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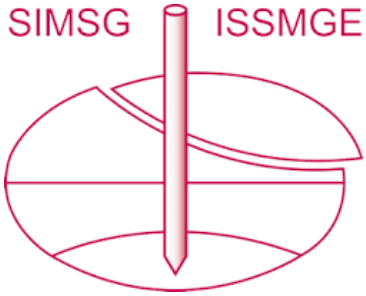

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Compensation grouting of piled foundations to mitigate tunneling settlements

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ABSTRACT: The Amsterdam North/South Metro line is a challenging project in an adverse urban environment of very soft soil and historical buildings founded on wooden piled foundations close to the tunnels. Following successful full scale trials, compensation grouting was selected as the most preferable method for mitigating movements. The final design was optimised by introducing an "interception design philosophy" with the TAMs installed midway between the tunnels and the pile toes, minimizing the risk of settlements during drilling. Being novel, an observational approach was applied, installing a single layer initially. Hydraulically jacked segmental shafts, new to the Netherlands, were able to meet the very strict settlement criteria and significantly reduce the hindrance to the urban environment. During the preconditioning phase, the buildings were heaved by approximately 4 mm. During tunnelling the single layer of TAM's provided good control and compensated the tunnelling induced settlements. In this paper the innovative design and observational construction approach will be explained and the results discussed.

1 INTRODUCTION

The Amsterdam North/south Metro scheme includes 3.8 km of twin tunnels of diameter 6.5 m. which pass through the centre of the city from Central station in the North to RAI in the south.

The tunnels are constructed using an Mixshield tunnel boring machine to reduce volume loss and disturbance to the environment. The previous section of the Amsterdam Metro was constructed in the 1970s through the city centre using cut and cover techniques and resulted in significant disruption and damage. The City Council was determined that the North-South section would be constructed with minimum environment disruption and so settlement mitigation was considered necessary for certain locations along the route.

Along the tunnel route more than 1000 historical buildings exist mainly all founded on wooden piles driven through the very soft clays to a sand layer. At locations where the tunnels are curving, volume loss would be expected to be higher and the design recognized that at these locations, mitigation of tunneling settlements would be needed (Kaalberg *et al*, 1999).

Design for the scheme commenced in 1995 and at an early stage (1999), compensation grouting was identified as a suitable solution to mitigate the settlements. As the use of compensation grouting in association with wooden piled foundations was not known, the project carried out a full scale trial (van der Stoel *et al*, 2002 and Hasnoot *et al*, 1999). Model foundations were constructed at a location along the line of the Sophia tunnel and compensation grouting during TBM passage was successfully carried out. This trial gave confidence to the use of this technique in Amsterdam and it then formed part of the contract requirements.

2 GROUND CONDITIONS

The ground conditions relating to the tunneling and compensation grouting comprised the following strata (and thicknesses):

1. Fill (1 m)
2. Very soft clays (12 m)
3. 1st Sand layer (2 m)
4. Allerod (2 m)
5. 2nd Sand layer (6 m)

The Allerod is a silty/clayey strata of variable composition. The general succession is illustrated on Figure 1 and 2.

Groundwater is very close to ground level.

3 CONTRACT DESIGN

The contractor initially had design responsibility for the compensation grouting and submitted an outline design for the required grouting and shafts specified within the documents.

3.1 *Compensation grouting design*

The contractor, as part of his bid submission, had produced an outline design which followed the geometry of the trial very closely with the injection pipes installed in a horizontal layer very close (1 m) to and below the pile toes, Figure 1. This had been necessary for the trial at Sophiatunnel as the TBM passed very close to the model pile foundations.

For the Amsterdam contract situation, the tunnels were significantly deeper and thus there was more leeway in positioning the pipes. As North/Southline in the end was carrying the associated risks for Compensation Grouting, the Adviesbureau North/Southline (ABNZL) changed the bid design so that the pipes were positioned further away from the piles, midway between the pile toes and tunnel crown, and installed at an angle to intercept the settlement contours. Figure 2 shows the redesign by ABNZL for the first location. Advantages of this design would be less potential settlement during installation of the pipes and the grout injection would be in a more uniform stress zone rather than very close to the end loaded driven piles. In addition it was felt that a single layer would provide sufficient control and thus would be trialed at the first location to be drilled and grouted.

