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Response of piled buildings to deep excavations in soft soils

Déformations des bâtiments liés aux excavations profondes situé dans les sols mous

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ABSTRACT: This paper explores the building displacements related to deep excavations for a case study from the Netherlands: the construction of the North South Metro Line in Amsterdam. The overall goal of the analysis of the displacement is to study the interaction of deep excavations with piled buildings. The response of buildings is governed by the soil displacements resulting from the excavation. These displacements are described in a second, related paper in this conference. In this paper, the response of the piled buildings is described.

RÉSUMÉ : Les auteurs ont analysé déformations des bâtiments liés aux excavations profondes à Amsterdam pour la Ligne nord/sud. L'objectif général de l'analyse des déformations est d'étudier l'interaction des excavations profondes avec des bâtiments sur pieux. La réponse des bâtiments est régie par les déformations du sol résultant de l'excavation. Ces déformations, du niveau de la surface et de niveaux plus profonds, sont décrites dans un article connexe à cette conférence. Dans le document présent, la réponse des bâtiments sur pieux est décrite.

KEYWORDS: deep excavation, ground displacement, piles.

1 INTRODUCTION

The North-South Line in Amsterdam passes under the historical centre of the city in twin tunnels. Five underground stations are currently under construction. Rokin, Vijzelgracht and Ceintuurbaan Station are three of the deep stations in the historic city centre. They are built using the top down method, see Figure 1. In a related paper for this conference by the same authors, the construction method and ground displacements related to the deep excavations have been described. The settlement measurements for the Amsterdam deep excavations have been compared to several, mostly empirical, relationships to determine the green field surface displacements and displacements at depth. In summary, the surface displacement behind the wall is 0.3 – 1.0% of the excavation depth, if all construction works are included. Surface displacements behind the wall can be much larger than the wall deflections and become negligible at 2-3 times the excavated depth away from the wall. The shape of the displacement fits the proposed profile by (Hsieh and Ou 1998) best. In all three of the Amsterdam cases, the largest effect on the ground surface displacement can be attributed to the preliminary activities, which include amongst others the diaphragm wall construction, jet grout strut installation and construction of the roof, and took in total about 4 years. See Table 1 for details.

Table 1 Construction activities and dates for Ceintuurbaan

Construction activity	End date
Base monitoring start 2001	2003-11-01
Preliminary activities	2007-04-01
Excavation to NAP –6.2m	2007-09-13
Excavation to NAP –15.3 m	2007-12-10
Excavation to NAP –19.4 m	2008-03-01
Excavation to NAP –24 m	2008-08-01
Excavation to NAP –25.6 m	2009-06-24
Floor construction, pumping test	

The actual excavation stage caused only about 25-45% of the surface displacements, with 55-75% attributed to the preliminary activities. At larger excavation depths the influence zone is significantly smaller than 2 times the excavation depth.

This paper describes the building displacements related to the excavation works in more detail.

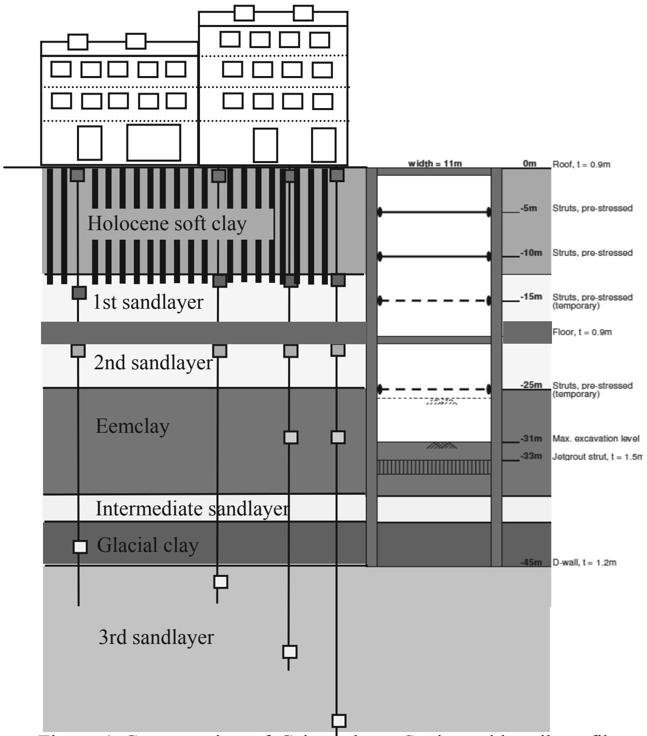

Figure 1 Cross section of Ceintuurbaan Station with soil profile and extensometer locations.

