Deformation Monitoring and Monitoring Data Management at the Metro Project Cityringen Copenhagen

K. Chmelina, K. Rabensteiner, A. Charalambides
Geodata Group, Hans Kudlichstraße 28, A-8700 Leoben, Austria

M. Amrhein
ANGERMEIER INGENIEURE GmbH, i-PARK Klingholz 16, D-97232 Giebelstadt, Germany

Abstract. At the currently running metro project Cityringen in Copenhagen (DK) a huge geotechnical monitoring programme has been designed and implemented. It consists of both automatic and manual readings stemming from numerous and various different types of geotechnical and geodetic sensors and measurement systems. All monitoring data is acquired and transferred to a central information system where it is stored, further processed, visualized and analyzed. Data collection and check, sensor control, alarming and reporting are carried out by automatic services provided by the information system. This paper informs on the project, its geotechnical monitoring programme, the used information system, how the related data management is implemented and shows some selected monitoring examples. Finally, the paper lists the main monitoring challenges and highlights recent research activities aiming to further improve monitoring and data management in urban tunnel projects.

Keywords. 3D displacement monitoring, automated total station, alarming, reporting, tunnel information system, tunnel monitoring, tunnel data management

1 The Metro Project Cityringen

Cityringen (Figure 1) will be a completely new, fully automatic, driverless metro ring line expected to open in 2019. The ring line will be 15.5 km long and is situated under downtown Copenhagen, the ‘bridge quarters’ and Frederiksberg. It will serve major areas of the city of Copenhagen including the Danish Parliament, Central Station, City Hall, existing major S-train and metro stations and national monuments. The line will have transfer facilities to the existing metro stations at Kongens Nytorv and Frederiksberg. Furthermore, there will be transfer facilities to the existing regional and commuter railway station at København main station, at Østerport station and at Nørrebro station. In total, the ring line will consist of 17 new underground stations on island platforms.

The line is to have 32 km twin tubes bored by TBMs, 17 topdown station structures, each 64 m long and 20-22 m wide, and also several emergency and ventilation shafts, cross-over caverns and stub tunnels for future extensions. Major civil works started 2011. Up to four Kawasaki-Seli 5.78 m EPBMs (named Eva, Minerva, Nora and Tria) currently run, partly at the same time, at depths of 15-35 m. Geology along the alignment comprises glacial moraine on limestone, and the north west of the route features some sand beds. The client and owner Metroselskabet awarded the construction contract to the Salini-led JV Copenhagen Metro Team (CMT) of Salini-Impregilo, SELI and Tecnimont.

The double breakthrough of the tunnel boring machines Eva and Minerva into the new Central Station on January 29, 2015 marked a major milestone of the project where 9 km of the total 32 km of running tunnels had been built.

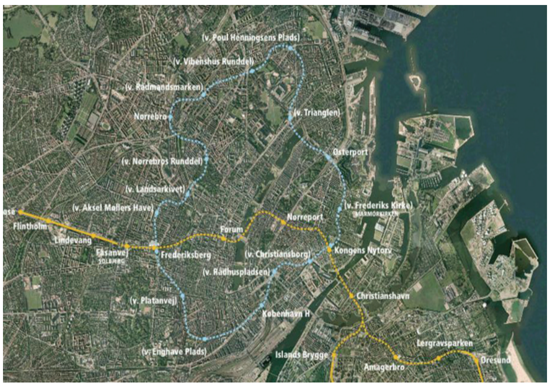

Fig. 1 Alignment of the new city circle line Cityringen in Copenhagen (Denmark).

2 Geotechnical Monitoring

The geotechnical monitoring programme of the project has been designed to

- record the impact of construction works on the existing structures,
- provide an early warning of critical developments,
- allow for the prediction of developments,
- trigger emergency procedures in order to implement mitigation measures,
- contribute to the construction methods optimization,
- verify/confirm the design assumptions and design models and to
- provide suitable data for back analysis purposes.

To meet the requirements the programme includes surface and in-ground monitoring measurements taken with latest-generation monitoring systems and sensors, both manually and automatically. Special focus has been put to groundwater monitoring and the monitoring of deformations on all existing surface structures (buildings, roads) in the influence zone of the construction along the whole inner city tunnel alignment. In addition, the monitoring of deformations of stations, shafts, mined and bored tunnels, environmental parameters, construction progress, TBM operating parameters and vertical ground movements at grouting areas must be performed.

