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ORIGINAL PAPER

A Tunnel Information System for the Management and Utilization of Geo-Engineering Data in Urban Tunnel Projects

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Abstract The contribution presents the current state and latest capabilities of information technology (particularly tunnel information systems) used for urban tunnel projects. In detail, it informs on the system architecture and the latest data management, monitoring, alarming and reporting functions and services of the tunnel information system KRONOS of Geodata. To assess the systems' benefits, installation examples and experiences from four currently running, urban European tunnelling projects are described. Finally, the most recent and promising R&D activities in this field are emphasized.

Keywords Monitoring · Alarming · Reporting · Tunnel information system · Urban Tunnelling

1 Introduction

The first IT-tools that already may be called *tunnel information systems* were developed and introduced in the early years of 2000. In their beginnings, they constituted proprietary self-made software and database applications developed to meet the special requirements of a single tunnel project. Soon they emerged to commercially available, comprehensive software products offering advanced functions and services that are useful for any kind of tunnel. Today, an increasing number of professionally developed and practically proved products exist on the market and can be obtained from several different vendors (e.g. KRONOS by Geodata, TUNNEL:Monitor by iC/IGT/3G, TISSY®GKSPro by GGB, 2doc by Pöyry, IRIS by ITC engineering, GEOSCOPE by Soldata). These products offer a large variety of data management options and application modules that can be individually selected, licensed and configured to meet given project requirements. Nowadays, almost all urban tunnel construction sites (especially all metro sites) have one or even more of these IT tools installed. In all these installations, the two most essential system functions are:

- to efficiently manage (input/import, store/archive, edit, output/export) the increasing volumes and different kinds of data (e.g. design data, monitoring data, geological data, machine data) produced on tunnel sites in one single data management system and
- to provide access to these data to all parties and engineers involved in the tunnel project at all time, at the click of a button and from everywhere.

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As this is not enough, most systems already also offer various further functions and services, for example allowing for

- connecting to tunnelling machines such as TBMs and road headers for online machine data acquisition, machine control and machine guidance,
- connecting to monitoring sensors and sensor networks for automatic data acquisition and sensor/sensor network control,
- generating sophisticated data visualisations like Virtual Reality visualisations and 3d-animations (Beer 2010; Chmelina 2010; Rabensteiner et al. 2010; Chmelina 2009),
- the automatic execution and surveillance of comprehensive geotechnical monitoring programmes together with all required alarming and reporting procedures (Chmelina 2009),
- risk assessment based on Artificial Intelligence (Chmelina and Grossauer 2010; Chungsik and Jae-Hoon 2003) and
- connecting to the internet for accessing web services for different purposes like data fusion, data analysis, data quality check, finite element tunnel simulation and prognose, etc.

In what follows, the tunnel information system KRONOS of Geodata shall be described more closely. Initially, its concept and first parts were developed in the frame of the biggest ever funded European underground construction research project TUNCONSTRUCT (Beer 2010) between 2006 and 2009. Since then it had been continuously further extended and improved. Currently it is successfully used in numerous European tunnelling projects like Metro Thessaloniki in Greece, Metro Budapest in Hungary, the Copenhagen Cityringen project in Denmark and the Crossrail Project in London, England. The system is particularly strong in supporting urban projects like metro and underground railway lines where critical structures are underpassed and where an advanced and integrated automatic monitoring, alarming and reporting solution is required to guarantee a quick response in case of unexpected events and, thus, a safe, productive and high-quality tunnel construction.

The main intention of the contribution is to provide information on the current state and potential of information technology (particularly tunnel information systems) used in recent tunnel construction projects and on some R&D activities promising new and advanced information technologies in future.

2 Tunnel Information System KRONOS

2.1 System Architecture

Kronos is based on the database technology of the MS SQL Server, the commercial relational model database server produced by Microsoft. The Kronos data model has been designed to cover all relevant data of an underground construction project, be it produced during design, construction or service phase. Figure 1 depicts the overall covered data categories on top of the *Kronos DBMS* (Data Base Management System) and the two available user interfaces, the *Kronos Client* (= a local .NET Windows application software) and *Kronos Web* (= a web-browser based access to the Kronos DBMS).

2.2 System User Interfaces

Kronos Web basically allows for download of data in different data formats and for data display in form of conventional 2-d diagrams. To access Kronos Web only a standard PC-based web-browser (e.g. the MS Internet Explorer, Fig. 2) or a smartphone (Fig. 3) and (mobile) internet access are needed but no software has to be installed on the local PC or smartphone.

Contrary, the *Kronos Client* is a local MS Windows software application that provides the user with menus and dialogues for all commonly required data management procedures. In addition, the user is supported by GIS-like interactive maps and diverse kinds of data diagrams (Fig. 4). Besides offering all typically needed functions for data manipulation (input, output, query, sorting, editing, deleting, visualizing) the monitoring, alarming and reporting functions and associated automatic services can be configured and executed.

The Kronos Client is installed at each user PC and can be connected to the Kronos DBMS either via internet or intranet. In a typical site setup, all engineers working on site are connected via intranet while extern users (e.g. the system administrator) connect via internet by VPN connection.

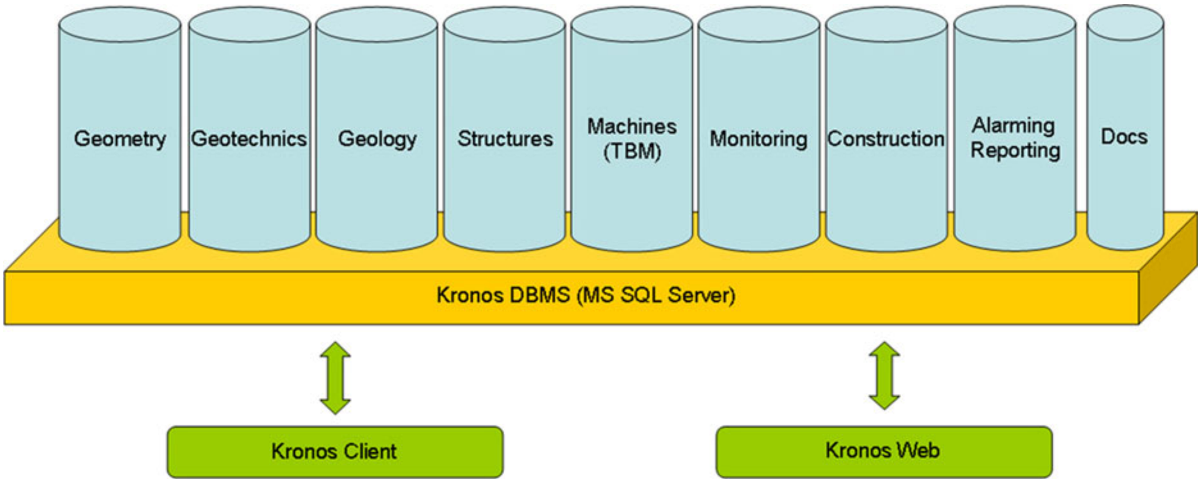

Fig. 1 Kronos system overview including the covered Kronos data categories, the Kronos DBMS and the Kronos user interfaces Kronos Client and Kronos Web