2 SOIL-STRUCTURE INTERACTION

The excavation–induced displacements described in the related paper can be considered as green field displacements. To assess the potential impact of these ground displacements on buildings, these displacements are usually directly projected onto the building, leading to bending and shear strains in the structure. It is however known that the presence of the building and the interface between building and soil also influences the settlement trough and transfer of deformations to the building. (Potts and Addenbrooke 1996, Franzius et al. 2006 and Farrell 2010) have shown this for displacements related to tunnels and (Goh and Mair 2011) for buildings influenced by deep excavations. (Goh and Mair 2011) modified the relative stiffness proposed by Potts and Addenbrooke for tunnelling to the following for deep excavations:

$$\rho^{*}_{exc} = \frac{EI}{E_s L^3} \qquad (1)$$

$$\alpha^{*}_{exc} = \frac{EA}{E_s B} \qquad (2)$$

where EI is the building stiffness, Es a representative soil stiffness and L the length of the building in either hogging or sagging. EA is the axial stiffness of the building and B is the total length of the building.

Furthermore (Jacobsz et al. 2005) described the soil-structure interaction in more detail for piled buildings related to tunnelling. In Amsterdam the piled buildings were influenced by deep excavations, which requires a combined approach influenced by the presence of pile foundations: the initial stresses in the foundation and the ground, and possible load transfer within the building. If these effects are not considered, the current assessment methods may be too conservative or too optimistic, leading to costly measures either being taken unnecessarily or having to be applied at a late stage in the project.

3 BUILDING AND FOUNDATION CHARACTERISTICS

Most buildings in the historic centre of Amsterdam are built with masonry walls, wooden floors and timber pile foundations, the piles being founded in the First Sand Layer at about 12m below the surface level (see Figure 1). More recent buildings with 1-4 storeys are built with concrete walls and floors and prefabricated concrete or steel piles. Foundations for some recent buildings are in deeper layers such as the second sand layer. The buildings considered in this paper are from the older type, see Figure 2.

Figure 2 Historic buildings at Vijzelgracht (left) and Ceintuurbaan Station (right), dated 1880-1920

The wooden piles are installed in pairs, see Figure 3, with 0.8m between the pairs. Pile diameters for the timber piles vary from 160 - 300 mm (typical 180-200 mm) at the head and usually diminish by 8 mm/m to about 70-200 mm (typical 120-140 mm) at the toe. Based on several pile load tests in the historic centre it is known that the wooden pile foundations have low factors of safety. Up to 15% of the buildings of this age in Amsterdam are not up to current standards, according to (van Tol 1994). A large number of timber piles deteriorate due to decay of the wood, which may lead to a different kind of building response; this effect is not described here.

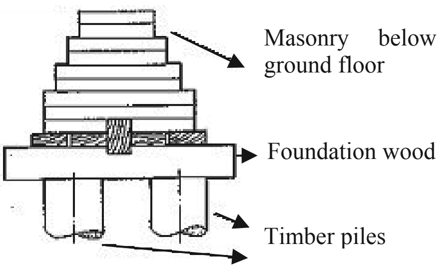

Figure 3 Typical cross section of base of the wall in masonry buildings (Zantkuyl 1993)

Two typical load-displacement curves are shown in Figure 4. The timber piles in failure generally find 60% of their capacity at the toe, 10% as friction in the sand layer and 30% as friction in the Holocene layers. In the soft Holocene clay the maximum shaft friction develops at a relative displacement of about 25 mm and in the base sand layer at about 15 mm. The maximum base capacity for piles with average diameter at the base of 130 mm is reached at about 10% of the diameter, which is consistent with common design methods. The high horizontal flexibility assures that the piles can move rather easily with the soil in horizontal direction, compared to concrete piles.

