Corrective and Compensation Grouting in Sand – Case Histories

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1. Introduction

Compensation grouting is nowadays a rather common technique to compensate for settlements that may occur due to underground construction. It is applied successfully underneath important buildings as for example the Big Ben in London (Davis et al, 1999), which means that it is a trusted technique. Although in most cases a reliable technique it is not free of problems. One of the problems that may occur is long term settlement. Au (2002) has shown that in normally consolidated clay the consolidation of clay may lead to even negative efficiencies (the soil shows settlement instead of heave some time after the grout injection) and in some cases the efficiency is positive but much lower than expected. Furthermore compensation grouting underneath piled foundations is a quite new application. Therefore it was decided by the project organization of the Amsterdam North/South line to perform an experiment before the tunnel boring starts. Two buildings in the centre of Amsterdam at the Rokin would be pre-grouted to achieve a minimal heave of 3 mm just to investigate how the compensation technique works under the circumstances present in Amsterdam. This work was performed in 2007.

Due to an incident during the construction of Vijzelgracht station (leakage through a diaphragm wall) it is possible to compare the results the pre-grouting described before with the results of corrective grouting that was necessary to stabilize the piled foundations of historical houses that had settled up to 0.15 m due to the leakage (Korff et al. 2009). Both situations had a comparable soil layering. The main difference is that the sand layers in the corrective grouting situation at Vijzelgracht are disturbed by the leakage and that the cone resistance of these layers is significantly reduced, as will be shown in the later sections and this was not the case at the pre-grouting location at Rokin.

Aim of the paper is to investigate the influence of the soil disturbance on the long term settlement behaviour and to compare this with an undisturbed situation.

2. Pre-grouting

The pre-grouting was performed at Amsterdam, Rokin in 2007. TAMs where installed from an installation shaft at 15 – 18 m depth, see Figure 1. The subsoil consists of silty sand called Alleröd and sand. Grout was injected to create a few millimetres of heave in the part of the building that is closest to the location where the tunnel will be constructed. The idea is that this allows for some settlement when the tunnel passes before more grout has to be injected and that, as in Perth, the soil is improved, which will also lead to a reduction of settlements.

The results show that a very controlled heave of the buildings below which the compensation grouting was performed was possible, see Figure 2. However, the amount of grout that had to be injected to obtain this heave was much more than expected, which may indicate that the efficiency of the process below a pile foundation is less than for other foundations.
The grout was injected at 10 l/min. 50 to 200 litres was injected at one injection point during one injection. The upper bound of 200 litres is quite a lot compared to the volumes injected in other programs where normally up to 50 litres will be injected during one injection at one opening.

Figure 3 shows the heave and settlement as function of time for the various measurement points indicated in Figure 2. At the beginning of the grouting campaign there is some settlement, which is corrected by grout injections. Most of the heave was generated rather quickly by the injections that were performed in September 2007 (9-2007 in the graph). This heave is followed by a relatively high settlement rate, for some measurement points this was 0.05 mm/day during the remaining days in September. Therefore some extra grout is injected at the end of October 2007 and after that there is only limited settlement. The maximum settlement is for instrument M3.13, which settles 2 mm after the pre-grouting. For the other instruments the settlement after the pre-grouting is 1.5 to less than 0.5 mm over more than a year. This is comparable to the natural settlement present in Amsterdam.

Figure 1. Cross-section installation shaft, pile foundation and TAM positions in the Amsterdam subsoil at the Rokin pre-grouting trial. Only the upper TAMs where used.
In June 2008 there was a leakage in a diaphragm wall that was made for the Vijzelgracht station of the Amsterdam North/South line. This leakage caused a sand-water mixture to pass through the wall, resulting in significant (up to 0.15 m) settlement of a block of 4 adjacent buildings (Korff et al, 2009). It was acknowledged that the piled foundations under 2 of these buildings had not only settled because of
the sand that disappeared, but that also the bearing capacity was significantly reduced because the remaining soil around the pile tips now had a much lower density than it had before the incident. The brickwork walls of the buildings were braced with timber beams immediately after the incident in order to avoid progressive collapse of the buildings. After this bracing, it was decided to use corrective grouting to increase the bearing capacity of the sand and consequently lift the buildings up to an agreed maximum of 10 mm. The soil is also strengthened due to densification. When lifting of the building would be possible, it would implicitly be proven that the end bearing capacity was restored, and stability of the building was guaranteed again. Moreover it would be proven that it was possible to compensate for future settlements that may possibly occur by ongoing construction of the station.

