Validation of design methods with in situ monitoring of deep excavations

Validation du méthodes de dimensionnement avec mesures d’excavations profondes

M. Korff
Department of Foundation Engineering and Underground Construction, GeoDelft, Netherlands

J. Herbschleb
Royal Haskoning/ Adviesbureau Noord/Zuidlijn, Netherlands

ABSTRACT
During the last 10 years several shield tunnelling projects have been carried out in the Netherlands. The Netherlands Centre for Underground Construction (COB) performs studies at all shield tunnelling projects in the Netherlands. These studies include the behaviour of the start and reception shafts during excavation at two of the tunnels built so far. This paper describes the results of measurements and analyses performed at two such characteristic deep excavations. Both investigations resulted in improved knowledge on the prediction of the movements and forces acting on construction parts of deep excavations in clays and sands.

RéSUMÉ
Pendant les 10 dernières années plusieurs projets de tunnels creusés ont été effectué aux Pays-Bas. Le Centre de la Construction Souterraine Hollandaise (COB) réalise des études sur tous les projets de tunnels creusés aux Pays-Bas. Ces études incluent le comportement des puits d’amorce et de réception de deux tunnels construits jusqu’à présent. Cet article décrit les résultats des mesures et des analyses effectuées pour deux excavations caractéristiques. Ces deux études ont résulté dans des méthodes améliorées pour la prédiction des mouvements et des forces agissant sur les parties de la construction d’excavations dans les argiles et les sables.

1 INTRODUCTION
During the last 10 years several shield tunnelling projects have been carried out in the Netherlands. Tunnelling in soft soils has become an important way of constructing the necessary infrastructure in dense populated areas. Because of the need for shield tunnels to be constructed with sufficient cover, the shafts at the start and reception of the tunnel boring machine are usually made with deep excavations in building pits.

The Netherlands Centre for Underground Construction (COB) performs studies at all shield tunnelling projects in the Netherlands. These studies include the behaviour of the start and reception shafts at two of the tunnels built so far. This paper describes the results of measurements and analyses performed at two characteristic deep excavations for start and reception shafts. To complete the overview of Dutch building pit research, reference is also made to specific validation projects in recent years and projects in the near future.

2 TEST SITES
The building pit test sites at which measurements were performed are part of two of the tunnels that are constructed for the Betuw Route cargo railway, which crosses The Netherlands from West (Rotterdam Harbour) to East (Germany). The first test location is the start shaft of the Sophia Rail Tunnel constructed in typical soft soil conditions. The second test location is the reception shaft of the Tunnel Pannerdensch Kanaal in the Eastern part of the country, mainly constructed in sands.

At the Sophia Rail Tunnel the deep excavation (20 m.) is constructed to just above a stiff clay layer. During excavation of the building pit the underlying soil layers are unloaded, which causes heave during and after excavation. The deep excavation was made with the use of a combi-wall into the stiff clay layer to provide a dry workspace in an artificial polder. Under water concrete with reinforcement was used to resist the water pressures during the final stage with the tunnel in use. The measurements focused on the horizontal deformations of the combi-wall and the heave of the soil-layers beneath excavation level.

At the Sophia tunnel site a typical situation for the soft Western part of the Netherlands is found, having about 11 m of soft to very soft clays and peats overlying the Pleistocene sand. The stiff clay layer is situated about 5 m below the deepest excavation level. Ground water pressures are close to surface level.

At the Pannerdensch Kanaal tunnel the behaviour of the building pit as a whole is studied. The deep excavation (about 15 m.) is constructed in quite homogene sand layers. The shafts are constructed with combi-walls and an underwater concrete floor (reinforced with steel fibres) and tied down with vertical anchors. The ground water pressures are strongly influenced by the water level in the canal which the tunnel is crossing. The possible fluctuations may be several meters during (heavy) rain periods. An advantage of the quite homogene sand layer in which the building pit was constructed is that design methods can be validated more easily due to the absence of “disturbing” layers. At this location measurements were done on the horizontal deformation, and strain levels in the supports and under water concrete.

