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# Monitoring dataset of deformations related to deep excavations for North-South Line in Amsterdam

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ABSTRACT: For the construction of the Amsterdam North-South-Line subway, an extensive monitoring program has been established since 2001. Currently the stations have been finished structurally and the close out monitoring has taken place. Monitoring includes buildings deformations with automatic and manual levelling, surface settlements and subsurface deformations (inclinometers and extensometers). In this paper the main monitoring results are given as well as references to the background reports that will be publically available. The monitoring data are related to the subsequent construction stages. This paper is intended to serve as a reference for back calculation of existing and new design methods related to deformations caused by the construction of deep excavations.

## 1 INTRODUCTION

In many TC204 conferences it has been mentioned that the number of well documented case histories is very limited for example by Boone (2005). For this purpose a tunnelling database has been set up by this TC. In this paper field data from three deep excavations recently completed will be presented. The data has partly been published before for the purpose of validation of design methods in Korff (2013) and Korff & Mair (2013). In this paper however, the focus is not on the analysis of the data but on the background information to make it available for further use by others. The data may for example be used for validation of the process of construction of diaphragm walls, the consequences of predrilling with a large auger, installation of jet grout struts and the deformations related to the excavation itself. Also methods for soil structure interaction can be validated since both surface displacements as well as displacements at larger depth and building displacements are available. This dataset's most unique characteristics are the depth of the excavations (up to 30 m), the extensive monitoring system with both automatic and manual measurements and the presence of historic buildings with (mainly) old timber pile foundations at short distance (3–5 m minimum). This paper also gives references where to find additional data and analysis of this key project in Amsterdam.

## 2 THE NORTH-SOUTH LINE

### 2.1 *Introduction to the project*

In Amsterdam a 9.5 km long new metro line is under construction, the North South Metro line. The line starts above ground in the North of Amsterdam, continues under the river IJ and Amsterdam Central Station and continues with two bored tunnels under the streets Rokin, Vijzelgracht, Ferdinand Bolstraat and the Scheldestraat. The North South Line comes above the ground at the ring road A10 between RAI and WorldTradeCentre. The bored tunnel is 3.1 kilometre long. Two tunnels are constructed under the historical centre, one for each underground railway track. In total 5 underground stations are built along the line. For the construction of the most centrally located underground stations, Central Station, Rokin, Vijzelgracht and Ceintuurbaan the top-down method is used.

The construction of the line started in 2003 with preparation works for the stations, tunnelling commenced in 2009 and finished in 2011. The three inner city stations have been structurally finished in 2014. It is expected that trains will be using the tracks in 2017.

The dataset presented in this paper relates to the three inner city stations Rokin (RKN), Vijzelgracht (VZG), see Figure 1, and Ceintuurbaan (CTB).

### 2.2 *Soil conditions*

The soil stratigraphy in the historic centre of Amsterdam are fairly characteristic and consist mainly of Holocene and Pleistocene, soft clay, peat and sand deposits, underlain by a stiff, lightly over consolidated clay. Ground level is around NAP +1.0 m (NAP is Dutch Reference Level). Fill and soft Holocene deposits are present to a level of about NAP −11.0 m (RKN) to NAP −12.5 m (CTB). These are underlain by the 1st sand layer. The 2nd sand layer is found at about NAP −14 m to NAP −16 m, extending to NAP −25 m. Below the 2nd sand layer the stiff clay layer of

