Monitoring for construction of the North/South metro line in Amsterdam, The Netherlands

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ABSTRACT: In Amsterdam a new 9.5 km long metro line, the North/South line, is constructed. Over a length of 3.8 km the line consists of a bored tunnel and three deep stations. As the line is constructed in the very soft Amsterdam soil, actual information on the status of the surrounding objects and the performance of the works with respect to these objects is obtained through an extensive monitoring scheme. From one year prior to the start of the works until the end of the works on-line measurements are performed on 5400 points on residences, offices and bridges. Also, approximately 250 deep extensometer strings and 450 deep inclinometers strings for underground monitoring are measured. The monitoring is performed by fully automatic instruments.

The measurement data are on-line transferred into a GIS database in which the status of each relevant object is monitored. In this paper the first results of the construction phase are presented.

1 INTRODUCTION

About 3.8 km of the new North/South metro line in Amsterdam will be constructed under the old historic centre of the city (fig. 1). Historic Amsterdam buildings, up to 400 years old, are founded on 20 m deep timber piles reaching the first sand layer. The route under the inner city (fig. 2) will be constructed with two bored tunnels of 7 m diameter, varying in depth between 20 and 31 m below ground level. There are three underground stations to be constructed using a strutted excavation with the cut and cover method.

The tunnelling and the construction of the deep underground stations will induce soil deformation in the surrounding ground. The deformations occur due to a large variety of possible causes. The consequences are potential damage of surrounding objects and a negative attitude towards the project. Therefore, the observational method will be applied for both construction methods to combine design and work on site with the aim to achieve the best performance regarding the minimisation of settlement induced damage.

Figure 1. Construction work in old city.

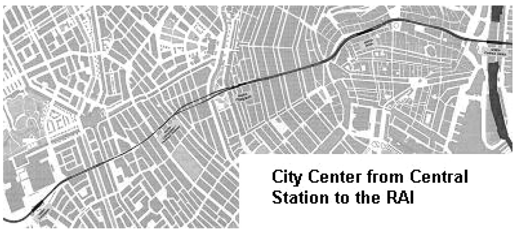

Figure 2. North/South line route in old city.

On-line monitoring and control of the effect of soil deformation in the surrounding area such as on buildings, bridges and services has therefore been an essential aspect in the risk management philosophy of the North/South metro line. On-line automatic monitoring of the surrounding area is an essential part of the strategy of an interactive tunnelling system IBCS (Integrated Boring Control System) to guide the TBM to minimise ground deformations and damage risks.

The role of monitoring in risk management is the following:

- to check design assumptions on execution process, so a detailed deformation prediction was made for each phase;
- to have an early warning system, so improvements defined in the risk management system could be implemented in time;
- to have a juridical basis for liabilities.

SolData-Grontmij VoF were assigned by the municipality of Amsterdam to carry out the installation and operation of the system detailed in section 2.

Station construction started early 2003 and the North/South line should be open to the public mid-2011.

2 MONITORING SYSTEM

The monitoring system can be divided in two main categories:

- Surface monitoring
- Subsurface monitoring

An influence zone has been preliminary determined using 3D models. This zone stretches 50 m on either sides of the construction work location. Inside this zone, the settlement forecast is larger than 1 mm. Therefore the monitoring system is therefore concentrated inside this influence zone.

Beyond the influence area a buffer zone has been defined. The buffer zone is 35 m wide (beyond the 1 mm line) and is monitored only by precise levelling for juridical reasons.

2.1 *Surface monitoring system*

The surface monitoring system measures the movements of the buildings, quay walls, bridges and streets settlement inside the influence zone.

- Automatic system

The installation started early 2001. The first step was the installation of a large wireless network in order to link the transmission points spread along the project to the office where the measurements are processed. At the time of installation, this consisted of the world's largest outdoor wireless network.

Figure 3. Robotic total station.

