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Settlement behaviour after compensation and corrective grouting

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ABSTRACT: Settlement of buildings on piles after compensation grouting and corrective grouting is studied for 2 different locations in Amsterdam. The following situations have been studied: Long term settlement behaviour after pre-grouting, settlement behaviour after corrective grouting and short term settlement behaviour after TBM passage. Settlement was measured with liquid level systems as well as with prisms. Differences between these systems will be discussed. The settlement behaviour appears to be time dependent with periods of one day and a longer period of one year, but the permanent settlement is only very small (1 mm in 3 years). Long term settlement of adjacent buildings, is measured after corrective grouting that was performed to stabilize the foundations after an incident with a leaking D-wall joint. This is likely to be caused by the soil disturbance due to the incident and such settlements were not measured at locations without soil disturbance. The passage of a TBM close to one building leads to a settlement of 2 mm at maximum during passage. Further settlement could be adequately arrested by compensation grouting.

1 INTRODUCTION

The importance of the compensation grouting technique is that it is capable to create heave in the soil or heave of buildings. This makes it possible to compensate for settlement that had occurred or that is likely to occur without compensation grouting.

The success, or failure, of a compensation grouting project depends on the heave that can be created. During the metro building in Barcelona, it appeared that it was not possible to create heave with the compensation grouting system (but only more unwanted settlement) and therefore the project was abandoned, and the metro was finished without compensation grouting. This is quite an unusual result and will be discussed further in this paper.

The construction of the underground North/South line in Amsterdam offered the opportunity to measure the heave and settlements of buildings close to this metro line. This heave was measured in the relative short periods that compensation grouting was performed. At locations where compensation grouting was planned, an accurate liquid leveling system was applied. This provides the opportunity to investigate the long term settlement behaviour.

The paper deals with the short and long term heave and settlement. The settlement discussed is the settlement of the foundations of buildings. All buildings are supported on piled foundations. Measurements are present and possible explanations are discussed. Settlement measurements from the locations dealt with have been published before Bezuijen et al. (2009) and Bezuijen (2010). In this paper the measurements stretch out over a longer period, showing also yearly fluctuations and for one location the TBM has passed the location and the influence of this passage regarding settlements will be shown.

2 LOCATIONS

This paper is focused on the measurements of two locations. One location is the building ‘Industria’ at the ‘Rokin’ close to the Dam square in Amsterdam.
Pre-grouting was performed as a start of compensation grouting because one TBM of the North/South line passes close to this historical building. The results of these measurements are representative for the results obtained at other locations along the North/South line.

The second location was at the Vijzelgracht station where a leakage had occurred in a diaphragm wall (Korff et al. 2009). This had led to settlements of up to 0.25 m for the historic houses close to the building pit. Corrective grouting was applied to re-strengthen the subsoil and arrest the settlements.

Monitoring was performed at both locations by means of a liquid leveling system. The reference position was remote from the tunnel so as not to be affected by the construction process.

2.1 Location Industria

The pre-grouting at Rokin was performed in 2007. TAMs were installed from an installation shaft at 15–18 m depth, see Figure 1. The subsoil consists of a silt called the Alleröd and a sand layer.

After the installation of the TAM’s (Tubes à Manchettes, the injection tubes), grout was injected to create a few millimetres of pre-heave in the part of the building that is closest to the TBM passage. The idea of this pre-grouting is that it allows for some settlement when the tunnel passes before more grout has to be injected and that importantly the soil is improved, which will also lead to a reduction of settlements at the moment the TBM passes. The TBM passed this location 2.5 years after the pre-grouting, in 2010. Shortly before the TBM passage about 16,000 l of grout was injected to compensate for settlements that had occurred after the pre-grouting. The grouting area underneath the Industria building is approximately 636 m$^2$. The average heave in this area is 1.3 mm and this means that the efficiency (defined as the average heave times the grouting area divided by the total volume of grout injected) of this second pre-grouting is 4.8%.

During TBM passage (from 18-06-2010, 9:00 until 19-06-2010, 3:40) 5,000 l of grout was injected.

2.2 Location Vijzelgracht

The layout of the location Vijzelgracht is shown in Figure 2. The diaphragm wall is shown on the right side of the picture. The big grey area is the corrective grouting area, the lines are the TAMs and the thick, grey lines show the positions of the foundations of the settled buildings.