3.1. The corrective grouting program

The layout of the site is shown in Figure 4. 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 7 (Netzel and Kaalberg, 2000). 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 4 as well as the position in the diaphragm wall where the leakage occurred (between panels 89 and 90).

A cross-section is shown in Figure 5. The TAM’s were placed at an angle of 16 degrees. Horizontal TAM layout was not possible because it was not allowed to excavate the box further before stabilizing the buildings.

Corrective grouting was performed using a 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, 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 at 10 l/min on average using different TAMs at the same time in the injection periods. The injected volume during one injection was up to 70 litres in the very beginning, but after the first week of injection this was reduced to 20 to 40 litres. Injection
pressures varied between 6 and 45 bar, and were 17 bar on average. The number of injections at each injection point varied between 30 and 72.

Table 1: Data on injection grout mixtures used, see also text.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>kg dämmer/liter water</th>
<th>Density (kg/m³)</th>
<th>number 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>

3.2. Heave and settlement results

Figure 6 shows an overview of the corrective grouting site. 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 amounts of grout injected in liters during the project for each injection point during all injections (the grey circles) and the heave created at the end of the corrective grouting project (the contours). The heave indicated is the heave of the basement walls and is interpolated from the results of the liquid leveling system. Additionally Figure 6 shows the position of 2 CPTs: An ‘old CPT’ taken before the start of the works for the station, and the location of 2 CPTs in the basements of the building, taken before and after the corrective grouting taken at a distance of approximately 0.5 m. The results of the CPTs are shown in Figure 7.

The colors on the right side of the plot show the different layers in the Amsterdam subsoil at Vijzelgracht. Layers with a number less than 13 are soft Holocene layers (clay and peat) as can be seen from the CPTs. Layer 13 is the first sand layer in which the pile toes are founded and which consists originally of medium dense, medium fine sand, layer 14 is Alleröd, a sandy silt layer and layer 17 is the second sand layer, fine to medium coarse sand. In the depth were most of the grout is injected, there is a very large increase in cone resistance. More details on for example injection pressures can be found in Bezuijen et al. (2009).

Figure 6. Overview corrective grouting at Vijzelgracht, see also text.

Figure 7: CPT before (1) and after (112) the corrective grouting campaign, but both after the leakage compared with the ‘old CPT’. Locations see Figure 6.
Figure 8 shows the results of the liquid level instruments over time. The instruments were placed a few days before the start of the corrective grouting. The period that corrective grouting was performed and grout was injected is shown in the figure. The first injections resulted only in more settlement. It took several weeks before the settlement was reverted to heave. According to contract a maximum heave of 10 mm was realized. At the end of the corrective grouting ongoing settlements were measured for approximately 5.5 months for most of the instruments and even longer for 2 instruments (LL4 and LL5) that still have not reached equilibrium within the measurement period (until 1 November, 2009).

![Figure 8. Heave and settlement as a function of time.](image)

### 3.3 Extension of the affected sand layer

The incident showed that a relatively limited incident can lead to quite significant settlements. It is assumed that the sand that leaked through the diaphragm walls was from the pile bearing layers and that the sand removal led to an increase in porosity and a reduction of the tip resistance of the piles (Bosch and Broere, 2009). Consequently the pile tip resistance became too small to carry the building on top and settlement starts.

Tremblay and Oldakowski (2003) describe small scale experiments to investigate the sand behavior of a sand body where sand and water are removed. They also present a numerical model, but here the qualitative description of the process is of importance to understand the mechanism involved. Their experiments led to what they called a ‘wormhole’ an area with very loose sand an area with some ‘tensile failure’ bands and an area that is still the original sand core. The stiffness of the original sand is more than 30 times larger in their experiments than in the center of the wormhole and the wormhole act as a high permeability channel. The sand directly around the wormhole is in a very loose state.