To enable the management of monitoring data and to provide the required services, a central information system (Kronos of Geodata) has been installed. According to specification all monitoring data must be available in the system within six hours after the measurement for all manually read instruments. For automatically read instruments, the data must be online-transferred immediately.

Construction progress must be updated at the completion of each ring/round of excavation for tunnels/caverns and daily for stations and cut and cover structures.

For safety reasons a server mirroring system has been installed consisting of two database servers, a principal server at the contractor's office and a mirror server at a different and secret location that are both able to immediately replace each other in case of a server breakdown. Currently, about 140 users are given access to the data of the project.

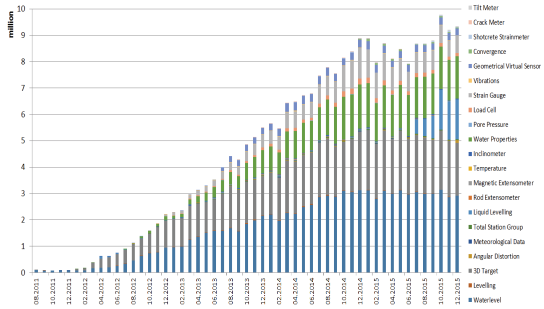

Fig. 2 Data records processed per month and type of monitoring sensor.

A particular challenge is to handle the seamless import of data records stemming from about 20,000 data producers (= manual and automatic measurement systems and sensors). They produce measuring data records independently from each other, at different and changing measuring times and frequencies and in heterogeneous data formats. All these data has to be acquired, checked and imported into the system's database by an automatic data collection service.

Figure 2 lists the data producers relevant for deformation monitoring and their monthly produced monitoring data records from August 2011 to Dec. 2015. In Dec. 2015 more than nine million such records have been produced adding up to a total sum of about 250 million. At peak times up to 15,000 records are produced and imported to the information system per hour. The vast majority is produced by 556 water level sensors (piezometers in open standpipes) and more than 100 Leica automated total stations (Figure 3) that measure about 4,500 prisms mounted on building facades etc.

Fig. 3 Automated total station on building facade.

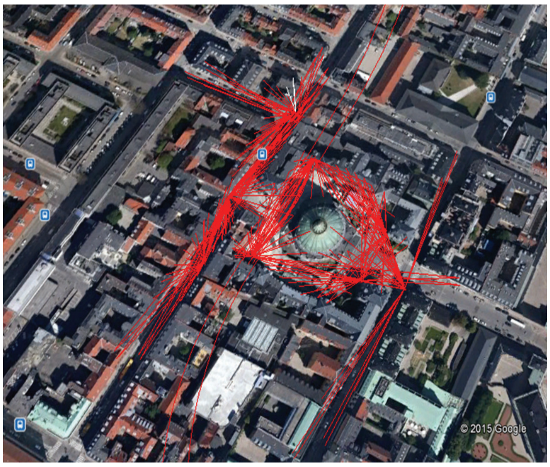

Fig. 4 Monitoring of a church and adjacent buildings in one monitoring network.

2.1 Automated Total Stations

Figure 4 shows the lines of sight of a local monitoring network consisting of eight interconnected total stations that measure the 3D displacements of a church, a group of adjacent buildings and a shaft. Figure 5 shows the overall Cityringen project overview and the monitoring area and points from fig. 4 in the user interface of the information system. As a minimum, every building within the monitoring zone is equipped with six prisms at every third floor.

Both the front and rear face of a building are monitored. Beside all existing surface structures, all metro stations under construction, shafts and existing tunnels located in the influence zone have been equipped with prisms.

The standard measurement interval is two hours. In special situations the measuring frequency is reduced to one hour or 30 minutes, depending on the particular number of points to be measured. In critical cases, e.g. when a TBM crosses existing tunnel tubes, the measurement interval is even reduced to 90 seconds in order to be able to give constant feedback regarding the 3D displacements during the crossing. The operated automated total stations are therefore centrally controlled and have performed more than 70 million measurements until Dec. 2015. Their robustness, almost noiseless operation, little maintenance effort and the high precision and quality of the results give the technology a major role in the geotechnical monitoring program.