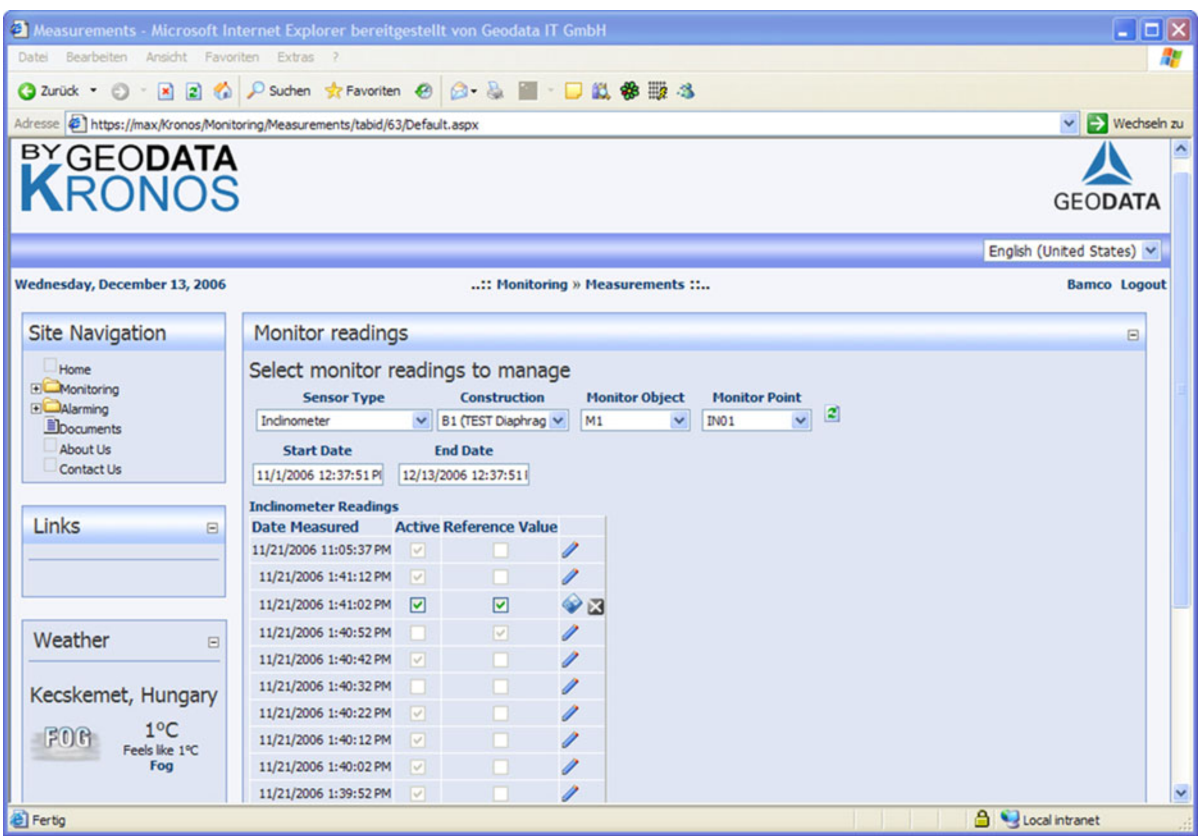

Fig. 2 Kronos Web showing a page for specifying data download options

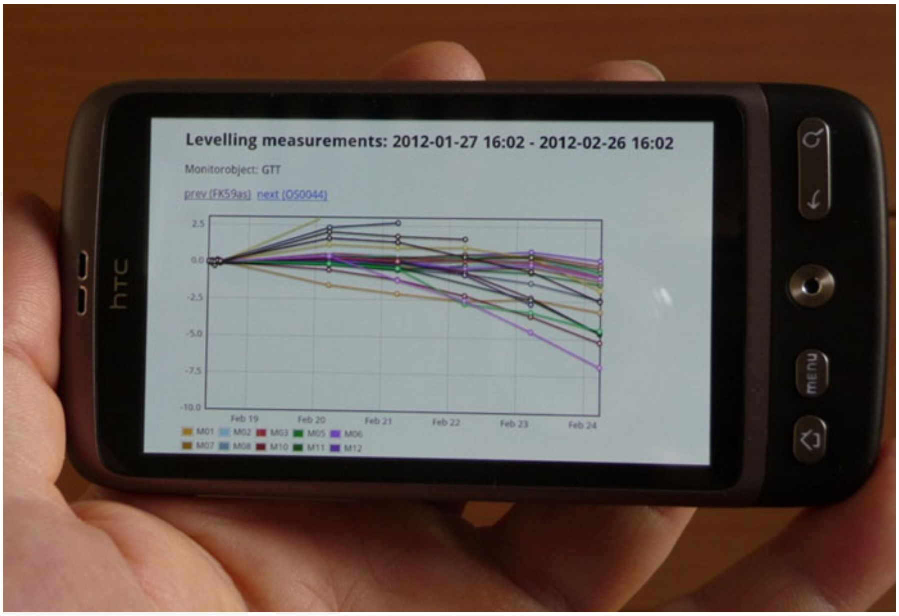

Fig. 3 Kronos Web live displaying monitoring data on a smartphone

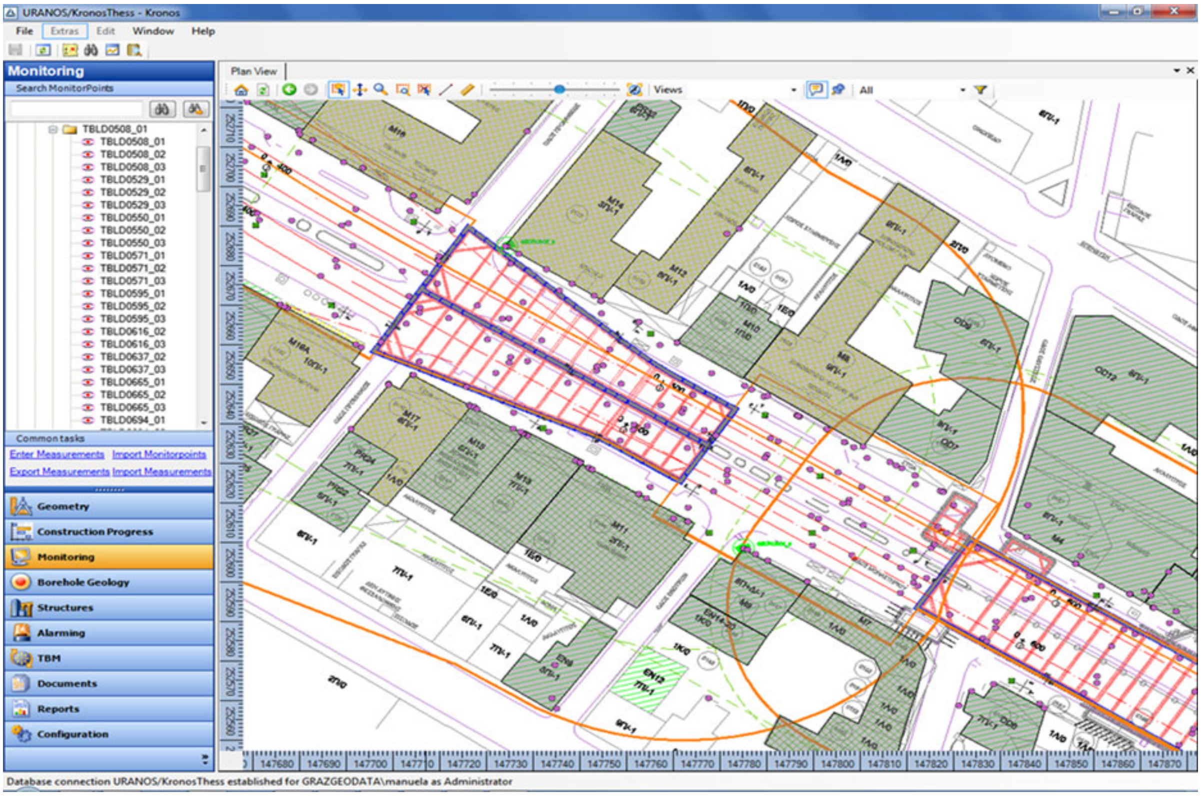

Fig. 4 Kronos Client showing the map of a metro tunnel project with monitoring points, surface buildings, tunnel alignment and construction zones