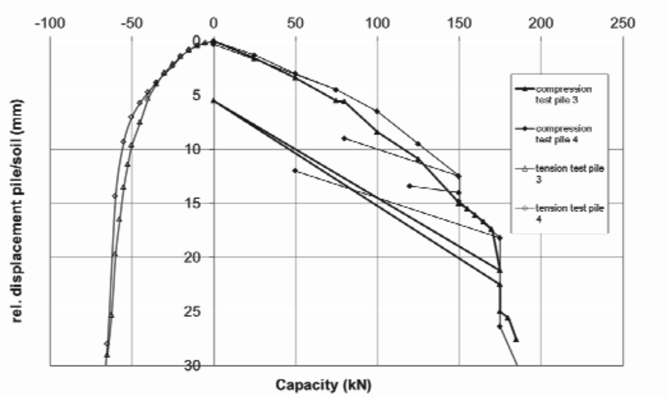

Figure 4 Representative load-settlement curves for timber piles in Amsterdam (Hoekstra 1974)

To determine the response of piled buildings to excavations knowledge of the current state of the piles is essential. Most piles in the historic centre of Amsterdam will already have experienced the maximum negative skin friction possible over time. The presence of soft soil layers combined with earlier city developments which included raising of the ground level causes on-going subsidence due to consolidation and creep. Negative skin friction develops as a result along the shaft of a pile when the soil surrounding the pile settles more than the pile itself. Positive skin friction occurs in opposite circumstances when the pile settles more than the surrounding soil. Both forces are likely to act on the timber piles in Amsterdam, see Figure 5.

4 RESPONSE OF PILED BUILDINGS

For end bearing piles with sufficient factor of safety the neutral level is found close to the location of the bearing layer. For the most historic Amsterdam foundations, the reserve capacity is smaller, and positive skin friction is also found in the soft or settling layers. The maximum force in the pile is found at the neutral level (the level at which the soil and pile settlements are the same and the shear stresses acting on the pile change direction). Usually in Amsterdam, it is considered that the negative skin friction is already fully mobilized before the excavation takes place.

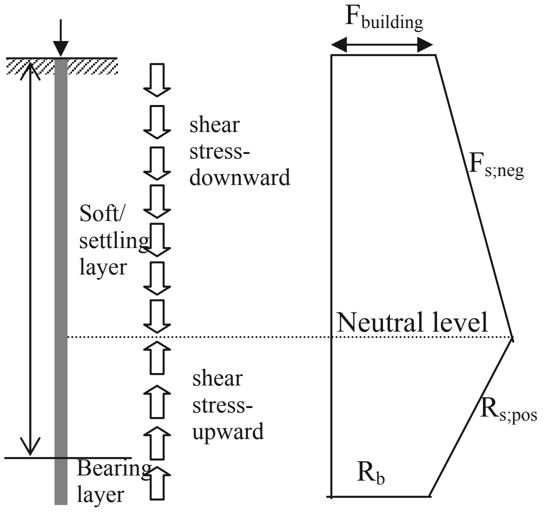

Figure 5 Development of negative and positive skin friction along a pile with low factor of safety

Buildings in the influence zone of the excavation may experience several phenomena:

1. reduction of pile capacity due to lower stress levels (s_1)
2. settlement of soil below the pile base (s_2)
3. development of negative (or positive) skin friction due to relative movements of the soil and the pile shaft (s_3)
4. redistribution of pile load between the piles (s_4)
5. horizontal deformations of the piles.

The settlement of the pile head is determined by the combination of the first four effects described above:

$$s = s_1 + s_2 + s_3 + s_4 \qquad (3)$$

Settlement s_1 for end bearing piles is significant if the pile tips are very close to the excavation and stress relief takes place around the pile tip. Settlement s_2 does not involve interaction with the piles, whereas s_3 is a true interaction component. For end bearing piles complying with current standards negative skin friction, if already fully developed, will not cause additional settlements, which means $s_3 = 0$. For all other piles s_3 depends on the amount of negative skin friction mobilized in the initial state. If the shaft friction is already fully mobilized, the neutral level will remain at about the same level and the pile follows the settlement of the soil at this level. If the shaft friction initially is not developed completely, the neutral level will change if soil displacements take place. For piles close to failure, the neutral level is found close to the surface and s_3 is about equal to the surface settlement.