74 robotic total stations (RTS, fig. 3), perched high on key building facades and roofs, have been installed. Each RTS is controlled by its own small onboard computer and reads up to 90 targets placed at up to 80 m distance. The system runs full time and the 5400 optical targets, in total, are each read roughly every 20 min. Their positions in 3D are relayed back to the office via the radio network for processing.

To obtain absolute measurements, the deformation measurements within the area of influence are related to stable reference points not subject to deformation. For this purpose, 19 deep level datums are installed close to the North/South metro line. These reference points are outside the area of influence in the soil and have their foundations in a deep soil layer, either the second or third sand layer. The deep datums for the North/South metro line are integrated in the existing surveying network in Amsterdam.

- Manual levelling

In addition to the automatic system detailed above, over 4000 traditional levelling points have been installed:

- 2700 on the building facades (building points)
- 1200 installed 50 cm under ground level in key perpendicular streets the length of the route (ground points).

These points are leveled on a regular basis. The measuring frequency depending on the phase of the construction works. The manual leveling results can be compared with the automatic system ones. The reliability of the results is therefore cross-checked.

2.2 *Subsurface monitoring system*

The subsurface monitoring system is measuring the movements of the soil inside the influence zone. About 170 bore holes between 20 m and 75 m deep have been drilled along the route. These boreholes are part of

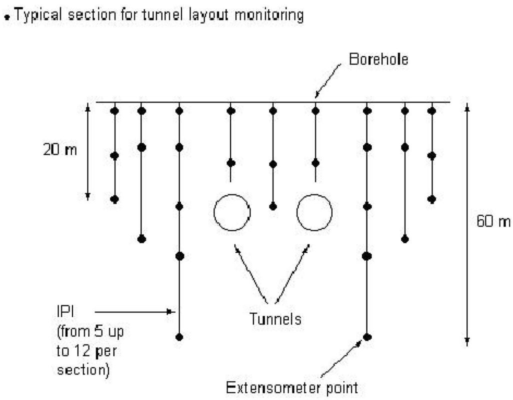

Figure 4. Subsurface monitoring.

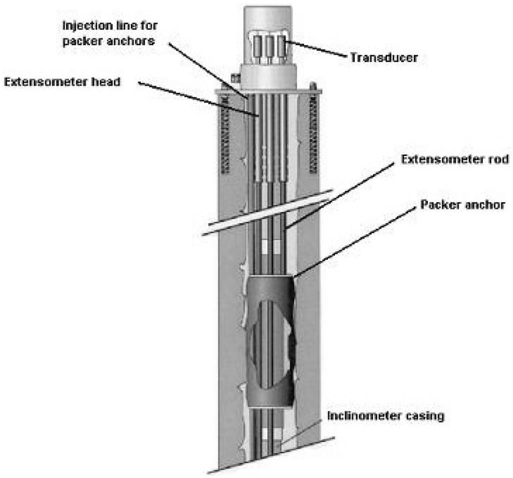

Figure 5. Combined inclinometer and extensometer.

roughly 40 profiles (see fig. 4) perpendicular to the metro route.

The information will be used during the boring process to calibrate and validate the numerical model. If the measurements in the surroundings, on the buildings and in the soil, indicate that the boring process should be modified, new predictions with the numerical calculation model will be made. Steering parameters, such as tail void grout pressure, jacking forces and face support pressure, are modelled so that if required, these parameters can be adjusted in the following section of the work.

Each bore hole is equipped with both in-place inclinometer chains (IPI) and extensometers. This system called a "combined system" records both horizontal and vertical ground movements from the same bore hole (fig. 5).

A total of roughly 1500 IPI's and 760 extensometer sensors are installed in these bore holes.