The foundations of these 17th century buildings consist of a row of 2 wooden piles under the brick walls to a depth of –13 m below surface into the 1st sand layer, see Figure 3. The positions of the liquid leveling instruments (LL1 through LL14) attached to basement walls that were used for the displacement monitoring, are presented in Figure 2 as well.
as the position in the diaphragm wall where the leakage occurred (between panels 89 and 90).

The TAM’s were placed at an angle of 16 degrees (see also Figure 3). Horizontal TAM layout was not possible because after the incident it was not allowed to excavate the box further before stabilizing the buildings.

Grouting was performed using Biltzdämmer, a hydraulically-setting premixed dry mortar (Heidelberg, 2009). Three different mixtures were used, see Table 1. The different mixtures were used for all pumps, sleeves and in the beginning and end of the grouting operations. However, mixture MF was used more in the beginning, M8 in the middle and M6 was mostly used at the end. In this table the average date is the mean date of all injections with this mixture. Grout was injected using different TAMs at the same time in the injection periods.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Binder/Water ratio</th>
<th>Density (kg/m³)</th>
<th>No of injections</th>
<th>Total litres</th>
<th>Average date</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6</td>
<td>0.714</td>
<td>1360</td>
<td>1636</td>
<td>41735</td>
<td>24-09</td>
</tr>
<tr>
<td>M8</td>
<td>0.625</td>
<td>1323</td>
<td>1298</td>
<td>29315</td>
<td>09-09</td>
</tr>
<tr>
<td>MF</td>
<td>0.5</td>
<td>1269</td>
<td>601</td>
<td>12500</td>
<td>23-08</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>3535</td>
<td>83550</td>
</tr>
</tbody>
</table>

Figure 4. Result of pre-grouting: Measured heave after pre-grouting. Note that the lines of equal heave are parallel to the tunnel axis. The gray lines show the walls of the building that were heaved. The contours present the heave created in mm (21-10-2007).

Figure 5. Measured heave and settlement from March 2007 up to 2 August 2010 on both sides of the building. Locations are indicated in Figure 4 (2 of these lines and M3.09 near the middle of the building are shown in Figure 10). Data taken every 2 hours with a moving average over 31 data points to reduce noise.

before the passing of the TBM, some extra pre-grouting was performed to reach the original level that was reached after the first pre-grouting. The passage of the TBM results in some settlement and after the passage of the TBM there is some heave which occurs relatively slowly and appeared to be caused by a measurement error as happened one year earlier, see Figure 5. Building prisms showed no such movement, see below.

3.1.2 Prism measurements
The liquid level system is an accurate measurement system that can deliver data with a relative high frequency as is necessary to follow the heave created...
during compensation grouting. However, it is susceptible to disturbance or drift, as was the case in the second half of 2009. Therefore the results of this system have been compared with the results of the prism measurement system that operates with a lower frequency but are more reliable. The results for Industria are shown in Figure 6.

The results show that the liquid level system results in quite comparable results as the prism measurements during TBM passage, but the slow heave that is measured after TBM passage with the liquid level system is very likely a measurement error, since this is not found in the prism measurements.

3.2 Location Vijzelgracht

3.2.1 Liquid level measurements

Figure 7 shows an overview of the corrective grouting site near the Vijzelgracht station. The figure shows in plan view the position of the piled foundations (the black lines), the positions of the liquid leveling points (the black dots), the total amount of grout injected in litres during the project at that particular injection point (the grey circles, proportional with the amount of grout injected) and the heave created at the end of the corrective grouting project. The heave indicated is the heave of the basement walls and is interpolated from the results of the liquid leveling system. The heave is shown just after the corrective grouting campaign.

The corrective grouting campaign resulted locally in a significant increase in cone resistance (Bezuijen et al. 2009, Bezuijen 2010) as was the primary objective. Remarkable was that after the compensation grouting campaign there was ongoing settlement for quite some time. For this paper it was possible to extend the measurements over a longer period, see Figure 8.

Figure 7. Corrective grouting Vijzelgracht. Volumes injected and heave created at 5–10–2008.

Figure 8. Heave and settlement measurements, Vijzelgracht location. Data taken every hour with a moving average over 31 data points to reduce noise.