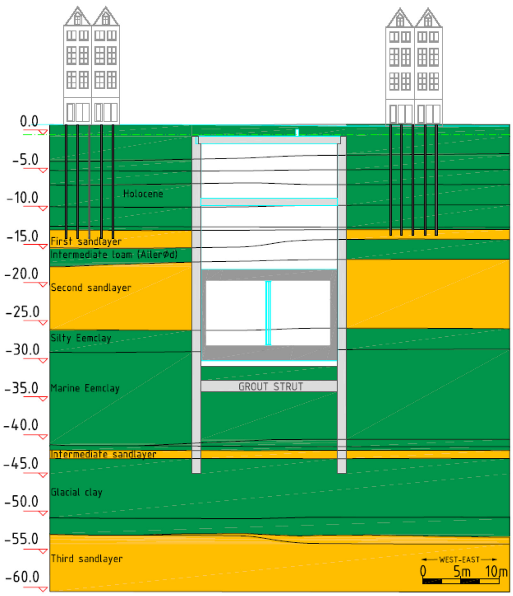


Figure 1. Cross section of VZG Station.

around 15 m thickness (the Eemclay) is found, sometimes separated by the Intermediate sand layer. The base is formed by the highly permeable 3rd sand layer. Phreatic ground water is maintained at NAP −0.4 m while the piezometric levels in the aquifers are influenced by deep pumping for the polders surrounding the city and found between NAP −2 m and NAP −3 m.

Details of the various soil profiles, their stratigraphy in more detail and soil properties can be found in (COB, 2011a). CPT data, ground water levels and characteristic test results of soil lab tests are also provided in this publically available report. Some specific values of the stiff Eemclay are given below.

The Eemclay has an average plasticity Ip of 19–30%. The average volumetric weight is 16.6–17.9 kN/m$^3$. Standard triaxial tests have been used to determine the soil strength and stiffness parameters, giving an angle of internal friction post peak of 32–34 degrees and cohesion of 10–15 kPa. The angle of internal friction at 0.5% strain is 28–30 degrees. The average stiffness E’50 determined from triaxial tests is 27 MPa with E’50, ref at 100 kPa being 10–14 MPa. E’50 at small strain levels is determined as 48–80 MPa according to Pound (1999). The average of Eoed; ref values for the Eemclay layer is 3–4.5 MPa. E’ur has been determined using several methods, including oedometer tests with relaxation, triaxial unloading (Consolidated Undrained Anisotropic Extension CAUE) tests, cyclic triaxial tests and CPM tests, as well as several correlations based on cone resistance and void ratio. Based on the CPM tests Eur; ref is 40–55 MPa. The Eemclay permeability is in the order of $10^{-10}$–$10^{-9}$ (m/s). All layers below the second sand layer (Eemclay and deeper) are overconsolidated. The overconsolidation ratio (OCR) is between 1.0 and 2.5, with 2.0 as average value for the Eemclay.

Figure 2. Historic buildings at Vijzelgracht (left) and Ceintuur-baan Station (right), dated 1880–1920.

## 2.3 *Construction methods*

The three stations have been built top-down to a depth of about 26–31 m, with 1.2 m thick diaphragm walls extending to approximately 45 m depth. See Figure 2 for a cross section of the deepest station (CTB). Before installing the D-walls, obstacles such as remains of wooden piles were removed from the Holocene deposits by using hollow core drilling. Ground improvement was implemented by replacing the subsoil with lean concrete up to 1st sand layer. The diaphragm walls consist of panels with lengths of approximately 2.8 m and 5.2 m. Traditional grabs and steel stop ends with water bars (PVC strips) are used to a depth of 36 m to provide waterproofing. The Eemclay layer provides a seal off for the bottom of the excavations, making it possible to work in dry conditions. To prevent uplift of the layers above the Eemclay, a passive system is installed to reduce the pressure in the sand layers while excavating. An active pumping system is installed in the intermediate sand layer locked in the Eemclay layer. CTB Station and VZG Station, both deeper than RKN, used over pressured air to finish the deepest parts of the excavation safely.

A large number of struts is placed in each station, with 5 layers above excavation level and one deep grout strut below the bottom of the excavation. Some of these layers include the final floors. The grout strut is installed prior to the excavation, as well as the top floor. The other struts have been installed during the top down excavation. For details on the grout strut, see Delfgaauw (2009) and Driesse et al. (2008).