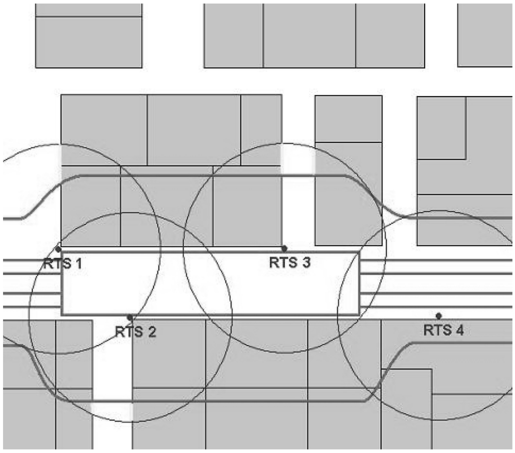

Figure 6. Group of 4 RTS inside the influence zone of an underground station.

Every profile is linked to a data logger that interrogates the instruments and collects the measurements every 20 mm. The data logger is connected to the nearest small on-board computer, which in turn sends the results by radio back to the office for processing.

In addition, 720 strain gauges will be installed on the struts inside the three station boxes during the excavation. About 40 piezometers and a number of electrolevels are also part of this extensive subsurface monitoring system.

3 PROCESSING OF THE MEASUREMENTS

A total of over 80 computers are part of the same network. Three categories can be identified:

- Small on-board computers spread along the project route for piloting the RTS and retrieving the results from the subsurface profiles (74 units).
- Processing computers in the office (7 units).
- Main server in the office (1 unit).
- Maintenance computers in the office (4 units) to control the system, so immediate action can be taken upon failure.

3.1 *Processing of surface monitoring measurements*

The RTS calculate in groups. Between 2 and 5 RTS are grouped together. The advantage of using calculation groups is that it allows the use fixed points as reference targets located outside the influence zone for several RTS. Despite the fact that these reference targets are beyond the reach of some of the RTS in the group (Ex: RTS 4 in the illustration shown in fig. 6).

The least square calculation method is used in real time to determine the X, Y and Z coordinates of the targets and RTS, relative to the reference targets, for all groups independently.

The results, with an accuracy of 0.9 mm, are then automatically sent via a dedicated FTP line to the ABNZL's (Adviesbureau Noord/Zuidlijn) GIS database in batches at a predetermined frequency: four-hourly during the station construction phase and hourly during tunnelling phase.

The ABNZL is in charge of the interpretation of the results using a three dimensional real time computer model of representative buildings.

The "intelligent" TBM will be capable of interacting with the computer analysis of surface movements during tunnelling both to predict and minimize surface settlement above it.

3.2 *Processing of subsurface monitoring measurements*

Every 20 min, each data logger sends the measurements to the office for processing. The results are compiled and sent hourly to ABNZL via the FTP line.

For efficient use of the data collected during passage of the TBM and construction works, it is essential to have rapid access to a large quantity of data and that data can be interpreted rapidly. For these reasons, the client has developed a GIS for the storage, rapid interpretation and visualisation of measurement data before, during and after construction activities. An estimation of the amount of data during the construction work of the North/South Line indicates that approximately five times as much data as for the JLE Extension will come available.

The GIS is linked with a database especially designed for the monitoring requirements. The structure of the GIS and the database use unique codes to identify each monitoring sensor, which is registered digitally in the GIS at its location. GIS is the important intermediary for settlement risk management with the IBCS (Netzel and Kaalberg, 1999). Therefore all the information is easily accessible in a central database associated with a 3D visual interface and a large panel of graphic views.

4 MONITORING CRITERIA

For each construction phase or part of a construction phase limit values are defined. These limit values are based on results of full scale trials, finite element model calculations or a combination of both. In the finite element calculations both most-likely and lower limit approaches are adopted.

Besides the maximum expected displacement (limit value) a number of sub limit values are defined that act as a warning code. Five colour codes are used, where values have been defined per construction phase. When the status RED is reached in a construction phase it means that for this certain construction phase the predicted value has been reached. The necessity for adapting the construction process is determined by the absolute value of the total displacement and the option for adapting the construction process in subsequent construction phases.