2.3 System Functions and Services

The *monitoring function* allows designing and executing a comprehensive monitoring programme comprising various different types of monitoring points, sensors and sensor networks and their attribute data such as sensor location in the project coordinate system, sensor configuration (e.g. measuring intervals), etc. During execution a user can define and configure new sensors flexibly and add them to the programme. Depending on the type and capability of the monitoring sensor its measuring data can either be online-transferred or an automatic file-based data transfer can be established that is then run as an automatic Windows Service. After monitoring data is received it is first checked (compatibility of file format, thresholds) and then inserted to the database.

The *alarming function* allows configuring a comprehensive alarm plan comprising alarm rules, alarm levels and alarm notification targets. The associated *alarming service* again runs as a Windows Service and permanently executes the defined alarm rules and, in case, immediately sends alarm messages (typically via SMS and/or e-mail) to the defined alarm notification targets (= alarm receivers).

The alarming service can be run on a local site server but can also be based on a server hosting concept. In this case, the Kronos DBMS is not installed locally but at a remote data management center (e.g. at a sub-contractor). For better information, the occurred alarms can be tracked on live-displays of the Kronos Client (Fig. 5). After sending an alarm, the service also keeps track of the answer from the alarm receiver that has to provide an alarm confirmation text within a certain time in order to make sure that the alarm had been recognized.

The *reporting function* enables the user to design and store problem-oriented monitoring report templates and to configure and start a *reporting service*. The service then produces reports based on these templates (e.g. in pdf-format) automatically out of the database and sends them (e.g. as an Email attachement) to defined report receivers following a reporting time schedule. The service efficiently reduces the work of the tunnel engineers (e.g. the experts responsible for the daily geotechnical interpretation of the

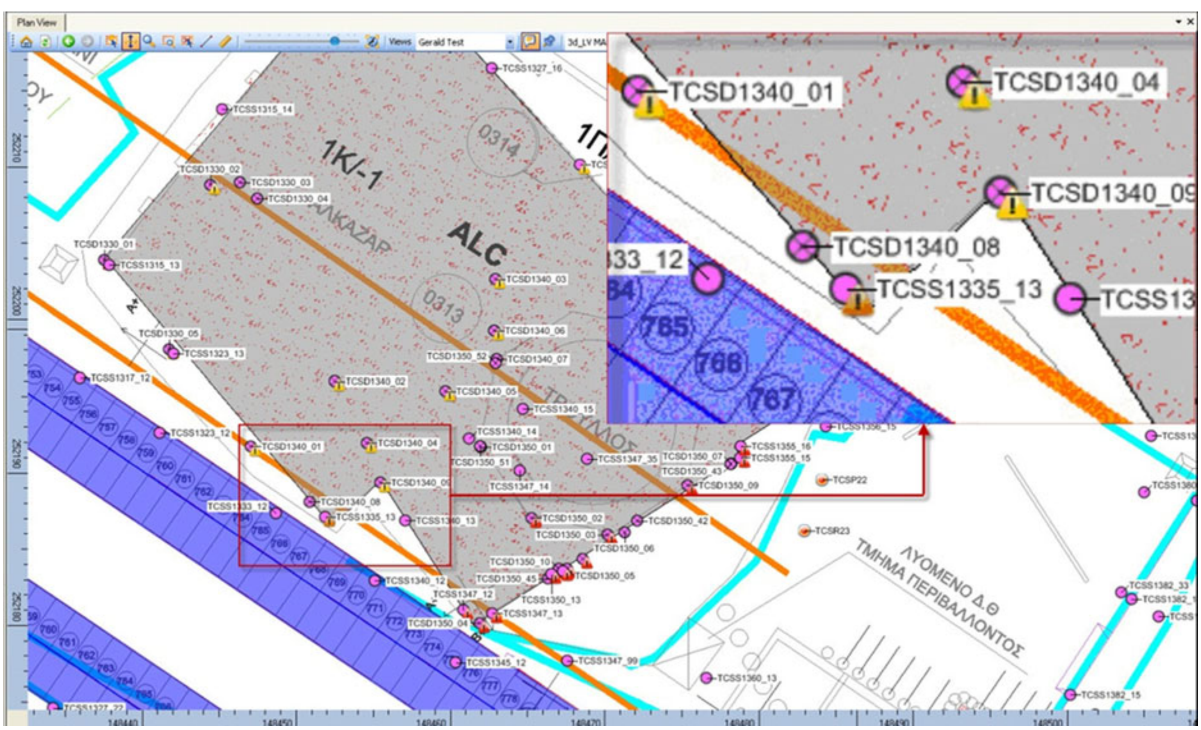

Fig. 5 Kronos Client live-displaying monitoring alarms indicated as *triangular symbols* next to the monitoring points. Different alarm levels are shown in *different colors*

monitoring data) as they no longer have to click around in software menus to search for and display the data they need. The service produces and delivers them automatically without the need of starting any software. The reports, for example, can be provided reliably every morning 08:00 to have the latest monitoring data ready for the daily meeting of the site management.

3 Examples of Installation

3.1 Metro Thessaloniki (Greece)

Valuable experience is gained from operating Kronos at the Metro Thessaloniki project since 2007. The currently built metro network (Fig. 6) comprises 13 center platform stations and 9.5 km of line (with two independent single track tunnels) constructed mostly (7.7 km) by means of two tunnel boring machines.

In the project Kronos is in charge of managing all relevant project data produced. Special focus is given to the monitoring data that stem from more than 13,000 monitoring sensors and automatic measurement systems of different types that are installed along the whole tunnel alignment, underground and on the surface. Their data are all transferred automatically to the Kronos database that is installed locally at the contractor's office. Table 1 lists in detail the current types and numbers of monitoring sensors that are connected to the information system and the number of data records (single sensor readings) stored in the database (status April 2011). In addition Kronos also manages

- the machine data of two running tunnel boring machines (Fig. 7) each producing 390 different parameters (e.g. machine position and orientation, torque, penetration, cylinder pressures, etc.) that are transferred every 10 s to the database,
- the data of all surface structures along the tunnel alignment that might be affected by the ongoing construction activities. So far, 660 buildings have been inspected and documented and the corresponding data (images, static and architectural data, etc.) stored in the database,
- the logging data of about 880 boreholes and