Based on the experiments described above, it is assumed that also the leakage of the diaphragm wall leads to the high permeability channel and around that channel is an area with a high porosity. The stresses in this high porosity area are just enough to support the arch that separates the high porosity sand from the original sand.

In such a situation only a limited amount of sand leakage can lead to quite a volume of sand that is affected. Assuming an initial porosity of 38% and a maximum porosity of 48%, 1 m³ of sand that has flown through the diaphragm wall means that for around 5 m³ of sand the porosity is increased.
3.4 Corrective grouting findings

The results show that the first injections led to even more settlement. This is in line with the statement above that the leakage had caused a relatively large area with relatively loose sand. Fracture grouting in loosely packed sand has only a limited efficiency (Kleinlugtenbelt et al., 2006) and the disturbance of the sand package leads to densification of the sand resulting in more pile settlement. Only after the injection of 21,000 litre of grout the pile foundation starts to rise. 83,550 litres were injected in total. The efficiency in general was only 1.7%. Several factors may have contributed to this low efficiency. It was mentioned already that the loose sand will densify, which decreases the efficiency. Furthermore, the grout used, creates a rather permeable filter cake. Consequently the grout will lose a lot of water due to pressure filtration before the hardening starts. In laboratory tests is was found that pressure filtration alone can reduce the efficiency to 30%. It should also be realized that the settlement and heave is measured on the building and not on the soil. When heave is created, it is still possible that the piles settle with respect to the soil because the end bearing capacity in the loosened sand is still too low. On the most Northern side of the building, the part with the highest Y-coordinate in Figure 6, the building is connected with another building preventing heave, although quite significant amounts of grout were injected here through TAMs 1, 2 and 3, see Figure 6.

4 Settlement after the corrective grouting campaign compared with pre-grouting

A remarkable result in the measured heave is the ongoing settlement after the corrective grouting campaign. As a consequence of this settlement the heave is negative for some instruments, see Figure 8. Ongoing settlements are recorded for 5.5 months. After this period most of the instruments of the liquid levelling system the settlement stops. However, LL4 an LL5 show settlement even after this period although the settlement rate decreases.

This ongoing settlement was not found in the pre grouting campaign at Rokin, described in Section 2. At that location, with comparable soil conditions, where compensation grouting was performed in undisturbed soil at a larger depth (18.5 m) only 0.5 to 2.0 mm of settlement was found in two years. It is therefore reasonable to assume that the soil disturbance due to the incident has reduced the efficiency of the corrective grouting and also plays a role in the ongoing settlements. Most likely the incident and the corrective grouting afterwards have led to stress changes in the Holocene layers above the First sand layer (see Figure 7). This caused to consolidation of these layers (Soga et al., 2004). The settlement of the piles during the incident have changed the negative skin friction to a positive skin friction, but the consolidation of the excess pore pressures in the Holocene layers led again to a negative skin friction an thus to an extra loading on the piles. The pile tip force is still equal to the maximum bearing capacity of the tip (must be when the piles settle with respect to the sand layer) and therefore an increase in loading caused by the skin friction changing from negative to positive led to further settlements.

Although it was possible to stabilize the foundation successfully with corrective grouting after the incident described, this case history shows that the behavior of the soil as well as the pile foundation is different from a 'virgin' situation without such an incident.

5 Conclusions

This case study led to the following conclusions:

- In undisturbed soil the results of the pre-grouting looks promising. It is possible to create heave in a controlled way.
- It is also possible to stabilize a foundation with corrective grouting after settlements that were caused by leakage of sand and water through a diaphragm wall.
- Efficiency of the corrective grouting will be (much) less in case of disturbed soil conditions with loose sand.
- Settlements can be expected after the corrective grouting campaign when the loading on the piles is influenced by skin friction caused by consolidating layers. In this case history these settlements went on for 5.5 months and for two of the instruments even longer.
6 Acknowledgements

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7 References