2.2 In-place Inclinometers

Another monitoring method that turned out highly efficient in the project is the use of in-place inclinometers (IPIs) to monitor horizontal displacements of diaphragm walls and secant pile walls during shaft excavation. Several deep shafts (e.g. for TBM launching chambers) have been

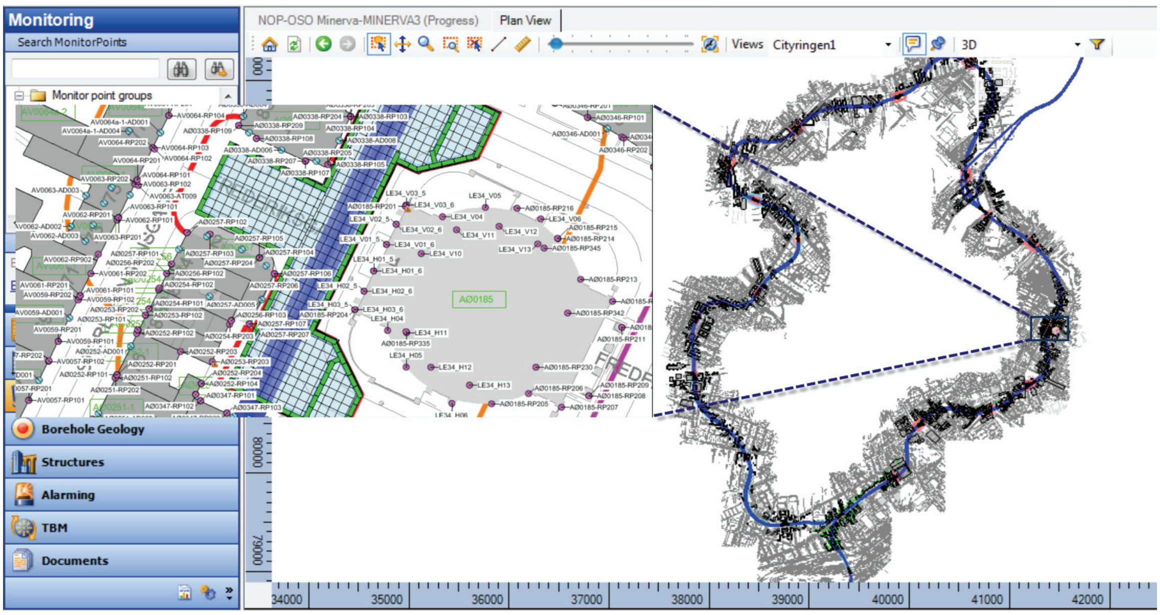

Fig. 5 Project overview and a particular monitoring area displayed by the information system.

constructed by help of diaphragm walls, often in close proximity to existing structure. Shaft instrumentation is based on special inclinometer casings that have been installed directly into the diaphragm wall at defined positions (fig. 7). The casings range from the top of the wall down to about 10 m below the bottom of the shaft to a depth assumed stable. In a first phase (before start of shaft excavation) daily measurements with a manual inclinometer probe have been carried out. Later, during shaft excavation, the probe has been replaced by in-place inclinometers (fig. 6) providing deformation curves automatically every few hours and transferring the data online to the central information system. Each system consists of a series of two-axis inclinometer sensors, each based on a high accuracy MEMS accelerometer, that are, chain-like, connected to each other. Each sensor provides the tilt with respect to gravity with an accuracy of ± 0.05 mm/m.
Fig. 8 views deformation curves of one such system that have been obtained during an eight months excavation phase. The diagram indicates significant horizontal displacements of up to 23 mm oriented towards the shaft center (perpendicular to the wall) occurring at a depth of 16 m that have been caused by excavation activities.

Fig. 6 In-place inclinometer and casing.

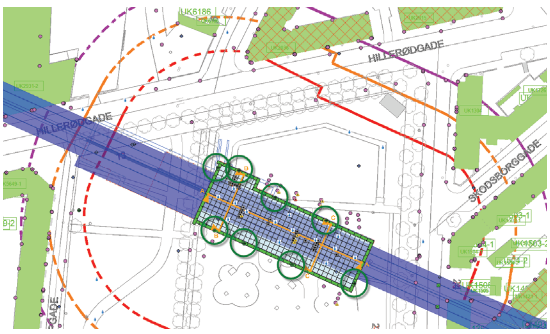

Fig. 7 Positions of eight in-place inclinometers in the diaphragm wall of a shaft.