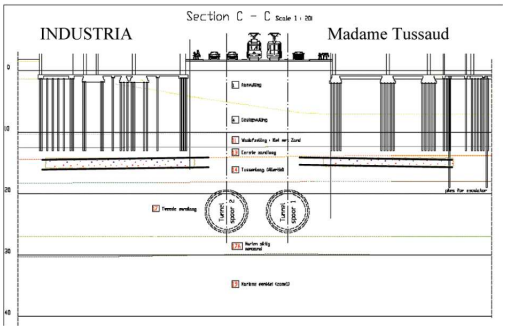

Figure 1. Original compensation grouting design section.

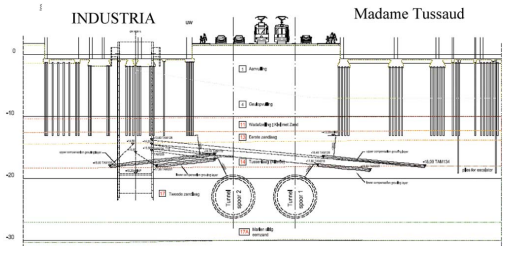

Figure 2. Revised compensation grouting design section.

3.2 *Grouting shaft design*

The Contractor had offered two types of shaft construction within his design:

Combi-shaft: Secant piled + freezing.
Caisson.

The Combi-shaft was designed on the basis of constructing the shaft using interlocking piles and then using ground freezing in the sandlayers to exclude the groundwater. The caisson type was designed using cast in situ concrete rings and then sinking the shaft by excavating the inside and then placing the base slab using underwater concrete.

The contractor advised that the caisson type was to be utilized where the shaft was relatively remote (10 m) from the nearest building as they predicted up to 50 mm of settlement and the Combi-shaft would be used close to the piled buildings as minimal settlements would arise.

The cost of the Combi-shaft was relatively high given the required use of ground freezing and therefore ABNZL suggested to the contractor that based on UK experience a jacked segmental shaft could be constructed without settlement close to a building.

This methodology differed from the conventional caisson in that the bottom edge of the shaft was jacked ahead of the excavation within the shaft which prevented loss of ground and hence settlement being generated. Special precast concrete segments were used which allowed Bentonite to be injected at the cutting edge through pipe channels that were aligned when the segments were bolted together. This provided a friction reduction and assisted the jacking process. In operation, the bottom edge would be jacked into the ground with the excavation being no closer than 0.5 m above the base. The segments were 1 m in depth, thus the jacking operation consisted of constructing a 5.2 m internal diameter ring of nine segments, jacking and excavating 1 m and repeating the process.

Therefore in addition to trialing the compensation grouting layout, the Industria location was chosen to trial this form of shaft construction.

3.3 *Monitoring*

The movements of the buildings during shaft sinking, drilling and grouting operations were extensively monitored. Monitoring was installed within the buildings, generally in the basement. The system chosen was a water level cell system where a reference cell is fixed remotely and provides a constant water level. Movement of the other cells connected to the reference cell then reflect a change in local head of water pressure at each location and thus the relative movement can be calculated. All cells were logged automatically and accessible through a web based system for all parties to follow.

In addition to the internal monitoring for the buildings a project wide system of remotely read total stations was installed along the line of the tunnels and could be also used to monitor external movements and would provide long term absolute level control.

The advantage of the water leveling cells was that they could be interrogated at very short intervals of time to allow control of the grouting and they had a high resolution of 0.1 mm to 0.2 mm.

3.4 *Performance requirements*

The contract specification set out the limits of movement for the buildings to be protected by compensation grouting and they were as follows:

Pretreatment Phase:.
- Maximum upward movement 2 mm.
- Maximum settlement 2 mm.
- Maximum angular rotation 1 in 2000.

Compensation Grouting Phase:
- Maximum upward movement 2 mm.
- Maximum settlement 3 mm.
- Maximum angular rotation 1 in 2000.

The movement limits for the compensation grouting phase were to be following pretreatment so that the maximum upward movement could technically be 4 mm and the maximum settlement could be 5 mm.

The contractor accepted the movement limits but it was agreed that the 1 in 2000 distortion limits would be a target with the contractor committed to pursuing these limits.

4 CONSTRUCTION

Construction on site commenced at the location of the Industria building.

