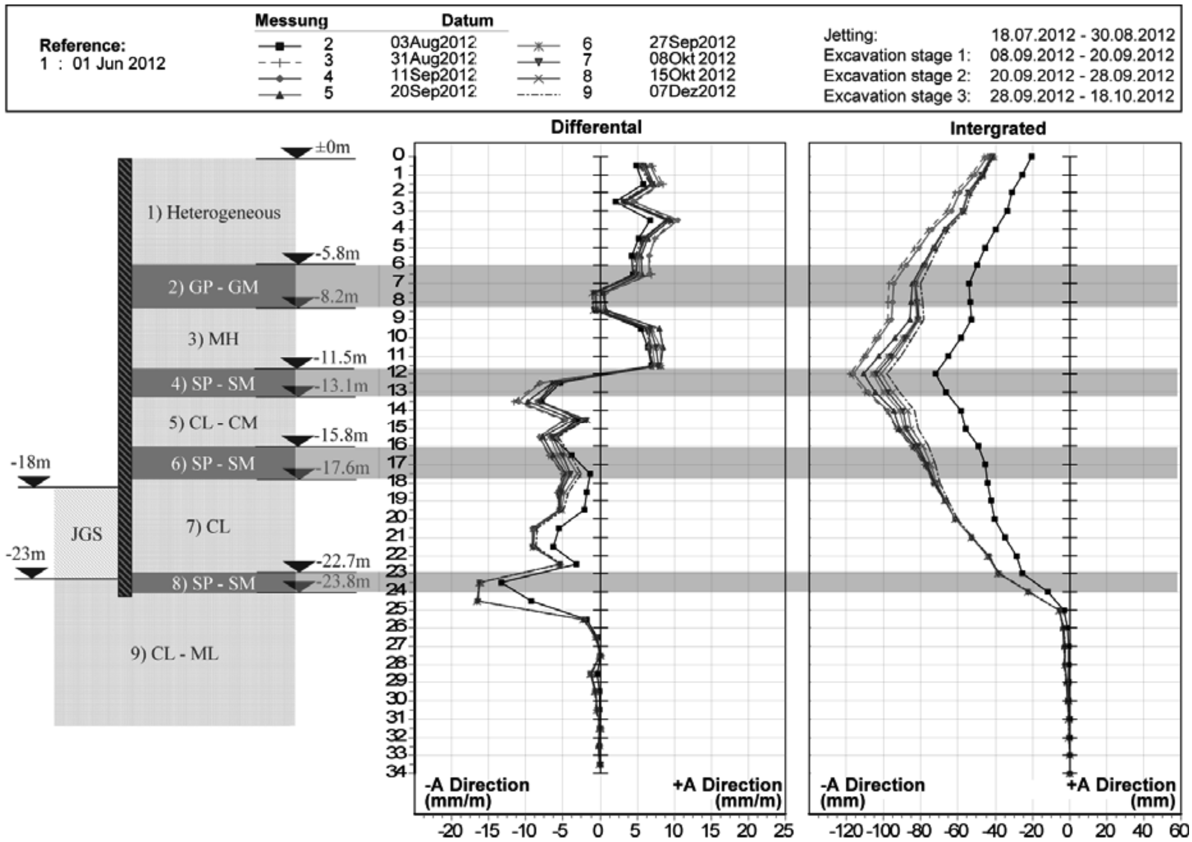

Figure 9 **Inclinometers measurements 1.5 m beside the shaft show displacements in similar order of magnitude. Differential displacements correspond with the soil stiffness**

Figure 10 **Additional struts on the left and the right side of the originally planned single strut, the new struts were also instrumented with strain gages**

4 Forensic analysis

The design of the wall was carried out with a conventional two dimensional truss analysis. The design forces taking into account the partial safety factors according to the Swiss standards are shown in

Figure 11. During the excavation the measured forces reached the design levels, therefore additional struts were installed to prevent failure (Figure 12).