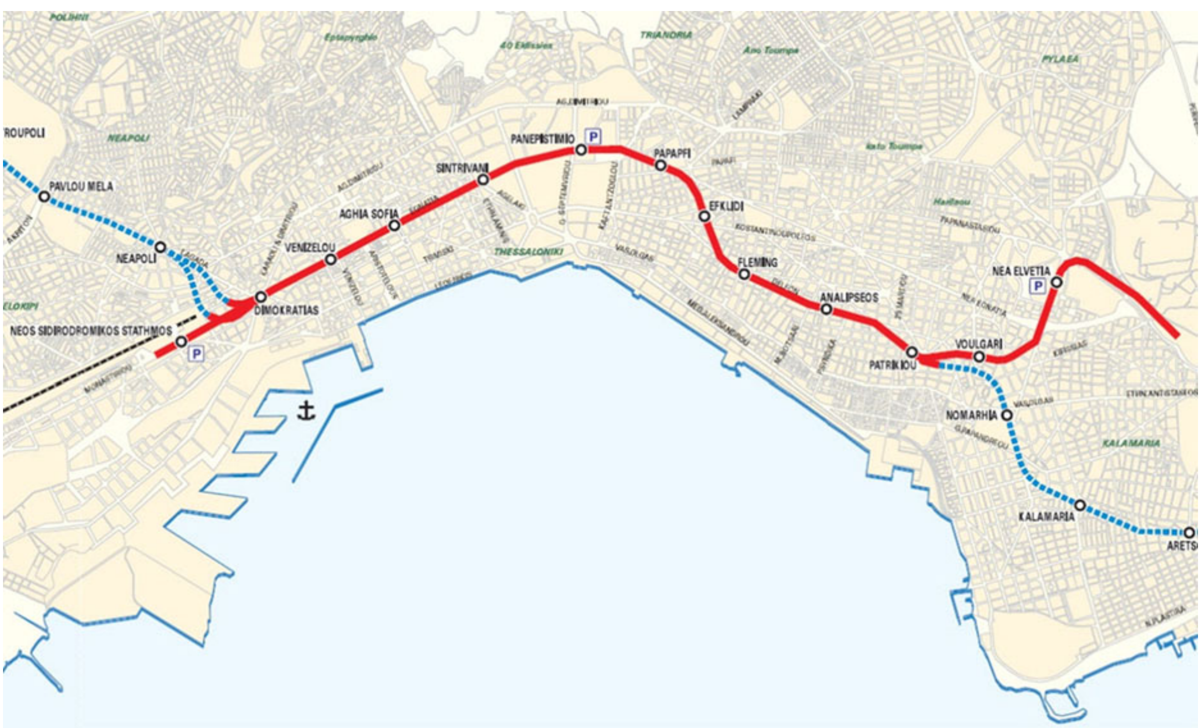

Fig. 6 Alignment of the new 9.5 km Metro Thessaloniki line

Table 1 Type and number of sensors and data sets (sensor readings) stored in the Kronos database of the Metro Thessaloniki project from Oct. 2007 until April 2011

Sensor type	Number of sensors	Number of data sets
3D target	4,128	18,118,705
Angular distortion	644	456,103
Crack meter	36	180,192
Geometrical virtual sensor	2	26
Inclinometer	180	6,561,452
Levelling point	7,985	379,004
Liquid levelling	7	1,326,329
Load cell	59	399,720
Magnetic extensometer	9	5,635,959
Meteorological station	1	44,662
Pore pressure	72	2,508,033
Pressure cell	155	1,628
Rod extensometer	246	5,635,959
Shotcrete strainmeter	155	1,671
Strain gauge	53	502,202
Tilt meter	1	15,094
Water inflow	6	665

- more than 600,000 documents in its document management system (e. g. data processing protocols). The geological, geotechnical and hydrogeological data acquired during design as well as the data obtained from investigations during construction are documented in particular technical reports. These reports (typically PDF or DOC-files produced by geotechnical experts) contain and describe all data typically produced in the course of tunnelling projects (e.g. stratigraphy, lithological characteristics, material parameters, etc.) and are stored in a special section of the document management system.

In 4 ½ years the total database size has grown to 180 GB. Fig. 8 shows this almost linear growth over the whole project duration from October 2007 until April 2011. To illustrate the data transfer volume, Fig. 9 depicts the average number of incoming measurements per ½ hour over a typical one year period in the project. To avoid any data loss or inconveniences caused by server downtimes, all data is automatically replicated to a second identical database that is maintained at a different location and can replace the first immediately and without notice.

In the project the monitoring, alarming and reporting functions and services are used extensively. On site, more than 30 registered users (experts from the client and contractor) work with the Kronos Client on a daily basis. The alarming service executes several hundred alarm rules automatically notifying about 30 different alarm receivers in case.

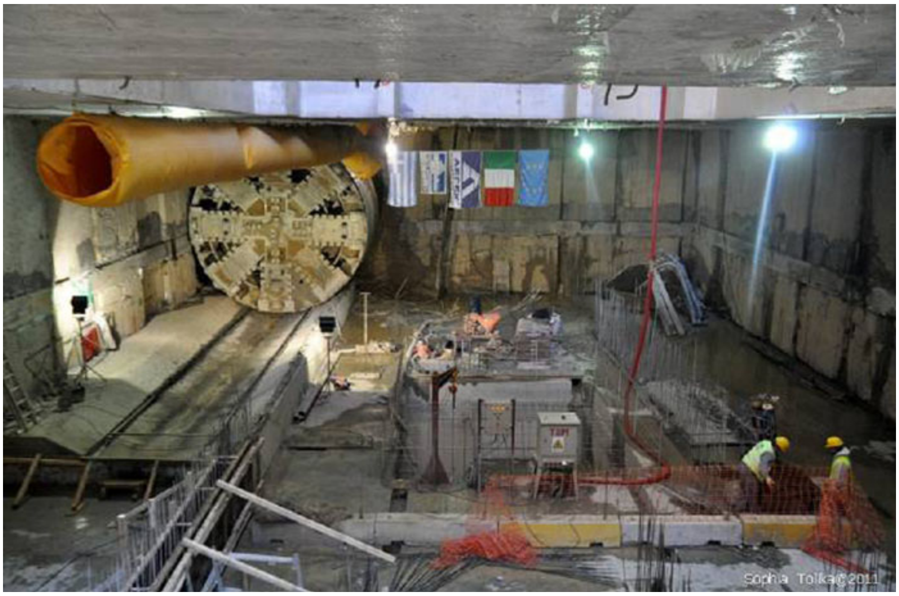

Fig. 7 TBM arriving at a station box at Metro Thessaloniki

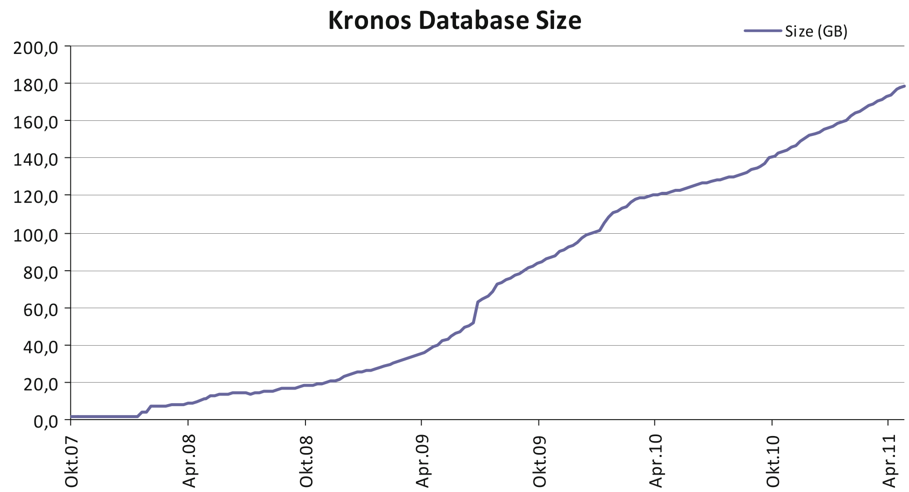

Fig. 8 Development of the Kronos database size in the Metro Thessaloniki project from Oct. 2007 to April 2011