Before the actual excavation took place, the following activities were executed in the order mentioned: raising the ground level (≈0.7 m), guide wall construction, diaphragm wall construction, jet grout strut installation, initial excavation to NAP −2 m, construction of the roof, backfilling above the roof and a pumping test for water tightness of the D-wall in the 1st and 2nd sand layers. After these activities, the final excavation took place in several stages.

## 2.4 *Geometrical data*

Over a period of about 10 years, preparations for the construction and the subsequent excavation of the deep

Table 1. Station dimensions.

| | RKN | VZG | CT B |
|---|---|---|---|
| Depth to NAP (m) | −26 | −29.5 | −31 |
| Depth of wall (m NAP) | −39 | −44.5 | −45 |
| Width (m) | 24.5 | 22 | 11 |
| Length (m) | 220 | 250 | 220 |

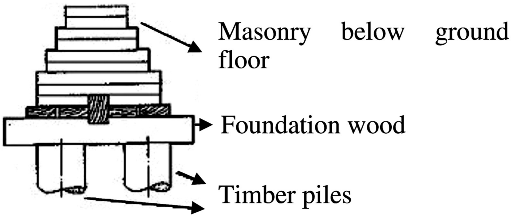


Figure 3. Typical cross section of base of the wall in masonry buildings (Zantkuyl, 1993).

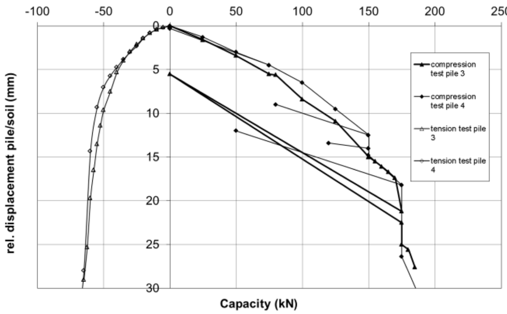


Figure 4. Representative load-settlement curves for timber piles in Amsterdam, after Hoekstra (1974).

stations and the structural finishing of the stations took place. The dimensions of the stations vary as shown in Table 1.

Details of the design of the stations can be found in Driesse et al. (1999) and Wit et al. (1999). For each station an extensive report is available with all construction details, information about the buildings and dates of the different construction activities. These reports can be found online as COB (2011b, 2011c, 2011d).

## 3 BUILDING AND FOUNDATION CHARACTERISTICS

Most buildings in the historic centre of Amsterdam are built with masonry walls, wooden floors and timber pile foundations, the piles being founded in the First Sand Layer at about 12 m below the surface level (see Figure 2). More recent buildings with 1–4 storeys are built with concrete walls and floors and prefabricated concrete or steel piles. Foundations for recent buildings are mainly in deeper layers such as the second sand layer. Some older buildings have a basement at half depth, with a raised ground floor level.

The masonry walls are typically 220 mm wide above the first floor, 330 mm wide above ground level and 440 mm wide below ground level. For foundations installed before the 1920's, the wooden piles were installed in pairs, with 0.8 m between the pairs, see Figure 3. Pile diameters for the timber piles vary from 160–300 mm (typical 180–200 mm) at the head and about 70–200 mm (typical 120–140 mm) at the toe. The average pile load at the head is about 90 kN/pile for the walls and 35 kN/pile for the facades.

Two typical load-displacement curves are shown in Figure 4. The timber piles in failure generally find 60% of their capacity at the toe, 10% as friction in the sand layer and 30% as friction in the Holocene layers. In the soft Holocene clay the maximum shaft friction develops at a relative displacement of about 25 mm and in the base sand layer at about 15 mm. The maximum base capacity for piles with average diameter at the base of 130 mm is reached at about 10% of the diameter, which is consistent with common design methods. The high horizontal flexibility assures that the piles can move rather easily with the soil in horizontal direction, compared to concrete piles.