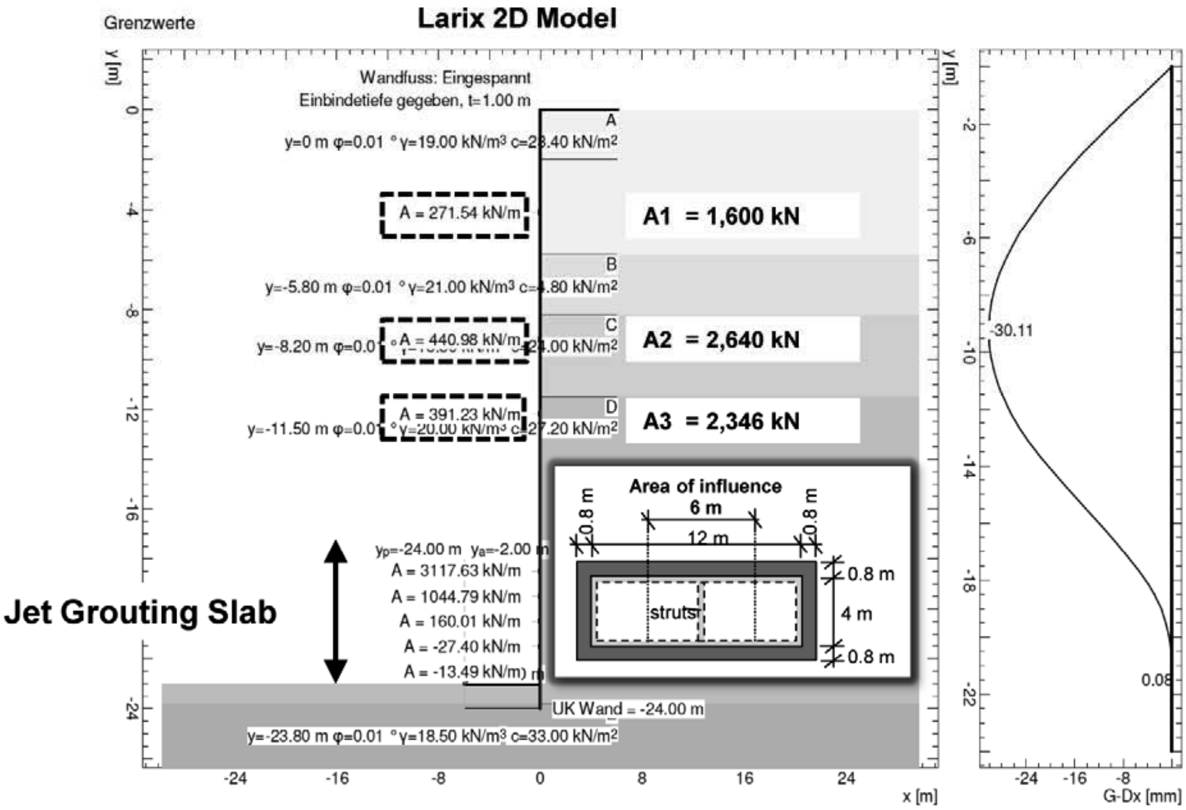

Figure 11 Design strut forces as determined by truss analysis

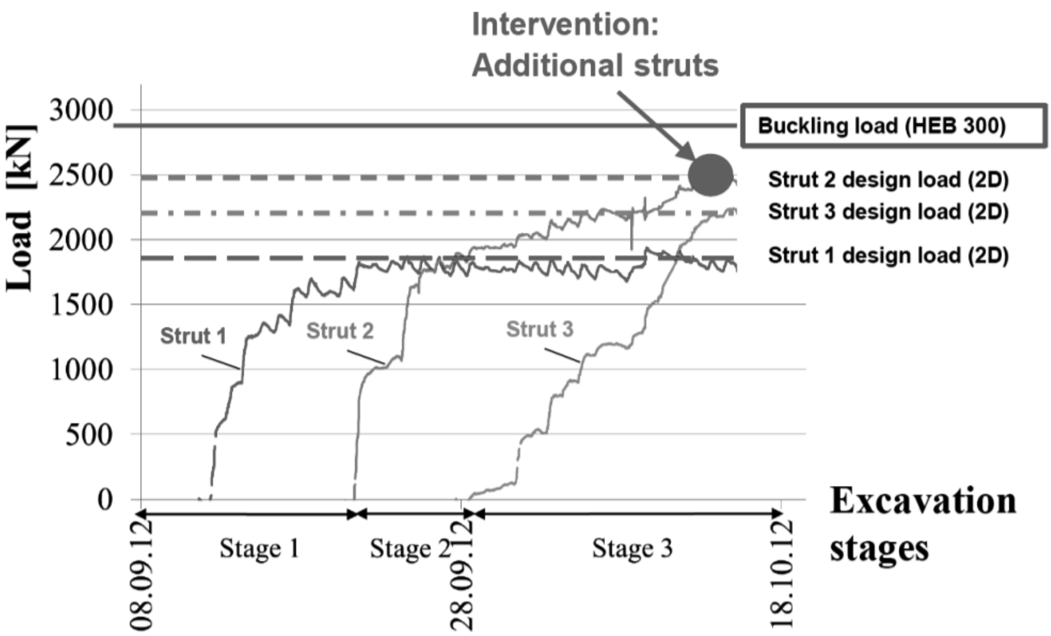

Figure 12 Measured and design forces of the struts during excavation

The loads in the struts reached the buckling levels of single struts, but no failure occurred because additional struts were added.

The high strut loads are mainly due to construction of the jet grouting columns in a very narrow environment and in difficult soils, sandy clay (Rabaiotti et al. 2015). The injected grout inflated the shaft with an additional volume (Figure 13).

In the process of the back calculation, the sensitivity of the wall displacements to changes in soil properties and jet grouting pressure was studied. Generally, the wall and soil displacements appeared to be sensitive to changes in the jet grouting equivalent pressure and its area of application. This is due to the yielding of the soil and structure. The yielding starts when jet grouting equivalent