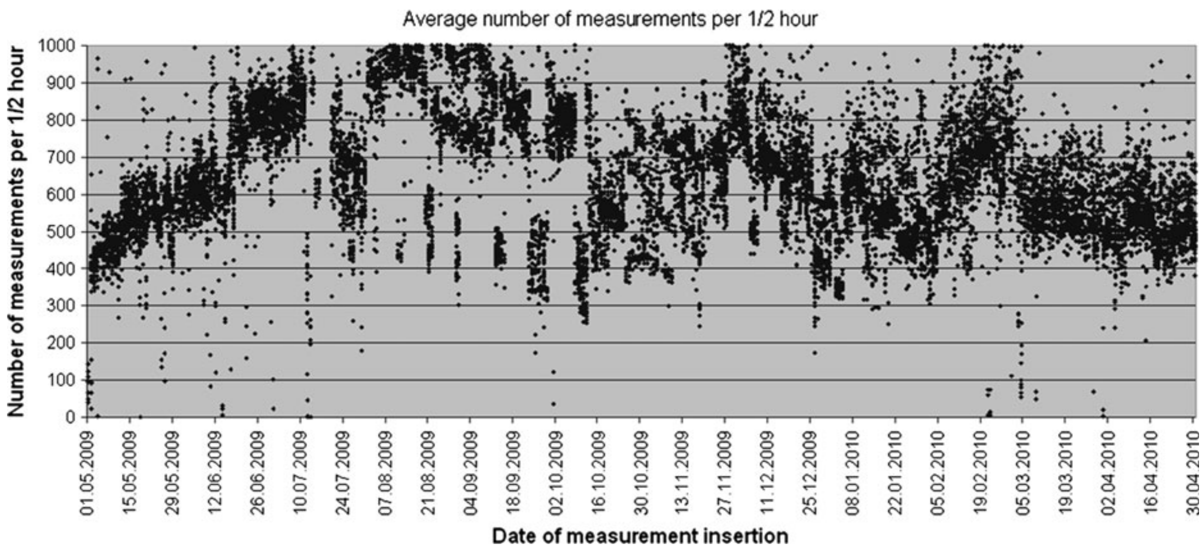

Fig. 9 Average number of incoming measurements per ½ hour in the Metro Thessaloniki project between May 2009 and April 2010

3.2 Metro Budapest (Hungary)

The new line M4 of Metro Budapest (Fig. 10) connects the districts Kelenföld in Buda and Rakospalota in Pest. The line has a length of 7.2 km with 10 stations. The excavation of the two parallel running tunnels was done with 2 Herrenknecht TBMs. Each machine has a total length of 113 m with a cutter head diameter of 6.1 m. Difficult geological conditions on the side of Pest, the underpassing of historical buildings and the crossing of the river Danube with low overburden were big challenges for the engineers. The station buildings have been constructed by cut and cover. An exception is the station Gellert, which was mainly excavated by NATM. The works of the M4 Project have reached 70 % completion in December 2011. Having completed tunnelling in 2010, the contractor dismantled and removed the TBM shields and their back-up equipment. By the end of 2011, the construction of all the station boxes on the line was completed. The works now being carried out are trackwork, fit-out and systems installation. Test runs are expected to start in the first half of 2014.

During TBM excavation the geotechnical monitoring was based on different types of geotechnical sensors such as 3-d targets (measured by electronic

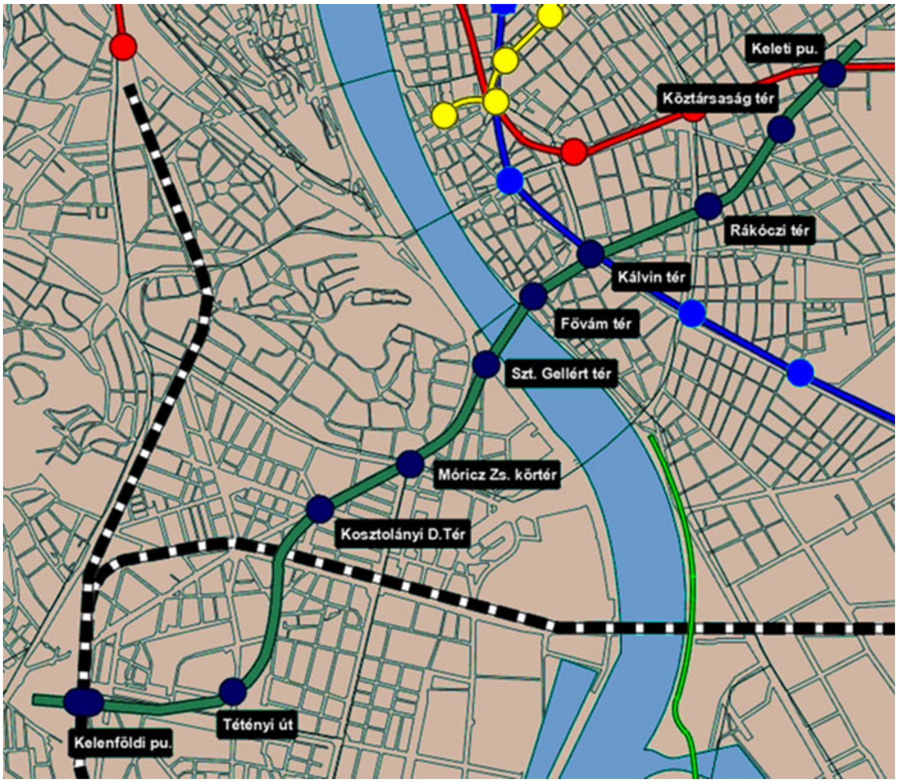

Fig. 10 Alignment of the new 7.2 km Metro Budapest M4 line

total stations), levelling points, inclinometers, tilt meters, rod extensometers, etc. A total number of nearly 10,000 geotechnical sensors and monitoring points were installed in the city, on the surface and underground. Figure 11 shows the whole project area in the Kronos Client together with a zoom-into the level of monitoring points.

In the Metro Budapest project the monitoring data were transferred periodically from Budapest to the Geodata office in Graz (Austria), where the Kronos database server was located. There, all data were stored and an automatic alarming service was run. The service managed and executed 260 alarm rules of 3 alarm levels (warning, alert, alarm) that permanently checked all incoming data and, in case, immediately and automatically sent alarms to about 30 different alarm receivers back to the construction site.

As the system not only captured monitoring data but also integrated further project data like the TBM excavation progress, the data could be linked and used for alarming and interpretation. Figure 12 shows an example where monitoring points on the surface (some indicating an alarm) were displayed live together with the actual positions of the two running TBMs so that their influence on the monitored deformations were better interpreted. The system was also able to use the TBM data to change the current alarm levels of monitoring sensors and points dynamically and/or even increase their measuring frequency automatically. In this way, a dynamic monitoring and alarming was performed. Highly special in this project was that the Kronos installation followed a modern server hosting concept where data was no longer stored locally on site but transferred via internet over hundreds of kilometres (even across a state border) to a remote, subcontracted data processing center.