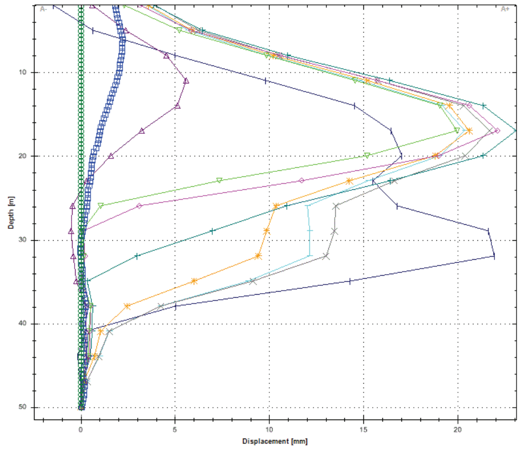

Fig. 8 Horizontal displacements of diaphragm wall measured by in-place inclinometer.

3 Data Management and Data Services

Beside the monitoring data transferred from the 20 different types of automatic sensors and from the many different data uploaders (the data of manual measurements such as precise levelling are uploaded manually by the survey teams) the following further data is collected:

- TBM machine data (e.g. TBM operating parameters such as thrust, ground penetration, actual machine status),
- construction progress data (e.g. the current station of TBMs and tunnel faces, the current excavation depth of shafts, the currently installed piles),
- building survey data (e.g. the location, type, condition and risk category of existing buildings and foundations),
- geotechnical/(hydro)geological data (e.g. the logs of boreholes, in-situ and laboratory tests, the data of groundwater monitoring),
- environmental data (e.g. meteorological data, noise and vibration),
- ground treatment data (e.g. drilling parameters, advance rates, injecting data) and
- design data (e.g. drawings, threshold values for monitored parameters)

To support monitoring data interpretation and to assure a safe ongoing of works the information system provides several automatic services:

A data collection service controls the automatic transfer of data from the many manual data uploaders by detecting if a new data file is present, checking its correctness (plausibility of content, format compatibility) and importing its data to the system's database.
An outlier detection service then automatically checks for outliers in monitoring data by computing a local regression analysis. For each new measurement to be checked the algorithm takes some measurements before the inspected measurement and calculates the trend. If the inspected value is too far away from the trend, it is marked as a potential outlier. The outlier removal algorithm then repeats this process as soon as further measurements are available. If the algorithm later on confirms the measurement as an outlier it is deactivated together with the already raised alarm. The relatively simple feature has turned out highly efficient to remove unnecessary alarms.

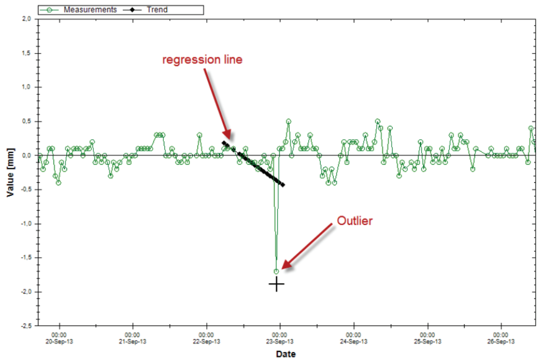

Fig. 9 Principle of implemented outlier detection by regression analysis.

An alarming service allows for configuring complex alarming plans consisting of alarming levels, rules, recipients, actions etc. making sure that critical developments, missing or erroneous monitoring data, non-functioning monitoring systems etc. are recognized immediately.
Finally, a reporting service is in place allowing for the configuration and automatic generation and distribution of monitoring reports at specified times.

4 Case Study – Compensation Grouting

The Figures 10 to 12 illustrate a case where the implemented information system and its services have played an important role in decision making.

Fig. 10 Monitored building next to a shaft under construction as shown in the user interface of the information system.

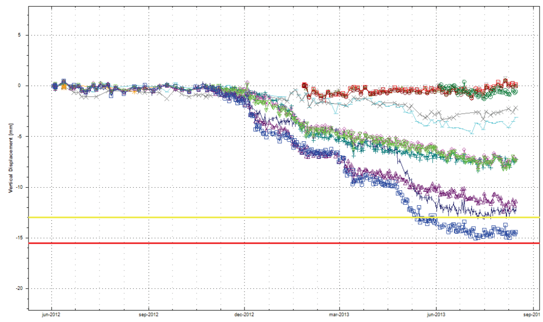

Fig. 11 Settlements of levelling marks on the building exceed first alarm level (yellow line at -13 mm).