pressure had reached approximately 200 to 250 kPa (Figure 14). The analysis of the TRIVEC measurements supports this theory by comparing the elastic deformation with the measured deformation (due to inclination) and the analytic back-calculation of the bending due the strain in the parallel measurement tubes based on the ideal elastic theory by Kovári et al. (1982) (Figure 15).

During construction the struts prevented the elastic rebound of the shaft taking larger forces than those predicted with conventional earth pressure theories (Figure 11). The pre-stressing of the soil due to the jet grouting loaded the struts after excavation (Figure 16). Pre-stressing of the soil, which did not dissipate until after the excavation, was also measured by the inclinodeformeter device installed outside the shaft (Schwager 2013).

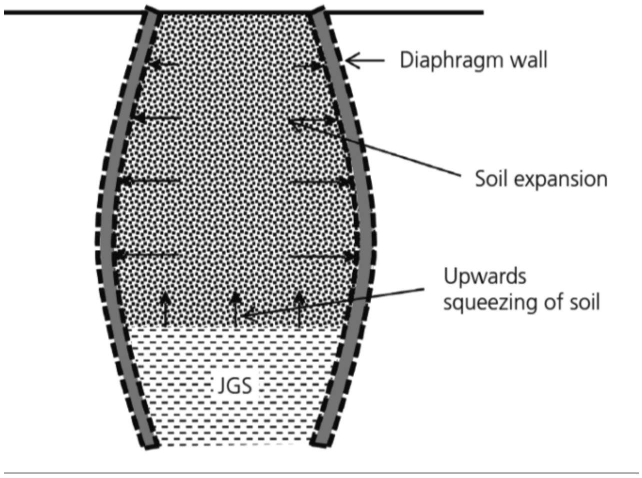

Figure 13 Expansion of the volume inside the shaft due to the insertion of the jet grout columns (after Rabaiotti et al. 2015)

