Instrumentation and Monitoring at Deep Excavation in Historic City of Amsterdam

Design and Performance Analysis of Monitoring System at Ceintuurbaan Station

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1 Introduction

1.1 Project

In Amsterdam, The Netherlands, one of Europe’s biggest settlement monitoring contracts is underway. As part of a 9.5 km long new metro line, a 3.8 km underground, twin-bore railway with three large cut and cover stations is being constructed beneath the busy, historic inner city as part of the Noord/Zuid Metrolijn (‘North/South line’). Working below the water table in fine sands, soft clays and peat layers places high demands on settlement control and monitoring of some 1200 historic structures as well as modern prestigious buildings which are potentially affected by the works. In addition the ground in Amsterdam is naturally settling due to the soft underlying clays. This makes ground and building settlement monitoring and control central to the project.

1.2 Stationbox Ceintuurbaan

In December 2009 one of the three cut and cover stations, Ceintuurbaan, was excavated to a depth of 30 m below surface. The excavation of the Stationbox reached this maximum excavation level over 75% of its 200 m length. An impression can be seen in Figure 2a and 2b.
Figure 2a and 2b indicate the depth (30 m) of the station related to its width (10 m) and length (200 m) to give an appreciation of the scale of the structure. Note that the picture was taken on top of the material air lock, so only the upper half of the station box is presented. Underneath the concrete slab another 10 m has been excavated under overpressure (0.5 up to 1.5 bar) for the deepest platform. The arrow presented next to the artist impression indicates the level at which the photograph has been taken.

1.3 Monitoring Stationbox Ceintuurbaan

Each station box site is monitored by multiple robotic total stations (RTS) to follow building response. The locations at Ceintuurbaan have been marked with a red R (Fig. 3 and 4). Deformations of soil and Diaphragm Wall (D-Wall) has been monitored in three cross sections per stationbox, using inclinometers, extensometers and leveling points (Fig. 3 and 4). Stand pipes and piezometers were installed in and around the stationbox subsoil to measure phreatic levels, aquifer levels and pore-pressures. Strain gauges have been used on every fifth prop to monitor reaction force, for each prop 4 sensors have been installed. A custom built, GIS-based monitoring system facilitated the effective processing and presentation of the collected data. In the following Figures 3 and 4 an overview from the GIS has been presented to explain the lay out. Figure 3 indicates the layout of the stationbox and the monitoring profiles in cross sections 13044 and 13110. Figure 4 shows a detailed picture of the lay out of profile 13110. The borehole numbers on the east and west side have been indicated with numbers and indicate the locations of the combined inclinometer and extensometer systems. Blue dots indicate the manual levelling points.

1.4 Evaluation Results Ceintuurbaan

Since the Ceintuurbaan stationbox has reached the maximum excavation depth at all monitoring cross sections, an opportunity occurred to analyse the accuracy achieved in comparison to the recorded total displacement. In this paper the performance of the building and subsurface monitoring system will be discussed using the results obtained during the construction and excavation process by analysis on an incremental and the total displacement recorded at profile 13110. Previous papers described the specification, procurement and installation of monitoring instrumentation (FMGM2003) and base monitoring / early construction results (FMGM2007) and the design of the stationbox and mitigating measures (both ITA2009).
2 Approach Performance Evaluation

The continuous flow of reliable data from sensors throughout the whole Monitoring System is crucial. Calibration sheets, installation reports, calculation and monitoring protocols etc are in place but cannot guarantee that all data will be continuous, stable, accurate and consistent. Active sensors can drift, be affected by third parties, exceed sensor range, exceed sensor life span etc.

For these reasons the data from connected instruments and uploaded recordings have automatically and manually been checked on data availability and recordings exceeding validation boundaries. In addition to these automated and formalised routines, periodic expert review and reporting on data volume and accuracy has been performed. Specific reviews have taken place during construction phases that could cause incremental effects, such as pre-stressing of struts or during pumping tests or air pressure tests.

Given the observational method has been applied in the project, it was mandatory to report Monitoring Results at the completion of each predefined construction phase of the station box. The evaluation of these phases gained a more detailed insight on incremental deformation. This understanding of the incremental deformation is essential when evaluating sensor accuracy. Especially given the fact that autonomous settlement in the Amsterdam subsoil and third party activities could influence results when analysing longer periods. The incremental movements have the benefit that the physical cause behind the movements is known and therefore a first impression on location, time of occurrence and orientation of deformations are available when starting the evaluation on effects and sensor accuracy. Its important to specify when and where to look, with seven years of data available on the whole trajectory. Even experienced users of the GIS with a fair share of knowledge on structural and geotechnical engineering need to have a starting point in the enormous amount of data and possible correlations between recordings.