The figure shows that although the grout injections start on 10th August 2008, at first the settlement rate increased, probably due to disturbance of the 1st sand layer by the TAM installation and the first injections. Most settlement was recorded at the instruments h03 and h04 at some distance from the leakage, see Figure 2. The injection of the first 21,000 litres of grout did not directly reduce the settlements but were needed to strengthen the soil and to reduce the progress of ongoing settlements. Grouting in September and the beginning of October of 2008, when another 62,000 litres were injected, led to heave of the buildings. Significant settlement occurred after the ending of the grout injection. This will be analysed further in the next sections.
It was not possible to find a relation between the location of the heave, measured at the building and the location of the injection. This is caused by the stiffness of the building that was strengthened by wooden beams after the incident (Bezuijen, 2010).

Injection pressures vary significantly during the project. No clear correlations were found with the location, time and the number of injections (Bezuijen & Tol, 2011).

3.2.2 Prism measurements
Three prisms where attached to the houses that were subject to corrective grouting. One, VZG26, is above the LL1 instrument (see Figure 2), two other prisms VZG24 and VZG22 are close to each other above LL5. Figure 9 compares the results of the instruments mentioned. The results show that there is good agreement between both measuring systems. Only the dip measured in h01 (data from LL1) was not found in VZG26, because some data points fail in VZG26 (around August 2008). Furthermore, the ongoing settlement measured with h05 (data from LL5) after November 2009 was not measured with VZG22 and VZG24. This may be caused by drift of LL5.

4 LONG TERM SETTLEMENTS
4.1 Location Industria
Three instruments were selected to investigate the long term settlement behaviour after compensation grouting. The one which showed the largest heave after the first pre-grouting M3.01, one which an average heave, M3.09 and one which hardly any heave (M3.17) after the first pre-grouting, see Figure 10.

The lines show that there is some seasonal variation of approximately 0.5 mm in the measurements. This may be temperature influences. It is not known whether this seasonal variation is instrument or structure driven or a combination. On top of that variation, there is a limited long term settlement for the locations where heave was created by compensation grouting. The settlement was measured just after the pre-grouting (from 24-10-2007 until 13-03-2008), called settlement short and over the whole period until the 2nd pre-grouting from 24-10-2007 until 01-04-2010, called settlement long. The results are presented in the table below.

The short term settlement rate is determined by linear regression. For the long term settlement rate this appeared to be complicated because this is disturbed by the long term fluctuations. Therefore the long term settlement rate was determined by the straight line that fits the data points from just after the first pre-grouting with the data points just before the second pre-grouting. Assuming that M3.17 presents the background situation, the results show that more than halve of the settlement measured on the short term is caused by the seasonal variations. The long term settlement rate after grouting is limited to 1 to 2 micron a day and is only slightly higher just after pre-grouting compared to the whole grouting period. From this it can be concluded that the settlements in the five months after pre-grouting are very limited.

<table>
<thead>
<tr>
<th>Instr.</th>
<th>Settlement short (mm/day)</th>
<th>Settlement long (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3.01</td>
<td>$3.7 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>M3.09</td>
<td>$3.2 \times 10^{-3}$</td>
<td>$1.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>M3.17</td>
<td>$1.9 \times 10^{-3}$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Figure 9. Vijzelgracht. Data liquid level system and prisms compared. (data every hour no averaging)

Figure 10. Three instruments selected for analysing the settlements (same averaging as Figure 5). Locations are indicated in Figure 4.
4.2 Vijzelgracht location

A much larger settlement rate was found at the Vijzelgracht location compared to the Industria location. This was explained by the disturbance of the soil after the incident. Settlement rates up to 0.2 mm a day were reported (Bezuijen et al. 2009). The average settlement recorded by h01 between 5-10-2008 and March 2009 was 0.05 mm a day. Looking at Figure 8, this fast settlement seems to stop at the end of March 2009, there is even a temporary heave. However, after that the settlement goes on with a lower rate until approximately November 2009. The rates measured for the different instruments over this period vary between 0.51 until 8.6 micron a day, but only 5 instruments recorded a settlement of less than 2.5 micron a day (approximately 3 and 1 mm a year respectively). The prism measurements show that the measurements are stable after November 2009.

From these results it can be concluded that for more than a year the settlement rate is increased, compared to the Industria location. Note that there were no measurements recorded from approximately October 2009 until May 2010, (the straight lines in Figure 8).

5 SETTLEMENT AND HEAVE DURING TBM PASSAGE

On the 18th and 19th of June 2010 the TBM passed the Industria location. The amount of grout injected and the settlement variations found just before and during TBM passage, are shown in Figure 11 for the same 3 measurements points that were also shown in Figure 10. Figure 11 is a zoom of Figure 5 and shows the total injected volume and deformations at the Industria location just before and during TBM passage. From the results it appears that the grouting prior to the TBM passage directly led to heave. During the TBM passage there is a settlement of 2 to 2.5 mm close to the tunnel. This settlement stops after the TBM passage and the compensation grouting. During TBM passage approximately 5,000 litres are injected, this did not lead to any heave but it effectively stops the settlement, which was the primary objective.

