Displacement of an apartment building next to a deep excavation in Rotterdam

Déplacements d´un bâtiment d'habitation adjacent à un chantier profond d'excavation à Rotterdam

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ABSTRACT: A new underground car park is being realized near the Rotterdam Central Railway Station. The car park will contain five stories and will be about 150 m long and 35 m wide. The depth of the underground car park is about 20 m. Tall office buildings are present at both sides. A 30 m high apartment building is situated perpendicular to the car park, and the distance of this building to the car park is only 7 m. This building is founded on prefabricated concrete piles with a base level that equals the excavation depth of the car park. The underground car park is being realized inside a dry building pit surrounded by 40 m deep diaphragm walls. Predictions, based on calculations with analytical as well as 2D and 3D finite element models, showed that the expected settlements of the apartment building were acceptable. The measured displacements remained well within the limits that were predicted.

RÉSUMÉ : Près de la gare ferroviaire centrale de Rotterdam, un parking souterrain est encore en construction. Ce parking sera pourvu de cinq niveaux et aura les dimensions de 150 m de long en 35 m de large. La profondeur de ce parking sera de 20 m. Le long des côtés du parking en construction se trouve de hauts bâtiments. En particulier, un bâtiment d'environ 30 m de haut est situé à peine a une distance de 7 m de ce parking et se tient perpendiculairement à celui-ci. Ce bâtiment est fondé sur des pieux en béton préfabriqués dont la base est au même niveau que celui de l'excavation réalisée pour la construction du parking. Cette excavation est délimitée par des parois moulées dont la base se trouve à 40 m de profondeur. Les prédictions, basées sur des calculs pour lesquelles des modèles d'éléments finis bi- et tridimensionnels ont été montés, ont montré que les tassements de ce bâtiment prédits étaient acceptables. Les déplacements mesurés durant la réalisation de l'excavation sont restés dans les limites des calculs de prédiction.

KEYWORDS: deep excavation, settlement of structures, finite element models, prediction, monitoring.

1 INTRODUCTION

In the centre of Rotterdam, extensive reconstruction works are executed as part of the overall project Rotterdam Centraal. The reconstruction comprises of the building of a large Public Transport Terminal to facilitate passenger transfer between (inter)national trains including the high-speed train, and local public transport like trams, buses and underground trains. The project also includes a new underground metro station, a new underground parking facility for bicycles, a new traffic tunnel below a newly created square, and a new underground car park.

The car park will contain five stories and will be about 150 m long and 35 m wide. The depth of the underground car park is about 20 m. Tall office buildings are present at both sides. A 30 m high apartment building is situated perpendicular to the car park and the distance of this building to the car park is only 7 m (see Figure 1).

The apartment building is founded on prefabricated concrete piles with a base level that equals the excavation depth of the car park. The underground car park is being realized inside a dry building pit surrounded by 40 m deep diaphragm walls.

Calculations of the expected settlement of the apartment building were made in the design stage of the project, and a fall-back option was thought out in case the settlement would exceed the criteria.

The apartment building was continuously monitored during the construction of the parking facility. This paper describes the expected impact of the construction of the underground car park on the apartment building, and the results of the monitoring. The car park is presently in the final stage of construction.

Engineering of the car park Kruisplein, and supervision of the execution of the project is performed by the Engineering Consultancy Division of the City of Rotterdam.

Figure 1. The construction of the underground car park Kruisplein (February 2012). The apartment building is situated in front, at the left (perpendicular to the car park). Photograph Nick de Jonge – Skeyes fotografie.

1.1 *Subsoil*

The ground level in the area is situated at about sea level (this corresponds to the Dutch reference level NAP). The subsurface conditions at the building site are presented in Table 1. The hydraulic head in the fill is about 1.5 m below sea level, and in the Pleistocene sand layers about 2 m below sea level.

Table 1. Soil conditions

Elevation (m NAP)		Origin – Type of soil
from	to	
-0.3	-4.5	Fill - sand
-4.5	-5.5	Holocene - soft clay
-5.5	-8.0	Holocene - peat
-8.0	-17.0	Holocene - soft clay
-17.0	-35.0	Pleistocene - sand
-35.0	-37.0	Pleistocene - stiff clay
-37.0	-40.0	Pleistocene - sand

1.2 *Challenge*

The horizontal as well as the vertical equilibrium of the foundation of the apartment building may be influenced by the building activities (see Figure 2). The foundation piles of the apartment building:
- will be horizontally loaded by the soil that displaces into the direction of the diaphragm wall, because of its deflection;
- will displace vertically, because the soil that displaces into the direction of the diaphragm walls also displaces slightly into the vertical direction;
- will displace vertically, because the deflection of the diaphragm wall causes some relaxation of the sand layer, and therefore results in a decrease of the bearing capacity.