Since building movement was the leading parameter to monitor and report, the GIS was equipped with the broadest functionality to present data on building movement and therefore the most efficient approach to start the evaluation. For incremental analysis the information obtained from the RTS and targeted prisms was used as a basis. For longer term (years) analysis manually levelled building and ground points were used for the first understanding of displacements.

Once an understanding of the building or surface movement was obtained, a broader, more detailed analysis could start on the full data set over the location and period involved on all available instruments. The movements recorded at structures determined the periods used in queries on subsurface instruments. All kinds of correlations between sensors could be identified. The results were compared in direction, magnitude, sensor position or time of occurrence.

In the assessment of sensor accuracy, in some cases, a direct comparison was possible between manual obtained data and data obtained from automated instruments installed at the same location. For instance manual levelling of the extensometer head versus automated extensometers, manual inclinometer measurements versus automated instruments, manual stand pipe recordings versus peizometer recordings etc. Also double base readings or redundant equipped sensors could indicate reproducibility on accuracy of recorded data.

In other cases an indirect comparison has been made. Indirect because sensors were not directly comparable due to different locations. Indirect given the fact that different types of sensors could monitor the same phenomena at the same location but in a physically different manner. (horizontal building movement versus In Place Inclinometer (IPI) recordings).

In this paper the approach of performance evaluation will be applied on profile 13110 by analysing a short term incremental displacement and by analysing a long term displacement which covers the whole monitoring period (January 2002 till November 2009). For the incremental analysis the pumping test on the second sandlayer has been presented. In this paper the horizontal displacement will be presented in chapter 3. For the determination of the long term accuracy the vertical displacement has been analysed for the whole monitoring period. These findings will be presented in chapter 4.
3 Horizontal displacement

In March and April 2006 a two staged, northern and southern, pumping test has been performed in the 2nd sand layer of station box Ceintuurbaan in order to assess effects on the watertable height outside the station box prior to excavation. Monitoring of the surrounding buildings and subsoil was in place to check on deformation and abort the pumptest if necessary.

During the test the water level was monitored at the well and at various standpipes throughout the station box. At cross section 13110 standpipe 41 CD was available for manual recording of the water level in the first and the second sand layer (see Fig 5). The first test in March 2006 was held at profile 13044. Although at that time monitoring did not take place at standpipe 41 CD in profile 13110, in hindsight it can be concluded that the drawdown in one part of the station manifested itself throughout the whole station box (see Fig 6). The direct effect of the drawdown recorded at standpipe 41 D on adjacent building no. 95 has been added in to Fig 6.

From Figure 6 the direct correlation in time of occurrence between the lowering of the water table inside the station box and the horizontal building movement outside the station box can be recognised. On that basis the correlation between horizontal building movement and manual inclino recordings in the D walls 21 and 111 could be analysed, as well as the horizontal soil deformation recorded with the automated IPI chains in the profiles. The combined result is presented in Figure 7. It should be noted that borehole BH01 on the East side at 3 m from the D wall was not available for analysis, therefore BH02 E has been presented, which is situated at 10 m from the D wall.

From Figure 7 it can be recognised that the IPI chains as well as the manual inclinometer readings are starting below the influenced zone above NAP ~40 m NAP, providing a stable basis. At BH04 W, situated at a distance of 3 m to the D wall, less deformation and over shallower depth has been recorded compared to the manual inclinometer recording at panel 111. This is consistent with a smaller magnitude at a bigger distance, also apparent when recordings at BH02 E are compared with panel 21. The results from the prisms on the corner buildings, two per side of the station, coincide on magnitude and direction with the IPI. The position and time of occurrence, movement and magnitude on both sides of the station is consistent. The accuracy achieved during this test on all movement recording sensors in this profile is estimated at 1 mm.
Fig 7: Correlation of horizontal displacement

Profile 13110

Prisms # 93 and 95

Prisms # 118 and 120
4 Vertical displacement

In the monitoring period January 2002 till November 2009 base monitoring (see FMGM 2007) and station construction (see ITA 2009) was undertaken. Vertical settlements have been induced by the construction process and autonomous settlement. In order to gain better understanding of sensor accuracy, first a better understanding of the total settlement per position, the settlement trough, and sensor correlation is required. Once the trough and correlation with other recordings is recognised, individual sensors can be assessed for accuracy. Given the autonomous settlement this trough analysis can only be based on recordings referred to the third sandlayer.