An important issue is to determine the initial neutral level. This could be done theoretically based on CPT data or from historic data of relative building settlements to surface settlements. Based on the average pile capacity, the neutral level for an old pile in Amsterdam is found to be between NAP -7 and NAP -12 m, depending on the load on the pile, see (Korff 2012). Assuming a linear relationship between the ground settlement at surface and pile tip level, the pile-soil interaction can be determined from the relative position of the neutral level to the surface and the tip level, see Figure 6.

If the negative skin friction is not fully mobilized at the initial state or if the tip resistance reduces, the skin friction will further mobilize, which will raise the neutral level. Settlement s_3 might also include an elastic component of the shortening of the pile if the total stress in the pile increases with increasing negative skin friction. If the pile redistributes its load, s_4 needs to be determined together with s_3. This could occur if the piles closest to the excavation settle more than the piles further away. The building stiffness will prevent the building from following the different pile movements and the pile load will redistribute accordingly. If this happens, the external load on the pile changes, leading to a new equilibrium. This effect should be determined by a coupled analysis for a pile group, such as with a boundary element method as described by (Xu and Poulos 2000).

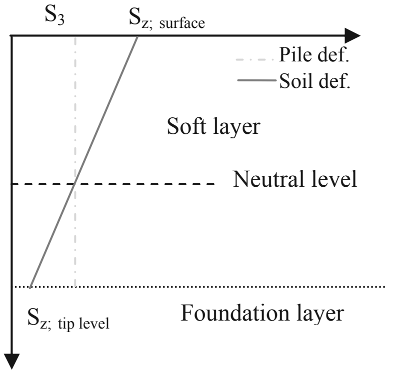

Figure 6 Settlement profile and neutral level, assuming linear relationship

5 BUILDING DISPLACEMENTS

The effects that cause the piles and hence the buildings to settle have been evaluated by analysing substantial amounts of monitoring data available from the Amsterdam cases. The settlement of the building is compared to the greenfield soil deformations at surface and pile tip level. It is not possible to distinguish between the contributions of s_1, s_3 and s_4. Settlement s_2 however can be directly evaluated against the results of the extensometer measurements at pile tip level. Figure 7 shows the building displacements (LevelingS) compared to the soil displacements at surface (GroundSurface) and pile tip level (ExtensoNAP-12m) for a series of buildings with old timber piles. The settlement of these buildings is equal to the soil settlement at approximately 0.3 to 0.5 times the pile length if a linear soil settlement profile between the surface settlement and the settlement at the first sand layer is assumed.

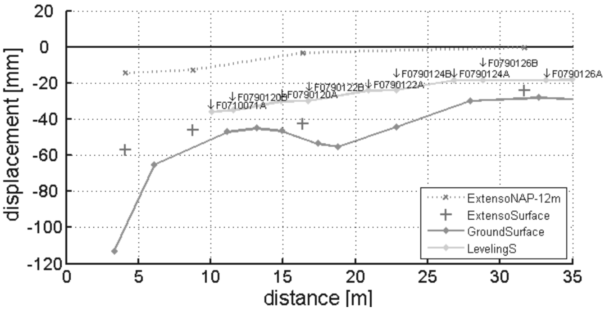

Figure 7 Ground and building displacements for CS13044 (at Ceintuurbaan).

In most cases in practice, no detailed information is present about the foundation and the soil-pile interaction has to be estimated or measured during construction.

For a second series of buildings with more modern foundations (old timber piles combined with renovation steel piles), the depth at which the pile and soil settlement are equal is found at approximately 0.8 – 1.0 times the pile length, see Figure 8.