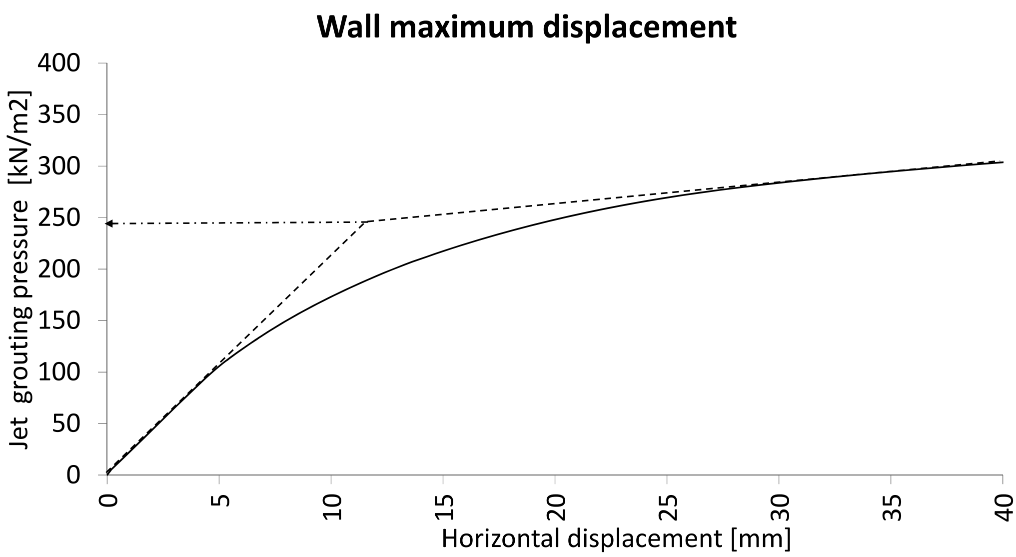

Figure 14 Yielding of the retaining wall starts at jetting pressures exceeding 200 to 250 kN/m^2

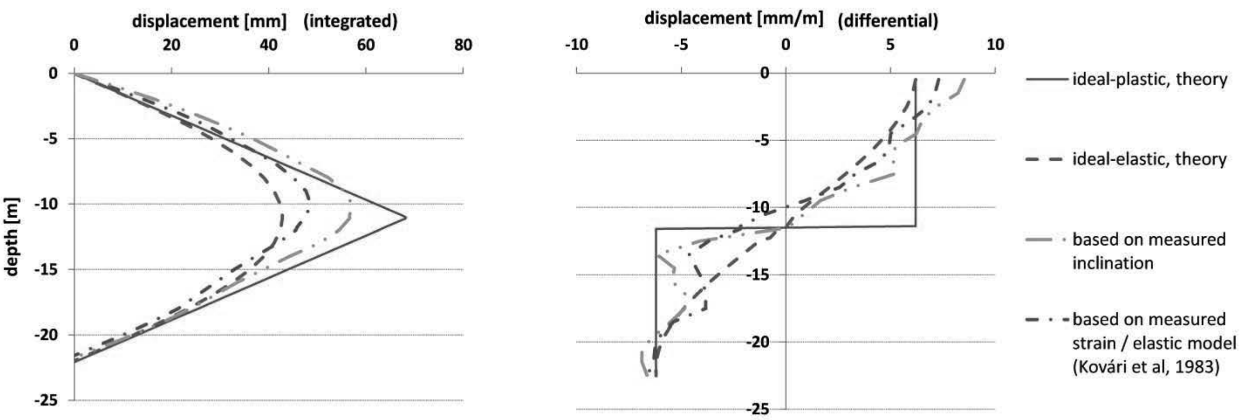

Figure 15 Wall displacements in theory and as measured (after final excavation, head displacement set to zero). TRIVEC measurements show the yielding of the retaining wall