Vertical displacement with 3rd sandlayer reference has been obtained on the extensometers and the manually levelled points (see FMGM 2007). Each extensometer reference anchor has been installed in the third sandlayer. The manual levelling points have been referred to CPT rods in the vicinity, which were also installed into the third sandlayer. The levelling covered annual recorded building points and extensometer heads. The ground points were levelled on a six weekly basis.

The first step in the accuracy analysis has been a first impression on all data available per vertically displacement recording instrument. The next step was to compare results on extensometers with the manual levelling of the extensometer head. Once the automated and manual obtained data coincided, the analysis was broadened by the introduction of the results obtained at the adjacent ground levelling points in comparison to the results obtained at the surface anchor of that particular extensometer. This combination is presented in Figure 8.

From Fig 8 it can be recognized that the results obtained by manual levelling (BH02, points 22 and 23) are identical to the automated results. This implies that the reference at NAP –55 m is stable (in graph set at 0) and, provided the other anchors have been equipped with calibrated instruments, the other anchors are proven as well. From the graph spikes or system malfunction can be recognised. Each extensometer is checked on this basis. The Autonomous settlement at surface can be recognised in the period till 2004. A rate of approx. 3 mm per year should be considered. For the date November 2009 (building points were monitored October) at each location the recorded value has been combined geometrically, thus creating a trough. In this case all information has been combined in one graph, see fig 9.

With the confirmation on the trough, the building points have been added into Figure 9, in the upper graph (surface results) and the middle graph (1st sandlayer extensometer results). It can be determined that building settlement generally finds itself between settlement of the surface and settlement of the first sandlayer (FMGM2007). Some buildings at more than 30 m distance from the D-Wall appear to be settling even faster than the surface, which would indicate a poor quality foundation. From Figure 9 it can be derived that at approx. 50 m distance from the D-wall the trough ends at surface. The recorded 20 mm settlement coincides with the autonomous rate. The maximum recorded surface settlement near the D-wall can be explained for up to 30% by this rate. The trough in the 1st sandlayer does not seem to stretch beyond 25 m. The west side is exposed to autonomous settlement in the 1st sandlayer given the higher settlement rate at bigger distance. The 2nd sandlayer indicates a significant effect only in the first 5 m to the D-wall. Given the confirmation by manual levelling and the constancy of the trough 2 mm accuracy is plausible.
Fig 9: Cross section 13110 vertical displacements 2002-2009
5 Conclusions
The following summarises the approach and findings on the analysis on the design and performance of the Monitoring System at Ceintuurbaan Station.

5.1 Approach
The approach on analysis on accuracy recognised in the results are summarised in table 1. The approach on analysis provided consistent results which were presented geometrically.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Incremental</th>
<th>Total Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recordings</td>
<td>Horizontal displ.</td>
<td>Vertical displ.</td>
</tr>
<tr>
<td>Start analysis</td>
<td>Prism data buildings</td>
<td>Manual levelling surface and heads</td>
</tr>
<tr>
<td>Correlated with</td>
<td>Manual Inclino results</td>
<td>D-walls Automated results extensometers</td>
</tr>
<tr>
<td>Driving Phenomena</td>
<td>Watertable draw down 2nd</td>
<td>sandlayer prior to excavation Construction stationbox and autonomous settlement</td>
</tr>
<tr>
<td>Understanding of</td>
<td>Horizontal displ.</td>
<td>Vertical trough and autonomous settlement</td>
</tr>
<tr>
<td>Used in analysis of</td>
<td>Automated inclinometers</td>
<td>Building levelling points</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1 mm</td>
<td>2 mm</td>
</tr>
<tr>
<td>Max. displacement</td>
<td>8 mm</td>
<td>60 mm</td>
</tr>
</tbody>
</table>

5.2 Design
- The monitoring system proved to be installed beyond the zone of influence of North/Southline effects. The system provided stable results at the maximum depth and maximum width of the profiles, indicating that effects did not reach beyond the predicted maximum reach. The system is therefore capable of distinguishing Autonomous settlement from North/Southline induced effects.
- The monitoring system proved to have sufficient redundancy. Monitoring results could be confirmed by more than one instrument, thus creating reliable results. This redundancy was crucial for further analysis on reliability of indirectly correlating instruments.
- The number of monitoring points proved to be of sufficient detail in order to determine the geometry of soil and construction deformations. The intervals chosen on instruments did not bring uncertainty on soil / structural behaviour between monitoring points.

5.3 Performance
- The monitoring system proved to be of sufficient accuracy. The recorded deformations are of a higher magnitude than instrument accuracy achieved on site.
- The evaluation examples presented in this paper demonstrate that the actual purpose of the system has been met: provide continuous, reliable data on Construction and its Environment.

References