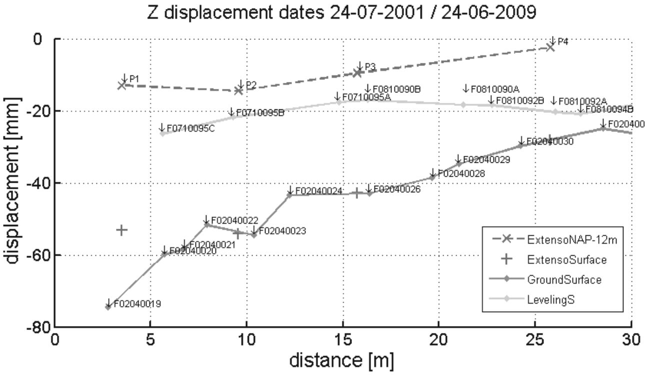

Figure 8 Ground and building displacements for CS13110 (at Ceintuurbaan) in the period 2001-2009

Based on the soil and building displacements as presented in more detail in (Korff 2012), the average interaction between pile and soil is found at 0.3 – 0.8 times the pile length for most original timber pile foundations and 0.8-1.0 times the pile length for most renewed foundations in the first sand layer. Some modern buildings settle very little and the pile settles the same as the pile tip level (1.0).

The settlement of the piles is shown to be between the settlement of the surface and the foundation layer. The deflection of the building is smaller than the deflection of either of the surface or base level soil deflections due to the stiffness of the building. The (Goh and Mair 2011) method to compare building settlement with greenfield settlement was used to determine the modification factors. In this case this was done comparing with greenfield surface settlement and with greenfield settlement of the foundation layer (first sand). For the deflection of buildings next to excavations, deforming in hogging shape, the modification factor is based on (Potts and Addenbrooke 1996):

$$M^{DR}_{hog} = \frac{\Delta/_{L}\ \text{hog, building}}{\Delta/_{L}\ \text{hog, greenfield}} \qquad (4)$$

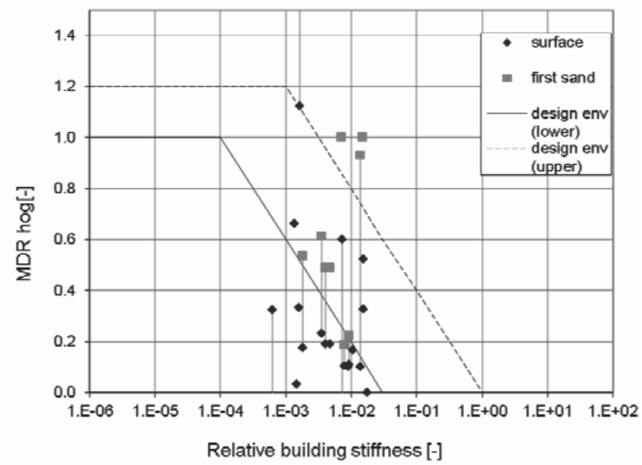

Figure 9 Modification factors from Amsterdam deep excavation for surface level and foundation level, compared with the design envelope presented by (Mair 2011)

The deflection of the buildings is clearly less than the deflected shape of the surface (70% reduction). A reduction of the deflection of 45% is found compared to the foundation level. The variation in these factors can to a certain degree be explained by the relative stiffness of the buildings compared to the soil as shown in Figure 9.

6 CONCLUSIONS

Piled buildings adjacent to deep excavations have to be assessed differently from buildings with shallow foundations. Piled buildings settle an amount between the surface settlement (for friction piles in failure) and tip level settlement (for end bearing piles with sufficient capacity to take full negative skin friction). The precise soil-pile interaction can be estimated based on the pile load, the pile capacity and the shaft friction development based on a method described in (Korff 2012). Based on measurements of Amsterdam timber pile foundations, the pile settlement is equal to the soil settlement at a depth of 0.3 – 0.8 times the pile length for most original timber pile foundations and 0.8-1.0 times the pile length for most renewed foundations in the first sand layer. Most of the modern buildings settle not more than the pile tip level.

The method proposed by (Goh and Mair 2011) provides a realistic, although rather large, range of possible modification factors to estimate the building deflection compared to the deflected shape of the soil surface and foundation level.

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