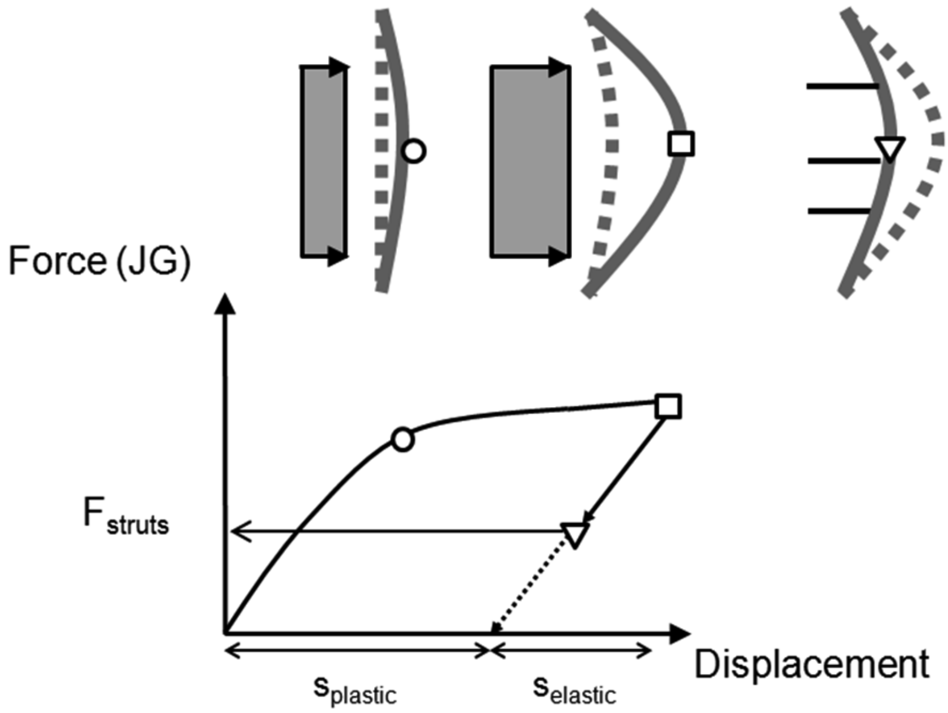

Figure 16 Mechanism illustrating the deformation, elastic rebound of the struts and increased forces in the struts, in addition to those due to earth pressure. The grey beam shows the wall, the grey rectangle the pressure induced by the jet grouting and volume increase inside the shaft

5 Summary and conclusion

The construction techniques for a planned large underground project in the city of Lucerne (Switzerland) have been tested by excavating, building and instrumenting a deep test shaft, preceded by many in situ and laboratory tests to characterise the soil properties. The installed TRIVEC and inclinometer devices showed large deformation of the wall during and after the jet grouting. During excavation, the strut forces were reaching the limits of the steel profiles and further struts were installed to prevent catastrophic collapse.

An extensive analysis has been carried out to find the reasons for the higher than expected strut forces measured during the braced excavation. The analysis was supported by a large amount of data (including soil displacements, soil pressures and strut forces) measured during the excavation.

The results of the analysis showed that jet grouting in soft soils can pre-stress soil-embedded structures such as diaphragm walls. TRIVEC measurements indicate that the structure sustained plastic deformation. These additional stresses have to be supported by the retaining system once material inside the walls is excavated. This overloading could be avoided by using appropriate jet grouting techniques allowing for elastic rebound before installing the retaining system; but the risk of failure should not be underestimated. The forces on struts can exceed the design loads and overload the retaining wall system.

The application of the observational method with instrumentation, alarming and possible countermeasures was found to be essential when jet grouting works are carried out close to sensitive structures.

Acknowledgement

We acknowledge the Swiss Federal Railways and the Canton Lucerne for approving and supporting the realisation of the test shaft as an important component of the design process for the construction of the future the structures of the future underground station.

References

Amstad, C, Köppel, J, Kovári, K 1987, 'TRIVEC-measurements in geotechnical engineering', in S Sakurai (ed.), *Proceedings of the 2nd International Symposium on Field Measurements in Geomechanics,* AA Balkema, Brookfield, VT, pp. 17-32.

European Standard 2007, *EN 1997-2:2007 Eurocode 7: Geotechnical design – Part 2: Ground investigation and testing*, European Committee for Standardization (CEN), Brussels.

Frodl, H & Naterop, D 2007, 'TRIVEC and Sliding micrometer: fully digital instruments for geotechnical displacement and deformation measurement', in J DiMaggio & P Osborn (eds*), Proceedings of the Seventh International Symposium on Field Measurements in Geomechanics,* American Society of Civil Engineers, Reston, VA, pp. 1-12.

IG TiBLU 2013, 'Geotechnische Vorversuche – Dokumentation der Ergebnisse', IG TiBLU, report no. B 5018-016, 1222 p., internal report.

Kovári, K & Amstad, C 1982, 'A new method of measuring deformations in diaphragm walls and piles', *Geotechnique*, vol. 32, no. 4, pp. 402-406.

Peck, RB 1969, 'Advantages and limitations of the observational method in applied soil mechanics', *Geotechnique*, vol. 19, no. 2, pp. 171-187.

Rabaiotti, C, Malecki, C, Amstad, M & Puzrin, M 2015, Pre-stressing of soil and structures due to jet grouting, http://www.icevirtuallibrary.com/content/article/10.1680/geng.14.00112.

Schwager, MV 2013, 'Development, analysis and applications of an inclinodeformeter device for earth pressure measurements' *PhD thesis*, ETH Zürich.