3.3 Cityringen Copenhagen (Denmark)

Cityringen is a completely new, recently started Metro line that will be constructed according to the same principles as the existing Copenhagen Metro net. The Cityringen circle line (Fig. 13) will be a 15 km underground railway under downtown Copenhagen, the "bridge quarters" and Frederiksberg. Cityringen will have 17 underground stations. Two TBM tunnels will be constructed, each approximately 15.5 km long, as well as a branch to a new Control and Maintenance

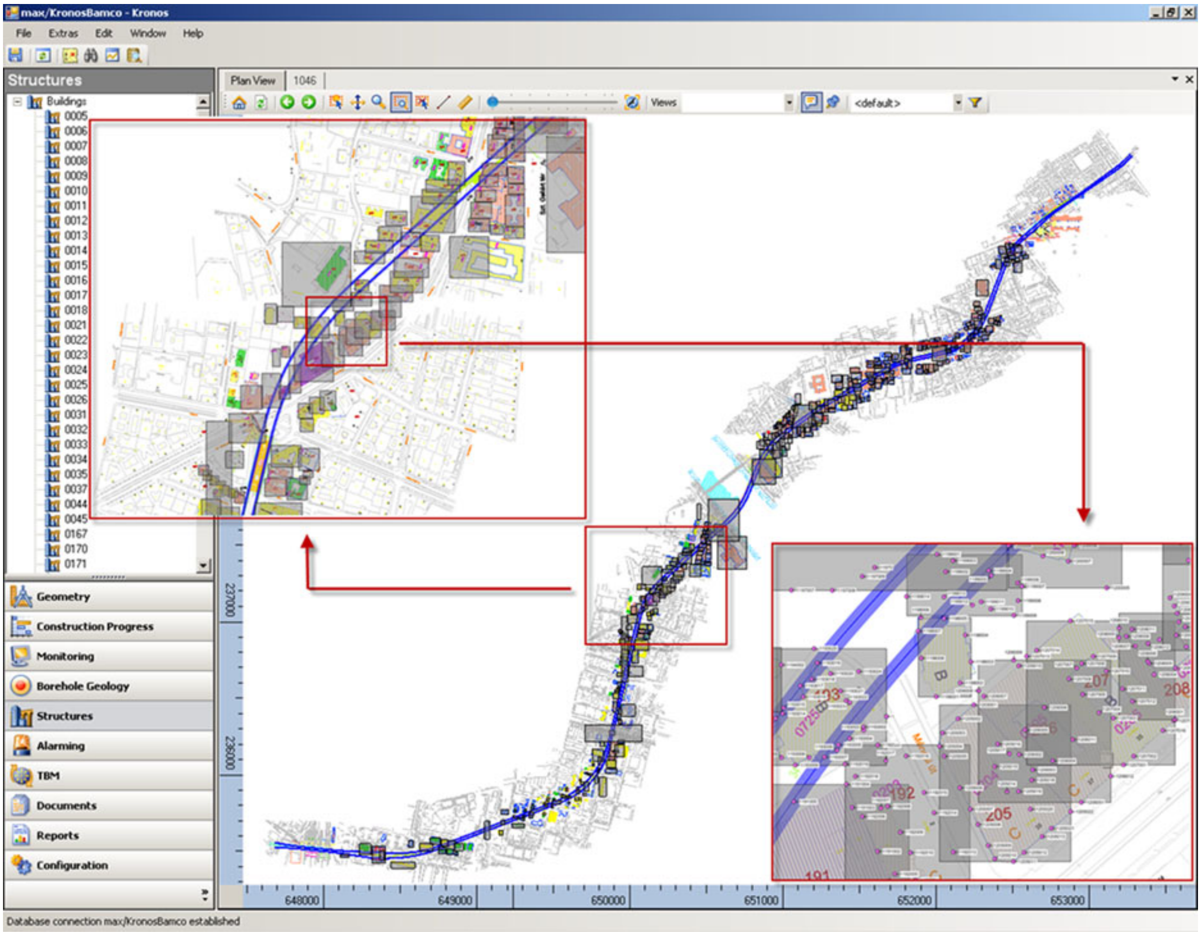

Fig. 11 Metro Budapest project area displayed in the Kronos Client

Centre. The tunnelling works also call for five shafts, four crossovers and stub tunnels for future extensions.

In the Cityringen project Kronos again takes over responsibility for the management, monitoring, alarming and reporting of various kinds of tunnelling data, particularly monitoring data and TBM data (Fig. 14). The system will be used for controlling all kinds of surface monitoring (manual and automatic), for all geotechnical and hydro-geological monitoring instruments on the surface and in the tunnels and for environmental monitoring (e.g. vibration, noise, etc.). For critical areas the alarming features will be used.

Additionally, the TBM machine data will be stored, displayed and if necessary an alarm will be sent. The monitoring data base already implements the AGS 3.1 format for the electronic transfer and storage of geotechnical and geo-environmental data, especially data from boreholes, and provides interfaces to other formats.

Special focus is on the safety of data. A sophisticated mirroring system has been established consisting of two Kronos database servers at different places to avoid damage of both servers in case of a disaster. The servers are installed at offices of the Copenhagen monitoring team, one server playing the principal server and one the mirror server. The principal server is installed as a rack mounted solution whereas the mirror server is a desktop type server with similar performance characteristics. In normal operation all database operations take place on the principal server. Changes in the data (insertion, modification, deletion) at the principal server are immediately copied to the mirror server by sending a stream of active transaction log records to the mirror server, which applies log records to the mirror database, in sequence and as quickly as possible. If the principal server becomes unavailable (e.g. due to hardware malfunctions) the

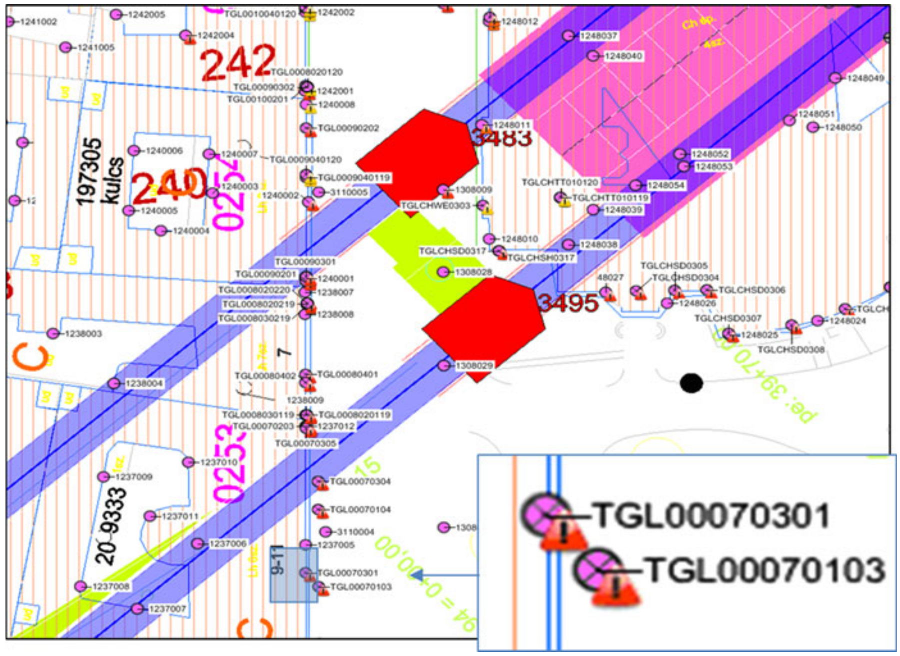

Fig. 12 Kronos Client live-displaying TBM positions and monitoring points in alarm status at Metro Budapest. The alarms are displayed in form of *triangles* of *different colors* identifying the alarm level

