Performance evaluation of the MT–pile® applied in the IBIS Amsterdam project

Évaluation des résultats de pieu-MT appliqué dans le projet IBIS Amsterdam.

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ABSTRACT
Within the project 'Extension of the Amsterdam IBIS Hotel' the MT-pile® has been applied. The pile is installed using a vertically driven Tunnel Boring Machine. At the time of the design, no proven models or parameters were available for this large diameter casing pile. Loss on effective stress at the pile tip was of most concern, resulting in unacceptable pile settlement. The monitoring program applied during construction resulted in load settlement curves for each pile. These curves indicate a uniform, direct pile response and a maximum pilehead settlement of 20 mm at completion of the project. These results indicate that the loss of effective stress at pile tip level is compensated during construction of the pile and that the MT-pile can be modelled without loss of soil stress.

RÉSUMÉ
Dans le cadre du projet "Extension de l'hotel Ibis d'Amsterdam", le procédé pieu-MT® a été apppliqué. Le pieu a été placé par le moyen d'un tunnelier mis en oevure verticalement. Au moment de l'étude technique, aucun modèle ou paramètres n'étaient connus et validés pour un ouvrage d'un tel diamètre. Les inquiétudes principales résidaient dans une perte de la contrainte effective en bout de pile, ce qui résulterait en un affaissement inacceptable. En phase de travaux, chaque pieu a été ausculté à l'aide de courbes de mise en charge. Ces courbes montrent une réponse directe et uniforme de la strucure avec un affaissement maximal de 20mm en tête de pieu après travaux. Ces résultats indiquent que la perte de contrainte effective en extrêmité de pieu est compensée pendant les travaux et que le pieu-MT peut être modélisé sans perte de contrainte dans le sol.

Keywords : Large diameter casing piles, load settlement curve, effective soil stress, Finite Element Modelling

1 INTRODUCTION

This project 'Extension of the Amsterdam IBIS Hotel' consists of an expansion of the existing IBIS Hotel at Amsterdam Central Station (the Netherlands). The six floor high expansion of the hotel has been erected above platforms 1 and 2, above three railway tracks (see figure 1).

Figure 1. IBIS Expansion at completion, Amsterdam, November 2008

During construction train service and use of the platforms could not be interrupted. The Micro Tunneling pile (MT-pile) technique was selected because of its high bearing capacity, the limited working height and area, capability of passing obstructions in the subsoil, achievable pile length and low vibrations during installation. The pile is installed by using a vertically driven Tunnel Boring Machine (TBM). The pile casing acts as a tunnel lining and the reaction force is applied at surface. Once the required depth has been reached the machine is retracted through the lining and hoisted up to the surface. The base of the casing is filled with gravel, after which the pileshaft grout injection can take place in order to replace the bentonite cake in the overcut of the lining. The pile can then be filled with concrete and after setting the pile tip can be injected with grout through the gravel base. In total 10 piles (length approximately 25 m, diameter 1,4 m, bearing capacity approximately. 10.000 kN) have been produced, of which eight piles had to pass a 2 to 4 m thick concrete slab. For each pile a CPT test was made. The pile tip level has been designed at 22,5 m below NAP (Dutch reference level), which equals 28 m below platform level. The pile is founded 9 m deep in the second sand layer of Amsterdam. At 10 m below the pile tip level the Amsterdam Eem Clay layer is encountered.

After completion of the first two floors, thus creating a rigid box, the legs of the structure were lowered hydraulically on to the concrete slabs at the pile heads. In order to prevent transmission of train vibrations to the hotel, the concrete slabs at each pile head have been equipped with a large number (56 to 84) of springs.