The Sophia Rail Tunnel shaft was constructed in 1999-2000, the Pannerdensch Kanaal reception shaft in 2002-2003.

3 DESIGN OF DEEP EXCAVATIONS
Deep excavations in the Netherlands are usually designed with several methods, each for a specific part of the construction. In more advanced cases Finite Element Calculations are made to determine the interaction of construction parts and deformations of the surroundings. The results described in this paper are related to (almost) all elements of deep excavations. The following aspects were studied in the validation cases: heave of soil below excavations, deformations of the combined walls, behaviour of struts and under water concrete floors and stiffness of vertical anchors. Use is made of figure 1 to describe all aspects of the two validation projects described above.
3.1 **Heave**

At the Sophia Rail Tunnel the deep excavation (20 m.) is constructed to just above a 7 m thick stiff clay layer (Kedichem clay) of marine origin. During excavation of the building pit the underlying stiff clay layer is unloaded, which causes heave during and after excavation. This heave influences the building pit floor because an upward force is exerted when the heave is “prevented” by the floor. These forces can become quite large if deformation is fully prevented. Results of the measurements are described in more detail in (Kwast et al., 2001) and (COB, 2002). The most relevant conclusions are:

- the clay layer reacts directly to the unloading due to the excavation. No negative pore pressures were measured. Some creep effects could occur;
- the unloading of the deeper sand layer attributes to the total deformation to a larger extent than expected (about 60% of the total heave measured);
- prediction of heave with Terzaghi-Buisman-Koppejan models (1D and semi 2D) is possible. However using the (heave) parameters as measured from laboratory tests an over prediction of the amount of heave in the clay layer was calculated;
- interaction of building pit walls, floor and soil below the floor is not taken into account in analytical analysis. This interaction causes compression of soil layers just below the floor in this case, which was not found in analytical analysis;
- estimation of heave using the FEM PLAXIS with the Hardening Soil model results in reasonable good approximation with the measurements. In this case soil deformations were predicted accurately, but deformations of the construction parts were overestimated;
- design methods for predicting heave depend mainly on the soil parameters. These soil parameters can be achieved from triaxial testing. This testing should be performed with the stress paths expected during construction. For design of heave unloading tests are needed with small strain measurements (about 0.01%).

3.2 **Floors**

Building pit floors are subjected to several loads during construction. The unloading due to excavation and dewatering of the building pit causes stresses due to the (soil) heave. Furthermore a resulting water pressure will occur under the floor. Deformation of the walls is partly prevented by the floor, causing a normal force in the floor. Bending moments are reduced if piles or anchors are installed. During the final construction (in this case the tunnel) the floor is loaded downwards.

In the Sophia project the under water concrete was not used to resist the water pressures during construction. It was designed for the final stage with the tunnel in use. No piles or anchors were used, but instead the floor was reinforced with traditional reinforcement to take the heave pressures. During dewatering the floor was lifted about 10 mm in total, resulting in only a small bending moment. This deformation was caused by movement of the shaft as a whole. Due to heave of the soil below the floor in the weeks after dewatering the shaft, the deformation in the middle of the floor increased to about 15 mm. The estimated pressure against the floor was 20 kPa.

In the Pannerdensch Kanaal project the floor was reinforced with steel fibres and anchors were placed at distances of about 2.5m – 3 m. This floor was used to resist the water pressures after dewatering. The deformation of the floor was about 5 -13 mm during dewatering. No time effects were seen. Special measurements were performed in the concrete floor, using a 3D frame with strain gauges (see figure 3).
Four of these frames were placed underwater before the concrete was poured. From the strain gauges the moment distribution in the floor is calculated. Since the strain measurements include the effect of hardening of the concrete the calculation of the moments is difficult. Compared to the bending moments predicted in the design phase the (interpreted) moments are about 10 - 40% higher. The design method however did not include the partly flexible connection of the ground anchors to the floor. This leads to under prediction of bending moments in the floor.