Fig. 13 Alignment of the new 15 km Cityringen circle line in Copenhagen

roles of principal and mirror server are switched so that the mirror server becomes the new principal server and operation can be continued. As soon as the new mirror server becomes active again, all data modifications which have taken place during its downtime are applied to its database. The roles will stay the same unless the next switch occurs. To allow an automatic failover, a third computer is involved in

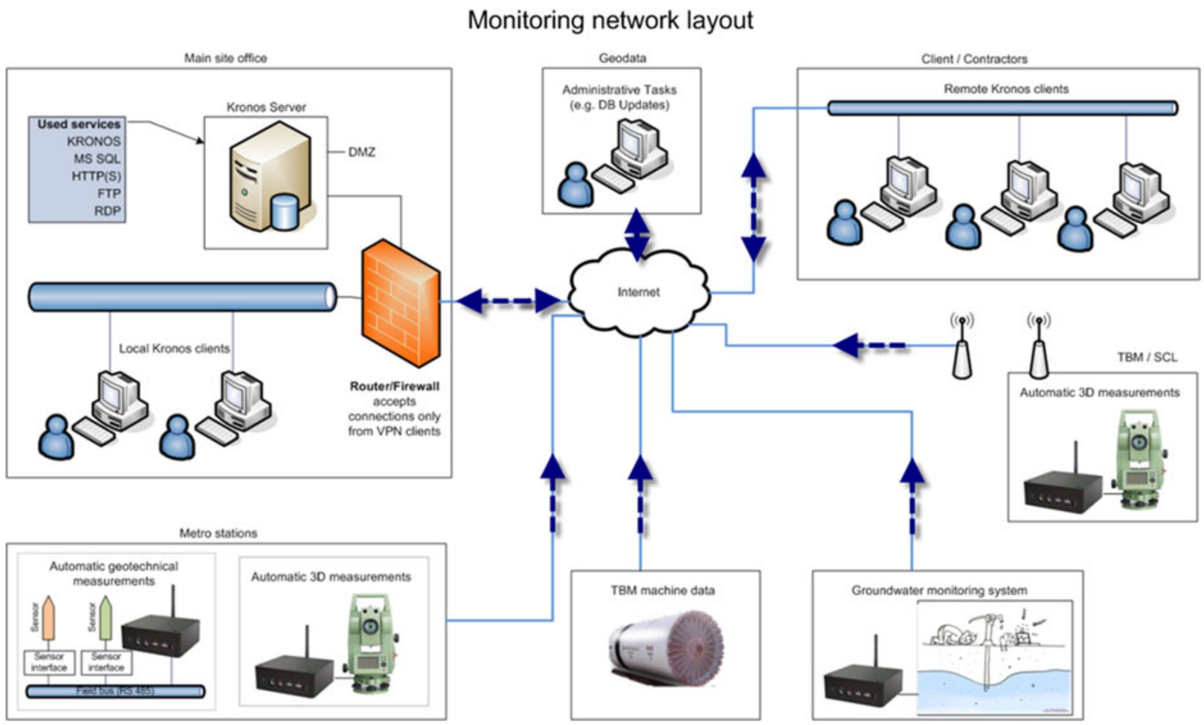

Fig. 14 Kronos and monitoring network layout at Cityringen project

the mirroring session: the witness server. It keeps connections to both database servers and conducts a role switch in case of a failure.

As an additional safety feature, all modifications of existing data are tracked meaning that the date of modification, the modification itself and the user who caused the modification are recorded.

For the Kronos alarming functions and services 4 different alarm categories, related to the type of alarm, are defined: Out of Range Alarms, Value Alarms, Rate Alarms and Frequency Alarms.

3.4 London Crossrail–Farringdon Station (England)

The Farringdon Crossrail station (Fig. 15) comprises two platform tunnels, each the length of two football pitches, linking two new ticket halls in the East and West. The West ticket hall will be shared with Thameslink services, and will have an entrance on Cowcross Street, opposite the existing Farringdon London Underground station. The East ticket hall will have entrances at the Long Lane end of the station, on Lindsey Street and Hayne Street. It will link directly with the existing London Underground platforms at Barbican Station and therefore provide access to the Metropolitan, Circle and Hammersmith and City lines.

In the project area a total number of 210 precise ground level studs, 132 levelling sockets, 304 3-d prism targets, 3 automatic total stations, 38 inclinometers, several piezometers and crack meters, 3 monitoring systems for existing tracks and 9 strain gauges for struts will be installed in the final stage. Baseline monitoring started already end of August 2011. In the project the tunnel information system Kronos serves as the central monitoring data management and alarming system. At current stage first results from the baseline monitoring are already available (Fig. 16).

4 R&D Activities

4.1 TBM Simulation Web Service

In a currently running European research project (Eurostars project EMSAT—Enhanced Monitoring and Simulation Assisted Tunnelling, 2010–2012) Kronos will be enabled to link with a Finite Element

Fig. 15 Farringdon station—project area

simulation software for TBM tunnelling via the internet. Therefore, a special simulation code (ekate) of the Institute for Structural Mechanics of the Ruhr University of Bochum (Germany) will be enhanced to allow for a full automatic generation and processing of simulation models. By means of a web service the needed input data like machine and tunnel geometry, lithological and material parameters will be transferred continuously/repeatedly from the Kronos database (located at the construction site) to the remote simulation center (located at the University). Its particular function then is to automatically start the Finite Element simulation software, compute the simulation by aid of massive parallelized computer power and return the results. Within very short time intervals, the obtained results (e.g. prognosed tunnel wall displacements) will be returned to the Kronos database on site where they will be stored and can be visualised and analysed. In this way, a continuous and dynamic on-site 4-d tunnel simulation web service will be established allowing for the comparison of measured with prognosed tunnel behavior. The new technology will provide tunnel designer and constructor with real time analysis and prediction capability while the tunnel is being constructed. The information will be used to enhance TBM efficiency, as well as to confirm and validate the design. Real time data collection and real time risk management will be integrated into the design and construction process. The use of simulation software will no longer be a time-consuming and interactive work of experts during design but a permanent and automatic service during construction.

4.2 NATM Simulation Web Service, Use of Mobile Display Devices

In a further project such a simulation web service is additionally planned to be developed for conventional tunnel construction methods like the NATM (New Austrian Tunnelling Method). Also it is tried to provide the data of the information system to the users in the tunnel (e.g. working at the tunnel face). To achieve this goal the use of suitable mobile display devices such as smartphones, tablet PCs up to specially adapted head mounted displays is investigated.