Based on several pile load tests in the historic centre it is known that the wooden pile foundations have low factors of safety. Most timber piles deteriorate due to decay of the wood, which was confirmed during a large scale renovation program of the buildings prior to construction. About 25% of the foundations needed improvement.

The presence of soft soil layers combined with earlier city developments which included raising of the ground level causes on-going subsidence due to consolidation and creep. The piles have already experienced the maximum negative skin friction. The average neutral level of the old timber piles is found between NAP −6 m and NAP −10 m, while for modern foundations this level is found at the top of the first sand layer, approximately NAP −12 m.

Buildings between 1920 and 1940 usually have a single row of piles with a reinforced concrete beam on top. After 1945 other pile types were introduced, especially the driven prefabricated concrete pile. From about 1965, it became common to account for negative skin friction in the design, although this effect was often underestimated until the 1980s (Van Tol 1994). Therefore, almost all foundations older than 1965 and even a smaller percentage before 1980 have a neutral level much higher than the tip level.

## 4 MONITORING SYSTEM

In order to determine the displacements of the historic structures along the deep stations an extensive, mostly automatic monitoring system was installed in the city centre from the year 2000. This included in total 74 robotic total stations for over 1700 prisms on the buildings. Each robotic total station monitors about 50 to

100 prisms. The displacement of the prisms is measured in three directions (x, y and z). Measurements made with the RTS are related to other RTS locations outside the zone of influence. Prisms are located on the fronts and the sides of the buildings, usually a minimum of 4 per building. Secondary instrumentation comprises of precise levelling points installed on structures being monitored primarily by robotic total stations. Precise levelling is made to deep datums in the Third Sand Layer outside the zone of influence for the extensometer heads and building levelling points. The secondary system is mainly used as a backup system and measured at intervals of 6–12 months.

In order to handle the large amount of monitoring data, software applications have been developed. The applications use the Geographical Information System (GIS) as user interface, see also Netzel & Kaalberg (1999). The GIS has been developed to store, analyse, structure and visualise the data used in settlement risk management, in order to provide rapid reaction opportunities. From each building within the influence zone numerous facts are stored, such as state of the foundation, photograph of the original state with prism locations, owner details and details of its use.

The monitoring instruments further included extensometers behind the wall, inclinometers in the soil and in the wall and manual levelling of the surface and the buildings, which are all stored in the GIS as well. Details of the monitoring system, its accuracy and sensors can be found in (COB, 2011a) and in Kaalberg et al. (2003). More information on the GIS system and the monitoring prior to construction can be found in Cooke et al. (2011).

Inclinometers and extensometers and surface measurements are placed to a distance of 50 m away from the diaphragm wall and a maximum depth of 65 m. Each station has 4 cross sections with subsurface measurement perpendicular to the station, see Figure 5 for an example of a cross section at CTB Station and Figure 6 for details of one of the arrays at Rokin station.

The extensometers are placed at NAP −1.5 m, NAP −13 m, NAP −22 m and NAP −30 m and the deepest anchors are fixed at NAP −73 m closest to the excavation to NAP −49 m further away from it.

The overall convention for the measurements is that in the X direction values are positive to the East, for the Y direction positive towards the North and for the Z direction positive for heave values.

## 5 SURFACE MEASUREMENTS

Figure 7 shows the measurements of the ground surface for all three stations, Rokin, Vijzelgracht and Ceintuurbaan, for various stages of the excavation. For each stage, the excavation depth H is mentioned in the figures.