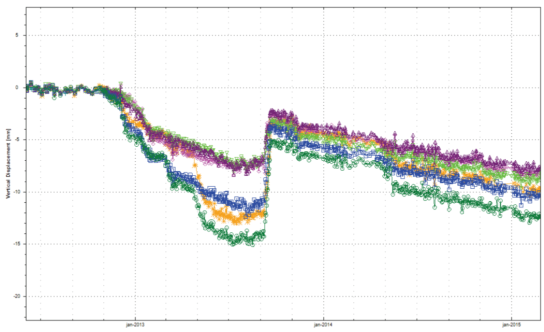

Fig. 12 Settlements of levelling marks on the building after compensation grouting applied to the building.

During excavation of a shaft (fig. 10) one of the buildings nearby started to develop settlements soon reaching the first alarm level specified by design (fig. 11). The information system warned the responsible experts and compensation grouting was decided as a mitigation measure as well as additional monitoring to be performed. During and after grouting settlement monitoring continued and proved the success of the measure (fig. 12). Periodic reporting accompanied the process ensuring that all experts were informed at all time.

4 Conclusion and R&D Activities

For monitoring and data management in the Cityringen project the main challenges so far have been:

- at the beginning of the project, to handle the number of different disciplines and subcontractors that are required to import their data into the system. Therefore, work procedures and import routines for different types of data had to be developed in order to allow the seamless incorporation of all the data into the database. This required an additional, underestimated effort for developing all the needed data interfaces.
- to manage the acquisition and check of the huge and quickly growing monitoring data amounts produced by heterogeneous types of (mostly automatic) monitoring sensors in an efficient way. In this respect, it had to be developed algorithms that:
  - inform the maintenance teams when sensors or systems are not functioning properly and
  - filter obviously erroneous measurements in order to maintain the alarms generated in a manageable level.
- to manage the natural dynamics of the project, for example the installation of new sensors, the removal of sensors and the change of sensor locations.
- to provide meaningful output in form of useful numeric and graphic representations suitable for an integrated further data analysis.
- to meet and support adequately the project's early warning and reporting requirements by providing efficient automatic alarming and reporting services.

Deformation monitoring in urban tunnel projects will further face rapidly increasing data amounts from growing numbers of automatic sensors. Measuring frequencies will further rise and data transfer will more and more be done by wireless technologies such as WLAN, ZigBee, Bluetooth, GSM/LTE, LowPan etc. leading to a further increase of urban data traffic. Due to these developments new problems arise, for example dealing with Internet security (cyber attacks), bandwith limitations and network connection quality within telecommunication networks, power supply and energy consumption of measuring systems.
Current research activities (e.g. in the Eureka project ASUA, http://asua.netcad.com) therefore focus on:

- Wireless Sensor Networks (WSNs) to ensure optimal and energy-efficient routing of monitoring data from the sensors to the end-users.
- Embedded Systems for intelligent local data processing and measuring system control. The aim is to have intelligent sensor nodes, each able to control a certain monitoring task (e.g. the monitoring of a whole shaft) autonomously and locally, even without connection to a central system. The node shall be able to understand the monitoring task and process and transmit all relevant results. Only the transmission of a reduced data amount to the central system shall then be needed, data traffic thus be reduced.
- Energy Harvesting (solar, wind). The energy consumption of monitoring systems has reached the ultra-low level. However, for battery-powered systems the possible duration of operation is a key factor in maintenance so that energy harvesting techniques are of great interest.
- Cloud- and Web Services. Tunnel projects already utilize and benefit from sophisticated applications (e.g. FE-simulations) and project-extern data and knowledge. In future these applications and data shall be accessed online via the Internet.
- Virtual Reality and 3D visualisation. Monitoring data interpretation requires meaningful graphics to extract the relevant information. New 3D visualization techniques involving Virtual Reality and interactivity concepts are currently under development.

Acknowledgement

The above mentioned research activities are partly funded by EUREKA Celtic Plus and the Austrian research promotion agency FFG.