The use of these devices will fundamentally improve site management by speeding up data communication between site management and users as well as among users on site. They will also be used by rescue teams (fire workers, medicals) during critical rescue operations and allow for radically new applications such as Augmented and Mixed Reality applications where reality (= the visible tunnel) will be enhanced/augmented by computer generated information. The development of these

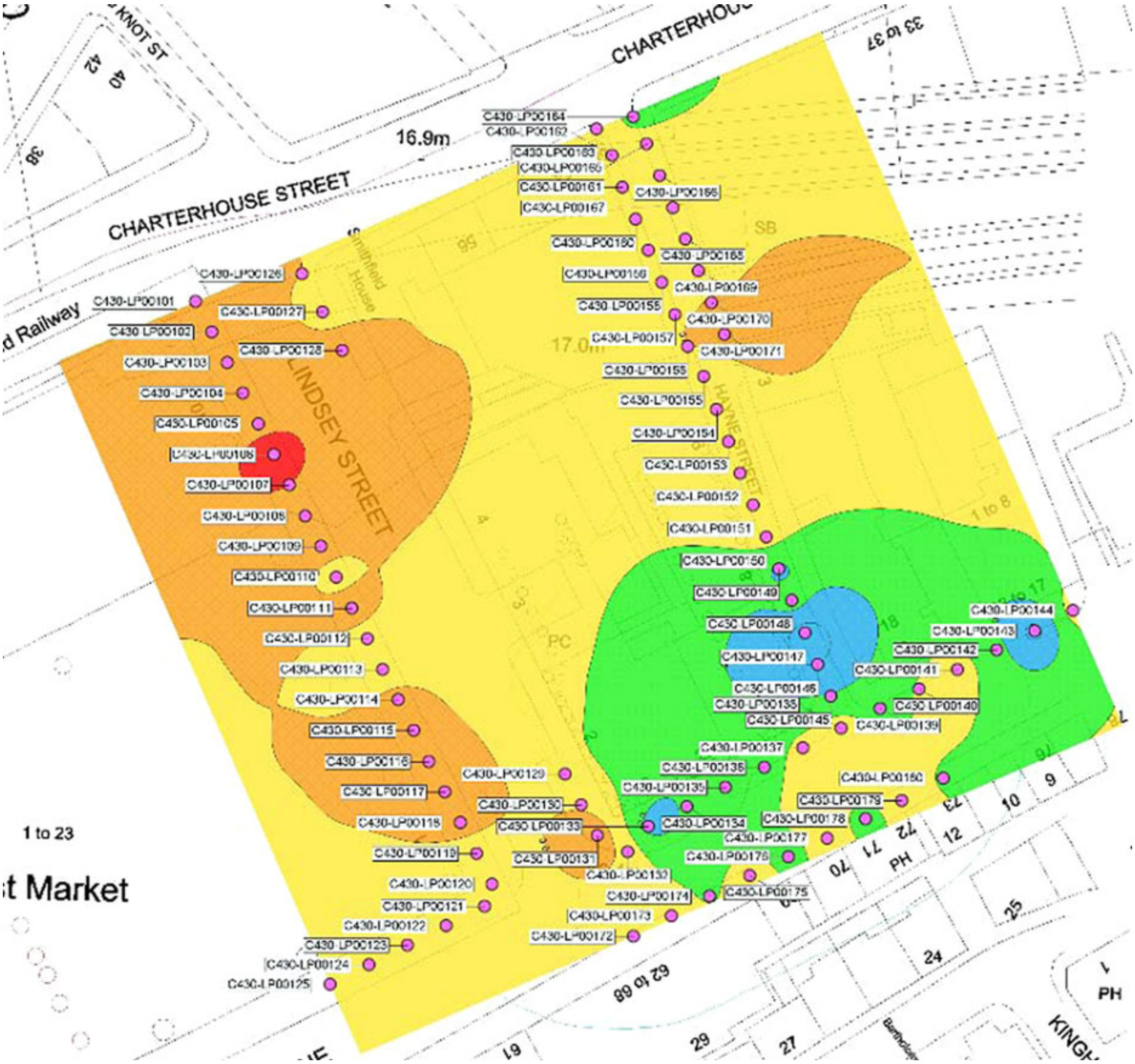

Fig. 16 Kronos Client showing monitored subsidence in the area of the eastern ticket hall caused by earthwork

technologies will also require and push the development and implementation of high performance tunnel data communication networks, new real time user tracking and locating systems and new machine guidance systems. It is to expect that tunnel information systems will play a central role in the data management and control of all these future systems.

4.3 Virtual Reality Visualisation

In order to enhance the presentation and visualisation capabilities of information systems Virtual Reality techniques have been researched and implemented in prototype viewer applications. These new techniques allow for combining different data sources and make possible individual walkthroughs of 3-dimensional tunnel models. Their main advantage is that they contribute to a better understanding of a planned or currently built tunnel and also the tunnelling processes going on. The currently researched data sources include:

- 3-d tunnel models (e.g. automatically processed from analytical tunnel geometry data or derived from measured laserscan data),

- 3-d geological ground models (e.g. stemming from a CAD model),
- other 3-d models (e.g. for tunnel equipment like lights, generators, ventilation, etc.),
- measured or predicted displacement vectors,
- real images or manual drawings (e.g. geological mapping of the tunnel face),
- construction progress documentation.

5 Summary, Conclusion

The contribution informs on the current state of information technology used in tunnelling projects by describing the latest monitoring, alarming and reporting functions and services of the tunnel information system Kronos of Geodata. From the manifold experience gained from the described system installations at current urban tunnelling projects like Metro Thessaloniki, Metro Budapest, Cityringen Copenhagen and Crossrail London can be concluded that tunnel information systems constitute highly valuable tools for all involved parties of a project. The described examples represent best practices of how customized geotechnical instrumentation and measurements in combination with an information system supports monitoring and alarming on tunnel construction sites. The main advantage is that it is accomplished a highly efficient site data management where all data is integrated into one central platform and where a well-organized and systematic data transfer from and to this platform is realized. No longer is it necessary to deal with data that are stored in various different, non-connected and non-compatible systems. Problems arising from time consuming data search, data loss and inconsistent, non-actual or redundant data are fully avoided. Further advantages are that all data can be accessed by multiple users, at every time, from everywhere and at a click of a button. All relevant information is permanently available which significantly improves decision making and communication among experts. A more intelligent and extensive alarming can be established taking all project data into account. Tunnel information systems, thus, essentially contribute to a safer, more productive and high-quality tunnel construction.

Current research aims to and will further expand the use of information technology, for example by implementing new and innovative visualisations, functions and web services.

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References

Beer G (ed) (2010) Technology innovation in underground construction. CRC Press, Taylor and Francis Group, Boca Raton

Chmelina K (2009) A virtual reality system for the visualisation of underground construction data. In: Proceeding of the IInd international conference on computational methods in tunnelling, Euro:Tun 2009, Bochum, Germany, vol 1, pp 883–890

Chmelina K (2009) Integrated tunnel monitoring and surveying supported by an information system. In: Proceedings of the ITA-AITES world tunnel congress, Budapest, Hungary

Chmelina K (2010) A New Information System for Underground Construction Projects. In: Proceedings of the 1st international conference on information technology in geo-engineering (ICITG), Shanghai, China, pp 329–337

Chmelina K, Grossauer K (2010) A decision support system for tunnel wall displacement interpretation. J Appl Geodesy 1:1–12

Chungsik Y, Jae-Hoon K (2003) A web-based tunneling-induced building/utility damage assessment system: TU-RISK. Tunn Undergr Space Technol 18(5):497–511

Rabensteiner K, Krusche G, Hesina G (2010) Integrated tunnelling data management, analysis and visualization—new IT tools for better projects. In: Proceedings of the ITA-AITES world tunnel congress, Vancouver, Canada