During the preliminary activities (Figure 7a) a hogging displacement is found. Most of the displacement

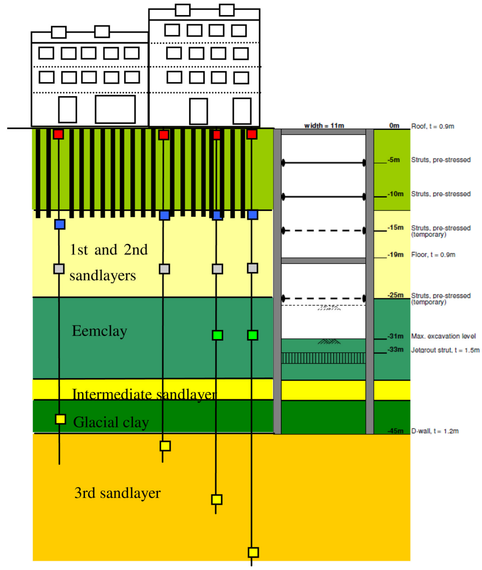


Figure 5. Cross section of Ceintuurbaan Station with soil profile and extensometer locations.

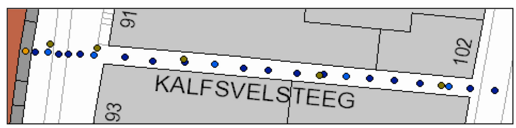


Figure 6. Measurement array at RKN Station with surface measurements (blue dots), inclinometers and extensometers (brown dots).

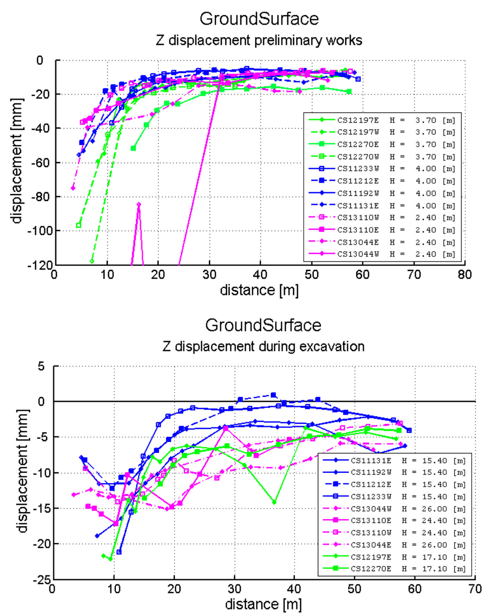


Figure 7. Surface settlements (a) due preliminary activities (b) during excavation. CS13xxx lines are for CTB, CS12xxx for VZG and CS11xxx for RKN.

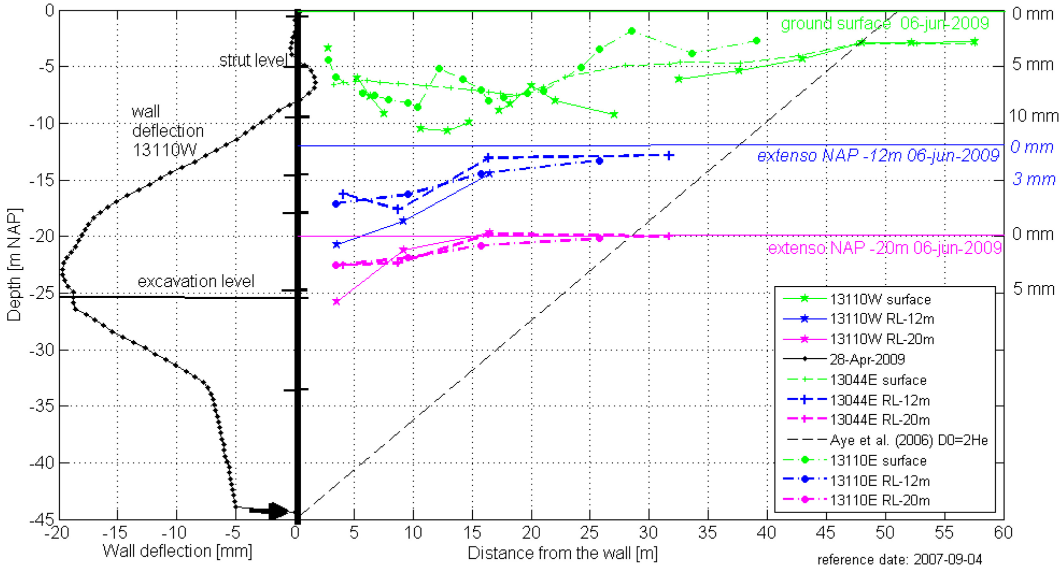


Figure 8. Measured ground displacements at Ceintuurbaan Station.

in this stage is caused by predrilling and raising of the ground level close to the edge of the excavation, both having the largest impact on the top layers, thus resulting in this curved profile.