4.1 *Shaft construction*

The works at the location of the Industria building commenced in March 2007 with removal of existing obstructions. It was decided that because there was the risk of historical masonry and wooden structures at the shaft location, predrilling using 1500 mm dia overlapping piles would be carried out to the first sand layer, a depth of around 12 m. The piles were backfilled with a special mix, DiWa Mix 230 produced by Heidelberg Cements which had a 28 day strength of less than 1 MPa. This was important to allow the follow on shaft jacking operation to be carried out without hindrance of any strong material being present.

Following the removal of obstructions the shaft was jacked in and the base slab cast during the period April to June 2007. Figure 4 shows the results of the monitoring of the prism attached to the building immediately opposite the shaft.

The results showed that the shaft had caused virtually no movement to the building and therefore this type of construction was then adopted for all the remaining shafts.

4.2 *Drilling and installing injection pipes*

Following completion of shaft sinking, a drill mounted on a rotating and jackable drill stand was installed within the shaft. The rotation allows the drill to be easily positioned for each drill hole and the jacking frame allows the drill to be simply

Figure 3. Monitoring layout within Industria.

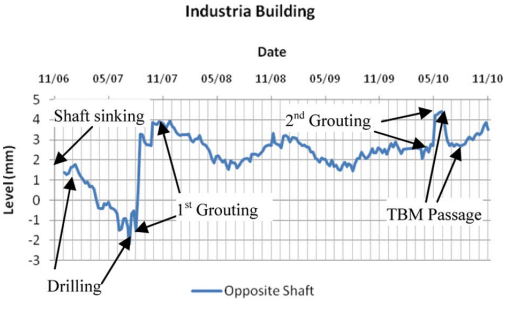

Figure 4. Monitoring of Industria building.

moved up and down. In order to accommodate the drill and frame around 3 m of space was required below the drilling level.

In order not to compromise the structural integrity of the shaft construction, special segments were installed during jacking at the levels of drilling. These segments allowed the drills to penetrate without cutting the reinforcement. In order to provide sufficient space between each drill hole, a number of entry levels had to be used. Figure 5 shows the entry hole layout for the Bijenkorf shaft.

At this time the design still incorporated the second lower layer of holes 201 to 212. The heavy dashed line shows the joints between rings of segments.

Drilling was carried out using special preventers to deal with the 1.5 Bar water pressure. Initially a number of systems were trialed by the contractor until the most suitable system was developed. Initially there was some settlement from the drilling as shown on Figure 4 however as the system was developed this did not continue.

In order to minimize the number of shafts, trial drilling with lengths of 60 m and 90 m were carried out to establish whether these design lengths could be utilized in the design. It was established that both 60 m and 90 m length holes were feasible in the first sand layer/Alleroid. Consequently the shaft opposite Madame Tussaud could be cancelled and all the work carried out from the Industria shaft.

On completion of drilling, the steel injection pipe was installed and with the help of a seal between the injection pipe and the drill casing, the casing was withdrawn while grouting the hole under pressure.

4.3 *Pregrouting*

It is always important to carry out a pregrouting exercise to ensure that there is a good contact

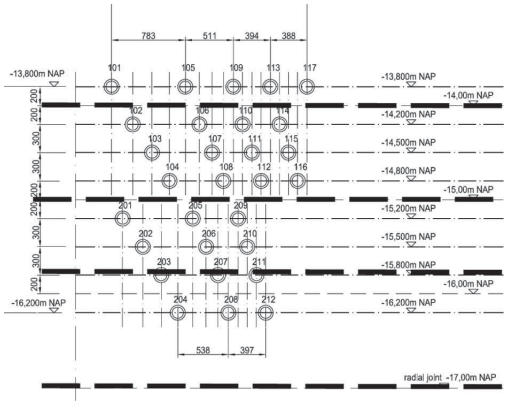

Figure 5. Layout of holes at entry level in shaft.

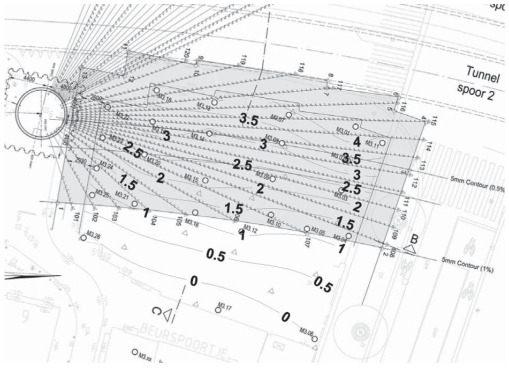

Figure 6. Pre-heave applied to Industria and Madam Tussaud-Building.

between the foundations and the grouting zone. Additionally the injection of the grout can stiffen the ground and reduce movements (Essler, 2000).