The effects of these phenomena had to be assessed, and taken into account during the design stage of the construction of the underground car park.

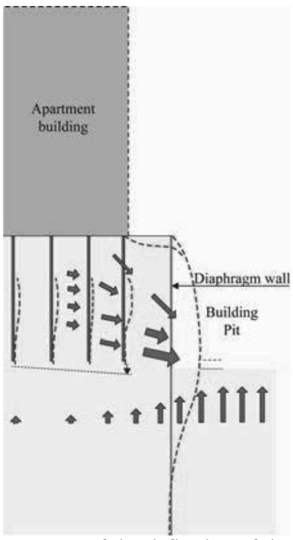

Figure 2. The consequences of the deflection of the diaphragm wall to the apartment building.

2 APARTMENT BUILDING

The length of the apartment building is 50 m, the width is 10 m. Prefabricated concrete piles 380 mm square and 450 mm square support the building. The foundation piles are connected by beams in north-south direction. The pile rows in the vicinity of the building pit support via columns bearing walls (see Figure 3). These walls distribute the load to the piles. The apartment building can therefore be considered as stiff in the north-south direction. In the east-west direction pile rows are not able to redistribute the loads. In that direction the apartment building is considered as flexible.

Figure 3. The apartment building.

Before analyzing the expected settlement behavior of the apartment building, the building regulations of the period in which the apartment building was constructed had to be translated, and compared with the current building regulations. Therefore calculations of the vertical bearing capacity of the foundation piles were made, based on the Dutch standard NEN 6743-1. The original building documents of the apartment building mentioned the design loads on the piles. These had to be converted first into representative and design values. This resulted in a ratio of 1.9 between the average bearing capacity of the pile foundation and the representative value of the load. This fits reasonably well with the overall safety factor of 2.0 that was used for this type of piles in the period the apartment building was constructed. Because of this small difference in safety level NEN 6743-1 was used to analyze the settlement behavior of the apartment building.

3 ANALYSIS

3.1 *Settlement due to the relaxation of the subsoil*

The analysis was directed to the first five rows of piles of the apartment building. The first row is situated at about 7 m distance of the diaphragm wall; the fifth at about 23 m. The distance between the pile rows is 3.9 m. Load-settlement diagrams have been derived for a single prefabricated concrete pile based on general curves presented in NEN 6743-1. Both a pile 380 mm square and a pile 450 mm square were considered.

The calculations with the computer code MFoundation 5.3.1.4 were based on data of six CPT's. The maximum bearing capacity for each CPT, the representative value of the average bearing capacity and the design value of the bearing capacity were determined for both pile sizes. The magnitude of the negative skin friction was also calculated.

The subsoil, in particularly the sand layer with the top at 17 m below sea level, will relax as a result of the excavation of the building pit. Based on CPT-measurements of the cone resistance at a comparable building pit, it was assumed that the relaxation amounts to 20% up to a distance of 12 m of the building pit, and that the relaxation from this distance decreases with 2.5% every 5 m. The decrease of the vertical bearing capacity was assumed to be proportional to the relaxation of the sand layer.

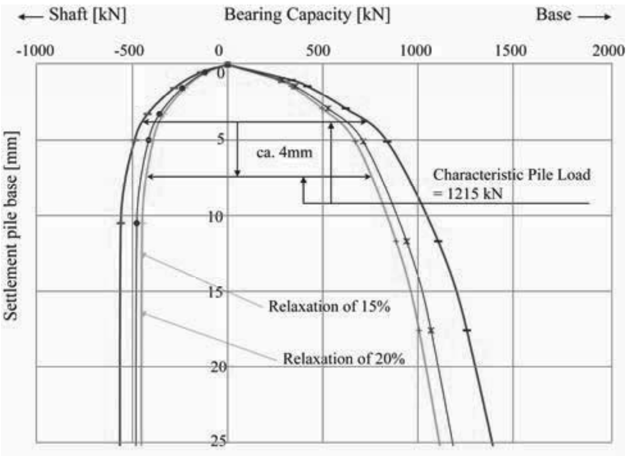

Figure 4. Graphical determination of the pile base settlement.

Load-settlement diagrams have been composed for the serviceability limit state, based on NEN 6743-1 (see Figure 4). For example, a pile base settlement of 4 mm is expected for the original situation. Due to a relaxation of the sand layer of 20% a pile base settlement of 8 mm is calculated, thus an additional settlement of 4 mm as a consequence of the relaxation.

It was concluded that the piles 380 mm square could settle 2 to 4 mm as a result of a relaxation of the sand layer of 12.5 to 20%. For piles 450 mm square these values varied between 3.5 and 5 mm.