Also for this location it was not possible to relate the injection at one location to heave or slowing down of the measured settlement rate. Figure 12 shows a further detail of the measured settlements, now for all measurements points, at the moment of TBM passage and showed measurement fluctuations that were measured with a daily period.

The daily variations were caused by temperature fluctuations and instrument problems. Figure 12 shows that measurement point M3.01 starts to settle when the TBM passes. This measurement point is at the upper right part of the Industria building (see Figure 4), where the TBM first passed close to the building. During TBM passage the other points close to the TBM start to settle later. The heave that should be the result of the grout injections is masked by the daily fluctuations and the ongoing settlement that is corrected.

6 DISCUSSION ON THE RESULTS

The results of the measurements at Industria show that it is possible to control settlement and heave of piled foundations by means of compensation grouting in saturated dense sand within millimeters.
In more disturbed soil, for example after an incident as occurred at Vijzelgracht Station, long term settlements after corrective grouting can be significant, although the CPT’s show that there is a significant improvement of soil properties after the corrective grouting. This may be caused by movement of the piles with respect to the soil. Up to a bit more than one year after the grouting there was still a slightly increased settlement rate. The different results compared to the ones found at Industria, are most probably caused by the very different disturbed soil conditions. Compensation grouting works with millimeter accuracy is possible in undisturbed soil conditions. In disturbed soil conditions it is possible to create a significant soil improvement as appears from CPT tests, Bezuijen et al. 2009). However, in the Vijzelgracht case the layers above the layer where compensation grouting is applied most likely influenced the pile foundations leading to long term settlements.

The passage of the TBM at the Industria location led to only a few millimeters of settlement. This could be stopped effectively by compensation grouting. Since compensation grouting was carried out, it is not known what would be the result without the compensation grouting during TBM passage. However, based on the settlement and heave registrations the injections carried out were effective in maintaining the building within the required limits. The injection of 16,000 litres of grout just before the TBM passage led to a maximum heave of 2–3 mm, see Figure 11. From that it can be expected that the injection of 5,000 litres during TBM passage led to a comparable heave (or a reduction of settlement) of 2–3 mm or less, considering the much smaller area of building affected.

The Barcelona case, mentioned in the introduction has possibly to do with the unsaturated conditions that were present. In unsaturated conditions it is possible to over excavate for example during the installation of the TAM’s without settlement of buildings on top as a direct result. During TBM-tunnelling in Toulouse, also under unsaturated conditions, settlements due to over excavation appeared at the surface months after the TBM had passed. In the saturated conditions present in Amsterdam there is an immediate response. This can be seen at the beginning of the measurements at the Industria location. The installation of the TAM’s resulted directly to some millimeters of settlement. This is an advantage when compensation grouting is used in saturated conditions and makes ‘surprises’ as in Barcelona unlikely for the compensation grouting works in Amsterdam.

7 CONCLUSIONS

Although measurements are extended over a longer period now, the conclusions are not really different from the conclusions in earlier publications (Bezuijen et al. 2009, Bezuijen 2010): For the soil conditions present in Amsterdam, and only limited soil disturbance, compensation grouting is able to control the settlement and heave of buildings on piled foundations within millimeters. The settlement of the Industria building due to the passage of the TBM could be halted effectively.

For really disturbed soil conditions, long term settlements might be expected, that can be quite significantly (nearly 10 mm was measured at the Vijzelgracht location).

When analyzing the reaction of buildings due to compensation grouting, even in pre-grouting without soil settlement, it is difficult to find the influence of a single grout injection due to the stiffness of the building.

In the saturated soft soil conditions present in Amsterdam all soil disturbances immediately lead to soil movements and thus to movement of the foundations. For compensation grouting this is an advantage, because it is possible to compensate promptly. From this experience it seems that compensation grouting in sand is more suitable when saturated conditions are present, compared to unsaturated conditions.

A liquid level system is very useful to measure settlements during compensation grouting. When such a system is used for several years to determine long term settlements, there has to be a control system, as for example prism measurements, to detect possible instrument drift or disturbance of the system.

REFERENCES