During the deep excavation stages, shown in Figure 7b, the shape of the surface displacement consists of both hogging and sagging parts.

The sagging part could not always be captured all the way to the wall, because some settlement markers were lost in the process of construction.

## 6 EXTENSO-INCLINOMETER MEASUREMENTS

Especially for buildings with deep foundations, the displacements at deeper levels in the ground are important. Figure 8 shows the measurements of the vertical ground displacement at the surface compared to the extensometer data at two additional depths, NAP-12 m and NAP-20 m.

The inclinometers were placed at some locations in tubes in the wall and at the cross sections in the soil. The automatic measurements in the soil initially worked well, but beyond the 10 year long construction period went over their guaranteed working life and often drifted. The manual measurements were fine, but only sparsely available and could obviously start not before the walls were installed.

Some interesting results can be taken from the early years of the inclinometers, such as presented by Korff et al. (2011) for the analysis of the effects of the predrilling activities and Haryano & Korff (2014) for the diaphragm wall installation. De Nijs & Buykx (2010) present data from the inclinometers in the wall at Ceintuurbaan Station.

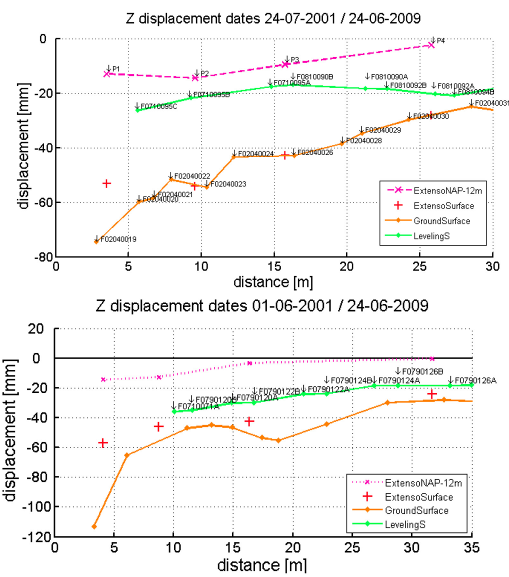


Figure 9. Ground and building displacements for (a) CS13044 and (b) CS13110 (at Ceintuurbaan) in the period 2001–2009.

## 7 BUILDING DISPLACEMENTS

Figure 9 shows the manual building displacements (LevelingS) compared to the soil displacements at surface (GroundSurface) and pile tip level (ExtensoNAP-12 m) for a series of buildings with old timber piles. The buildings settle more than the foundation layer, but less than the soil at the surface. The oldest foundations (Figure 9b) show the largest settlements.

Over this longer period, the manual measurements showed very reliable results, which are especially useful to compare them to the soil displacements. The automatic building monitoring system with prisms has a much higher measuring rate with which it was even possible to show temperature effects (Cooke et al., 2007) and detailed information about the relationship between the construction process and the settlements.

## 8 CONCLUSIONS

The dataset of the three deepest stations of the NorthSouthLine has now been published and made available for validation of design methods.

All the background data and information is published in COB (2011a, 2011b, 2011c and 2011d) which can be found on www.noordzuidlijnkennis.nl and www.cob.nl. The actual monitoring data can to a large extent be found in Korff (2013). The collection and publication of the data was performed in cooperation with the Dutch Centre for Underground Construction (COB). The authors wish to thank the city of Amsterdam for permission to publish the data.

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