3.2 *Horizontal soil displacement due to the deflection of the diaphragm wall*

The greenfield horizontal soil displacement at the position of the relevant foundation piles of the apartment building has been calculated by using the Hardening Soil (HS) model with the Small Strain Stiffness (HSS), of the computer code Plaxis 2D 8.5. Three cross-sections were considered (see Figure 5):
- at the middle section of the building pit where the excavation took place according to the conventional method;
- next to the apartment building, where the car park was built according to the top down method: after the construction of the diaphragm wall the roof is built, and after that the soil is excavated below the roof and the successive floors are made;
- in the transition zone between the two building methods.

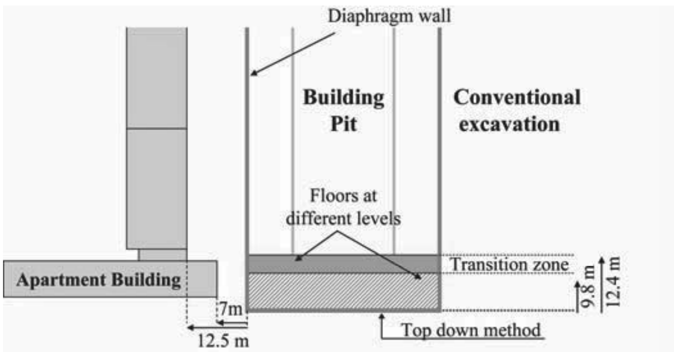

Figure 5. The cross-sections of the building pit that were considered with the Plaxis 2D computer code.

The different stages of the excavation with the corresponding lowering of the groundwater pressures in the building pit, and the installation of the successive layers of struts have been considered, and the displacements have been calculated. The stiffness of the diaphragm wall was based on cracked concrete.

The calculated deflection of the diaphragm wall was about 70 mm in the middle section of the building pit, at a depth of 18 m. Next to the apartment building, the deflection was about 40 mm, at a depth of 20 m. The expected deflection of the diaphragm wall was about 55 mm in the transition zone.

At the location of the first pile row of the apartment building, the calculated greenfield horizontal soil displacement was 20 mm. At the following pile rows this displacement was according to the calculations 10 to 15 mm.

From additional calculations with the elastoplastic spring model of the computer code MSheet 7.7, it was concluded that the expected moments and shear forces in the foundation piles would remain smaller than the acceptable values.

3.3 *Consequences of the soil displacement to the pile foundation*

The computer code Plaxis 3D Foundation 2.1 has been used to determine the combined effect of the horizontal and vertical ground displacements. With the computer code MFoundation 5.3.1.4 the vertical displacement was considered, and with the computer code Plaxis 2D 8.5 the greenfield horizontal soil displacement.

The diaphragm wall has been modeled from the southern wall up to the middle of the conventionally built section. The floors that are part of the section that was built according to the top down method form part of the model. Only the five pile rows next to the building pit, and the complete ground floor were part of the model.

The piles were modeled as embedded piles. This made it possible to determine the moments and shear forces as well as the displacement of the foundation piles directly from the calculations. The calculated settlements of the pile base may be exaggerated, because the model does not take into account the densification of the soil as a result of the installation of the piles.

The with the computer code Plaxis 2D calculated deflection of the different parts of the diaphragm wall was used to calibrate the Plaxis 3D model. For the greater part of the building pit the calculated maximum horizontal displacement of the diaphragm wall was about 70 mm, in accordance with the results of the calculations with the Plaxis 2D computer code. Near the southern part of the diaphragm wall the calculated displacement varied between 15 and 40 mm.

According to the calculations, the pile base of both the 380 mm pile, and the 450 mm piles will settle 8 to 12 mm as a consequence of the soil displacement. The calculated horizontal deflection of the foundation piles was 25 mm as a maximum. The calculated moments and shear forces are relatively small.

4 PREDICTION

Based on the calculations the predicted settlement of the apartment building was 2 to 5 mm due to relaxation and 8 to 12 mm due to the soil displacement. This means in total 10 to 15 mm as a consequence of the building activities for the underground car park. Damage was not expected, because of the decrease of settlement with distance from the building pit. The settlement difference of the piles was expected to be small.

Horizontal displacements of the pile foundation, varying between 10 and 25 mm, were also expected. Also no damage was expected in this case, because the displacement would manifest itself underground, with only a limited effect on the foundation piles and the superstructure.

5 MONITORING

5.1 *Set-up*

Measuring points at 4 m above ground level were installed on the columns that were supported by the first four rows of piles of the apartment building (see Figure 6).