Pregrouting was carried out immediately after drilling. It was decided that it would be beneficial to incorporate a small tilt of the buildings away from the tunnel drive to compensate for the settlement during TBM passage. The control of the grouting was very precise and the tilt was applied to the building with 4 mm at the façade and 1 mm at the rear of the building.

The grout utilized was a preblended mix provided by Heidelberg known as Blitzdammer 750. The inital water solids ratio was set at 2.0 but it was decided that a better response was noted with a water cement ratio of 1.4 and this was then adopted for all future grouting. Grout volumes varied from 20 to 100 litres.

The single layer was grouted and found to be successful in lifting and maintaining the building and was adopted for all other locations.

The initial conditioning of the ground required around 250 litres of grout to be injected for each square meter of grouting area. This is relatively high when compared to some other projects (Chambosse, 2002) and is probably attributed to the potential flexibility of the wooden piling system and the reestablishment of the ground stresses which may have been reduced due to settlement caused by the drilling. Figure 7 shows the actual distribution of grouting intensity. Very high grout quantities were required in the south east part of Industria to correct for the initial settlement caused by the drilling development.

5 TBM PASSAGE

Due to programme difficulties, although the pregrouting at Industria was completed in late 2007, the TBM was only launched in the summer of

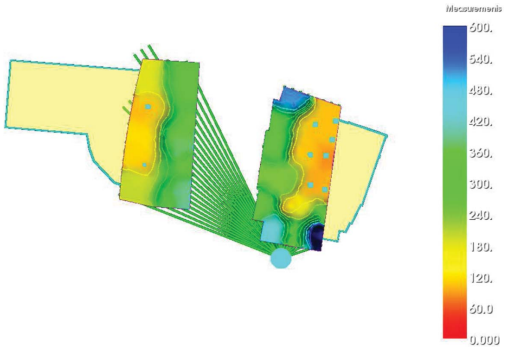

Figure 7. Variation in grouting intensity for Industria and Madam Tussaud.

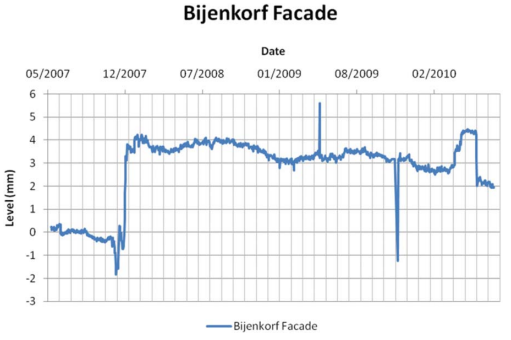

Figure 8. Change in level of Bijenkorf building.

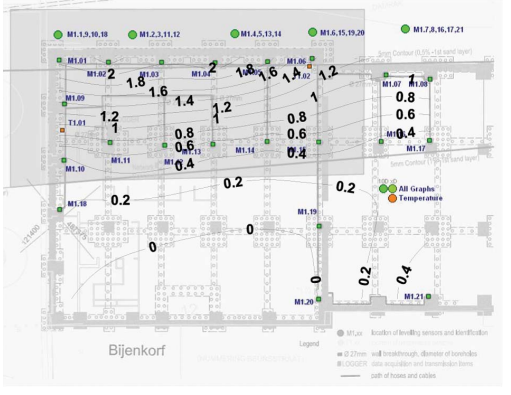

Figure 9. Change in level (mm) for Bijenkorf during TBM passage.

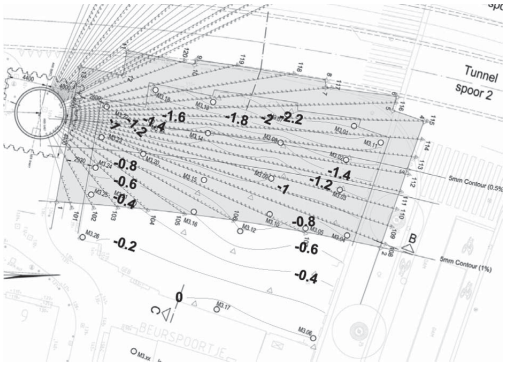

Figure 10. Change in level (mm) for Industria during TBM passage.