3.3 Struts

Strains were measured in the struts at Pannerdensch Kanaal. The measurements were influenced by temperature changes. Since part of the temperature effect is prevented by the walls on either site of the struts, resulting in unknown stresses, it was not possible to take the temperature effect into account. By using night time measurements (at constant temperatures) the normal force in the strut was determined to increase with about 600 kN per strut during dewatering of the shaft. Installation forces and forces during the first stages of construction were not measured, so absolute values are not given. Normal forces decreased strongly during further construction.

3.4 Walls

Deformation of the walls were measured in both cases and related to predicted ones.

In Pannerdensch Kanaal measurements were taken in the middle of the shaft (2D situation) and near a compartment wall (3D situation). The deformations near the compartment wall were significantly smaller than in the middle (maximum of 40 – 50 mm versus 5-10 mm). Distances to the compartment wall were about 0,4 and 2,7 times the width of the excavation. These results were however influenced by the location of the instruments, since the inclinometers at the 2D situation were put on the wall itself and the devices for the 3D situation were added a short time later at 2 m behind the wall. Deformations on opposite sides of the construction were similar but not exactly the same. Differences of about 10 mm occurred, although no significant different loading was present. Predictions for the deformations were a little smaller, but in the same range (35 mm) as the measurements.

Deformations of the walls at Sophia Rail project were in good accordance with the calculations. See also (Schiphouwer et al., 2001) and (COB, 2002). Differences appeared during dewatering of the shaft, when the polder construction caused a complex behaviour of the soil under the construction when it was partly compressed and partly heaving.

3.5 Anchors

For the behaviour of (vertical) anchors in the floor this research has only secondary results. In Pannerdensch Kanaal the deformations of the anchors were measured in the Western shaft. The deformations were very small (some millimetres), indicating a very stiff behaviour of the anchors.

3.6 Nearby structures & utilities

In the two cases for the Betuwe Route Cargo Rail no special attention was given to deformations and effects on nearby structures. This was the result of the position of the shafts having no structures nearby at all. It was still considered an important subject to study for future projects. Since most measurements would interfere with the contractors work, it was decided to move this topic to future research. In 2005 the COB starts the research on the behaviour of the deep excavations made for the Amsterdam North/South Metro link. With the help of a large amount of monitoring data on the construction and nearby structures this topic will be studied extensively in the coming years.

4 RESULTS OF THE VALIDATION PROJECTS

The validation of design methods resulted in conclusions and recommendations for design of deep excavations. Since the validation at Pannerdensch Kanaal is still ongoing, conclusions are not final yet.

The two COB-research projects show that validation of integral building pit design is difficult because of the complexity of construction activities and the methods of monitoring. Although finite element methods make it easier to design for interaction of construction parts, the combination of structural components with geotechnics is still not matured for overall building pit design validation.

Attention should be given to the monitoring system to ensure the quality of the validation. Reference measurements should be made to relate deformations and stress to absolute values to encounter for movements of pits as a whole.

Measurements in structural components of building pits are influenced by temperature and hardening of concrete.

Measurements in soil below building pit floors should comprise the full depth of the soil below the excavation until no influence is found left.

Good cooperation with the contractor on site ensures better quality of the measurement results. The research activities should interfere as little as possible with day to day work or better, should be part of it.

Wall deformations can be predicted reasonably well with design methods as spring models and finite element models. Interaction between wall, strut, floor and soil are more difficult to predict.

ACKNOWLEDGEMENTS

The conducted research is financed by the following organisations: Projectorganisation Betuwelijn, Projectorganisation Groene Harttunnel, Projectorganisation Noord/Zuidlijn, Rijkswaterstaat, Delft Cluster and COB. The (ultimate) goal of the research is to gain knowledge and expertise of underground construction in soft soil specifically for bored tunnels in the Netherlands.

The authors wish to thank the members of the research committees F210 and F501 for the use of the committees’ results.

REFERENCES