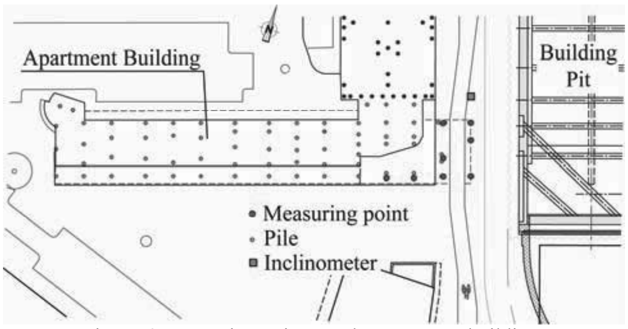

Figure 6. Measuring points on the apartment building.

Vertical and horizontal displacements were continuously monitored by a measuring device on top of a building at a distance of more than 50 m. The results of these measurements were periodically checked by measurements that were discontinuously executed as part of an extensive measuring program around the building pit.

The results of periodically executed inclinometer measurements offered another way to check the actual displacements. The inclinometers were situated next to the apartment building at a distance of 7 m from the diaphragm wall. This corresponds to the distance of the first pile row of the apartment building from the diaphragm wall.

The owner of the apartment building was fortnightly informed about the monitoring results.

5.2 *Criteria*

A relative rotation of the apartment building of 1:600 was used as the value to intervene, and a relative rotation of 1:750 served as the value to prepare mitigating measures. Because of practical reasons these values have been converted to settlement values of 15 and 12 mm respectively at any specific point.

5.3 *Results*

The continuous measurements started in January 2010. The measured displacements appear to be according to the prediction (see Figure 7). Meanwhile the apartment building is stable, and only a limited settlement has occurred.

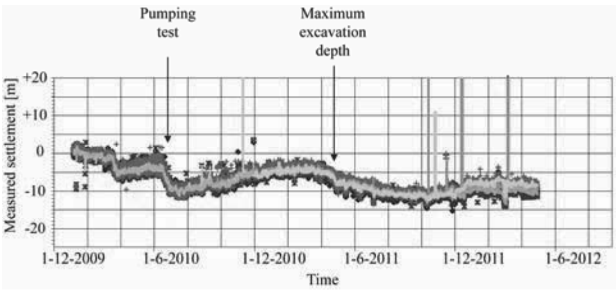

Figure 7. Measured vertical displacements in the period from January 2010 till May 2012.

The in June 2010 measured vertical displacement of the east front of the apartment building was the reason that the fall-back option was prepared. However, the further development of the settlement did not give rise to the actual installment of additional foundation piles below the east front.

The measurement results show that the apartment building rose again some 5 mm after the execution of the water tightness test. During the excavation of the deepest part of the building pit the apartment building settled some 8 mm. The maximum settlement of the east front appeared to be 10 to 15 mm, in accordance with the prediction.

The measured horizontal displacement of the apartment building varied between +10 and -10 mm (see Figure 8).

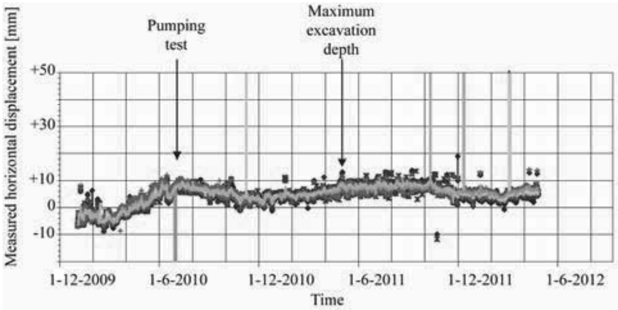

Figure 8. Measured horizontal displacements in the period from January 2010 till May 2012.

Inclinometer measurements started in July 2010, after the execution of the water tightness test. Next to the apartment building the maximum measured deflection of the diaphragm wall was about 35 mm at 15 m depth. At a distance of 7 m from the diaphragm wall the maximum horizontal soil displacement was about 40 mm at a depth between 5 and 10 m. From additional calculations with the elastoplastic spring model, it was concluded that the moments and shear forces in the foundation piles were smaller than the acceptable values.

6 CONCLUSIONS

Diaphragm walls are an appropriate type of retaining wall in an urban environment, but will also deflect as a result of a deep excavation. The consequences for adjacent structures must therefore be studied in the design stage.

A risk analysis helped to find the optimal design for the building pit as to restrict the uncertainties for adjacent structures to a minimum. It also helped to create fall-back options.

The results of the test of the water tightness of the building pit showed in an early stage that the apartment building was vulnerable to deformations of the subsoil. This resulted in a great attention for monitoring results during the whole construction period by all persons concerned.

Accurate predictions about the expected vertical and horizontal displacements appeared to be possible with the help of the available computer codes.

The case of the apartment building next to a deep building pit showed for all that a systematic approach is needed to overcome the presented challenges.

7 REFERENCES

NEN 6743-1 2006. *Geotechnics – Calculation method for bearing capacity of pile foundation – Compression piles.* Nederlands Normalisatie-instituut, Delft (in Dutch).