5 ALARM APPLICATION

Within the GIS an alarm application runs that automatically checks and visualises new monitoring data. When limit values are exceeded, the alarm application takes a number of actions. An important aspect in the procedures is when limit values are exceeded, warnings reach the proper actor. Furthermore, the number of irrelevant warnings must be kept low without an increase in the chance that no actions are taken on actual warnings. Regarding the last type of warnings it is obvious that when the number of irrelevant warnings becomes too large, the risk of a decrease in taking the warnings seriously becomes too high and actual warnings may be neglected.

For the supervision of the construction phase "diaphragm wall construction", two important risks can be distinguished that require immediate action: 1. trench instability and 2. sudden instability of surrounding structures. To control these risks measures are taken, both in the preparation of the project as well as in the construction phase. The procedures when limit values are exceeded, anticipate an adequate reaction in the unlikely situation that these risks actually occur.

When a limit value is exceeded this has to be reported to the proper actor. The alarm application in GIS is capable of sorting the destination of the report based on location (in or outside the influence zone of the diaphragm wall panel in progress) and time (who is present on the construction site). The proper actor is reported by SMS and email. Consequently the Actor should evaluate and react on the report. The email includes an automatically generated report form that provides all relevant monitoring data and acts as a guidance to deal with the report according to procedures.

6 DISPLACEMENTS

Figure 7 provides monitoring data for the diaphragm wall construction phase around Ceintuurbaan station. The RED limit value in this phase is 5 mm. It becomes clear that raising the street level gives 1 to 2 mm of displacement. This corresponds with the second horizontal line.

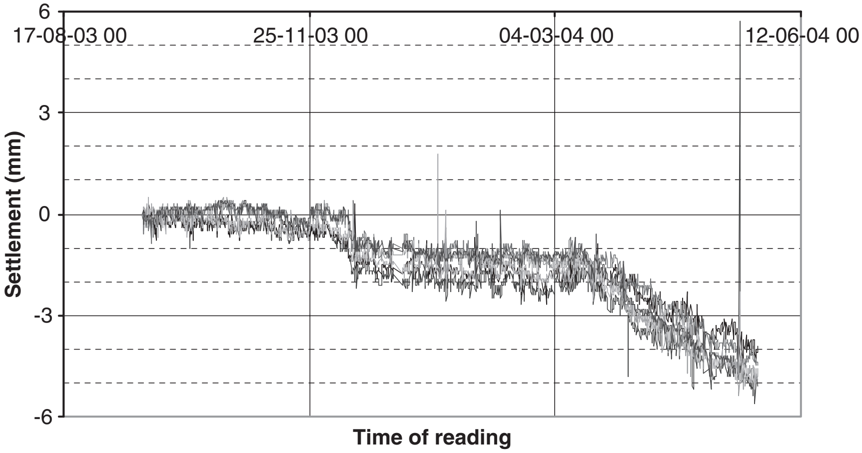

Figure 7. Settlement data diaphragm wall construction.

When the diaphragm wall is constructed in front of the structure it is interesting to see that no instantaneous displacement of the structures is observed, but that the displacement is clearly time dependent (line downward). The last part of the graph shows a stabilisation of the deformations. Also note the spikes which occur due to various causes of bad visibility of prisms. The displacement as a result of diaphragm wall construction is around 3 mm, which is within the limits that are defined based on the full scale trial.

The monitoring data serve as an early warning system. In several occasions working methods have been changed to prevent deformations to exceed the maximum values.

7 CONCLUSIONS

(1) A real time deformation monitoring network for 5000 targets along 3.8 km of the North/South metro line in Amsterdam has been installed and operated successfully for over 3 years.

(2) The real time least square method for reference transfer between total stations has proven successful and allows for accurate measurements in areas with poor visibility.

(3) Real time monitoring is an essential part of risk management for complex underground structures in a delicate environment.

(4) Monitoring in combination with an intelligent GIS and adequate interpretation serves as an early warning system and therefore prevents damage.

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