2010 and thus Industria, Madam Tussaud and Bijenkorf buildings sustained the preheave for nearly three years. Figure 4 shows that in addition to seasonal variations there was a slight loss of level of around 1 mm.

Immediately prior to tunneling the contractor remobilised to the shaft which had been covered over and carried out some reinjections to regain the required tilt levels. It was noted that grouting efficiencies were higher than the initial grouting which is a further justification in carrying out pre-grouting to stiffen the ground. Around 27 litres m^2 were injected and an additional 2 mm heave was re-established on the façade.

The reaction of the other buildings were similar and Figure 8 shows the change in level for one of the settlement cells within the basement and adjacent to the Bijenkorf façade.

The TBM passed the grouting zone of the Bijenkorf building on 9th June 2010. Figure 8 shows that there was only around 2 mm of movement. Figure 9 shows the change in level of the Bijenkorf during TBM passage.

This shows that in general the settlement contours are parallel to the line of the tunnel drive and quite smooth indicating that the grouting zone not only stiffens the ground but can smooth out movements.

No grouting was carried out as the settlement was not excessive. It had been decided that the levels of the buildings following TBM passage should be maintained at 50% of the initial preheave limit, thus the façade would only require grouting if the levels dropped below 2 mm.

The east TBM reached the Industria building on the 16th June 2010. It was interesting that the building did not move initially until the face of the TBM was well past the northern corner. This is probably attributed to the 3D effect of the corner providing more support by arching. Figure 4 shows the change in level of the building during TBM passage. The heave following TBM passage is most probably a seasonal effect as can be seen by the variation during 2008 and 2009.

Figure 10 shows the change in level of Industria as the TBM passed by.

Grouting was carried out on the 18th and 19th June 2010 to maintain the levels within specified limits. Approximately 4,500 litres of grout was injected, initially in volumes of 35 to 50 litres and then later with volumes of 150 litres.

For the Industria building the response was slightly more localized and this is probably due to the more complex shape of the building.

Based on the building settlements, the likely volume loss achieved was around 0.3% which indicated excellent TBM control and operation by the contractor Saturn (Zublin/Vermeer JV).

6 CONCLUSIONS

The redesign of the injection pipes was successful in that minimal effect was noticed on the building during drilling and the buildings could be compensated during TBM passage. The single layer approach was also successful in allowing good control of the building both during initial grouting and during TBM passage.

Increasing the drilled lengths to around 60 m allowed some shafts to be deleted with a significant cost saving.

The jacked segmental shaft construction was very successful in limiting settlements and providing an economical and efficient method of construction.

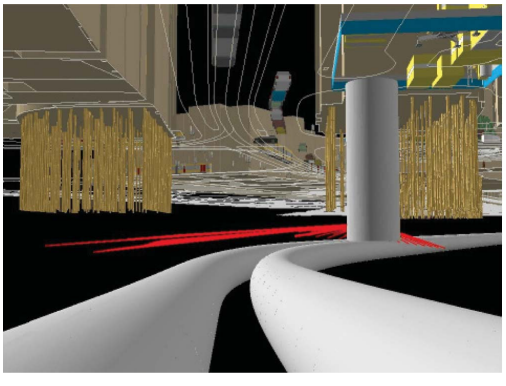

Figure 11. 3D of the single layered design based on the interception approach for Industria.

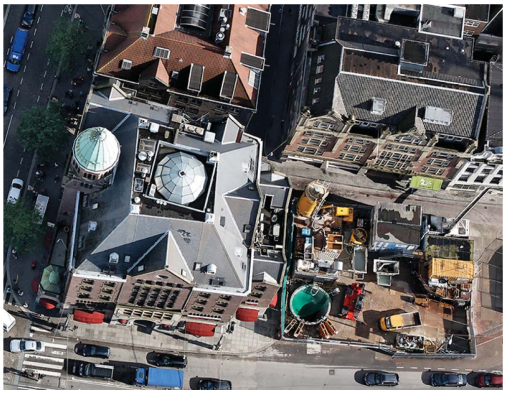

Figure 12. Working site at Industria from above.

ACKNOWLEDGEMENTS

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