The piles were installed early 2006 up to mid 2006. July 3, 2007 the structure, consisting of the first two floors, was lowered on to the piles. In August 2008 the structure was completed. Since November 2008 the hotel extension is in use.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-1309

2 PILE DESIGN

During design, carried out by Harmelen Engineering Consultants, uncertainty arose regarding the modelling of this large diameter pile and the parameters to be used. It was unproven technology and in general the determination of pile type and parameters require a large number of pile tests. The uncertainty did not concern ultimate bearing capacity, since various calculation methods indicated sufficient bearing capacity. Stiffness of the pile response was the major concern, given the nature of the structure to be supported. Loss of effective soil stress during casing installation and TBM retrieval was of most concern. The TBM (see figure 2) would have to apply a small overcut in order to reduce skin friction and after retrieval the pile tip would be left unsupported for several days. In order to minimise loss of effective soil stress various measures were undertaken. The radius of the cutting wheel would only exceed the outer casing diameter by one centimetre. To achieve a closed front a collar equal to the cutting wheel diameter would be applied at the outer lining, at pile tip level, over a length of 0,6 m. The one centimetre overcut would be supported by a bentonite slurry. Once at maximum pile depth and after retrieval of the TBM, the overcut of the pile shaft would be injected with grout from the pile tip upwards, to replace the bentonite slurry by pushing the lighter bentonite upwards. At the Holocene layers the bentonite would remain in order to avoid negative skin friction. Also a pile tip injection would be applied after the pile had been filled with concrete and hardened. The injection would be applied to a 0,6 m gravel bed at the pile tip, which would be installed immediately after retrieval of the TBM. The TBM could be retrieved since the spokes of the cutting wheel were specially adapted to fold, thus creating a smaller and therefore retractable TBM diameter.

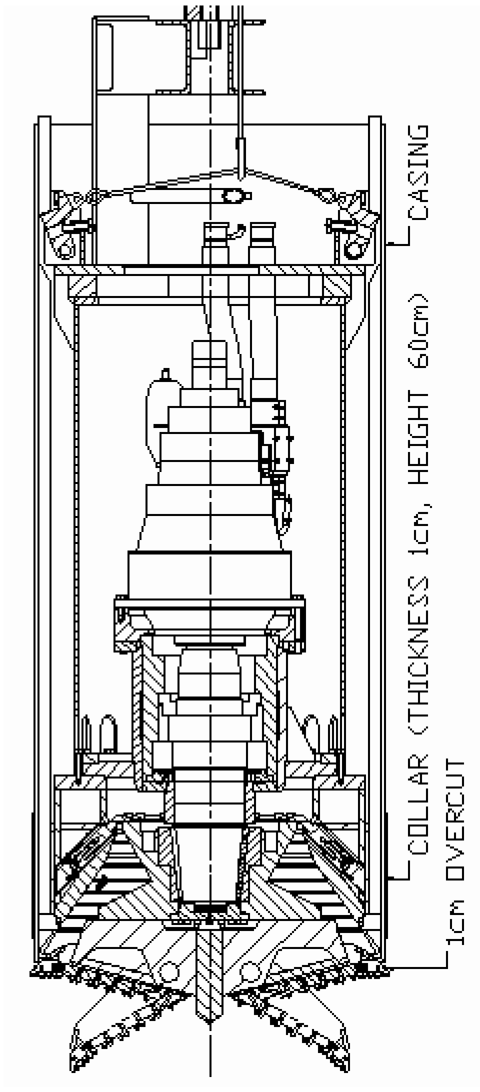

Figure 2. cross section TBM at pile tip MT-pile

After review by Witteveen+Bos and the Municipality of Amsterdam of the MT-pile design and method statement a final approach on pile design and observations during the construction was agreed. The pile would be regarded as a concept with limited stress relieve at the pile tip and a neutral stress state at the pile shaft combined with a partially rough, partially smooth pile shaft surface. In order to determine bearing capacity and more in particular the load settlement curve of the MT-pile, Dutch NEN6743 has been applied. The calculation method did not cover the chosen combination of pile tip and shaft behaviour. A pile type with a more conservative load settlement curve had to be selected in the calculation. Furthermore it was suspected that the load settlement curve would overestimate settlement, since the model has been based upon small diameter (less than 0,5 m) pile tests.

Negative skin friction and compression of underlying layers was not foreseen in the design. In order to create a robust, rigid and uniform design, all piles were designed to withstand the maximum pile load, although 8 out of 10 piles would be exposed to less than 80% of this load. The anticipated load settlement curve has been presented in figure 4 (line NEN6743 Harmelen), combined with the recorded load settlement curves (lines with markers) and Finite Element modelled curves (smooth lines without markers). Comparison indicates that the chosen NEN6743 model is not exceeded by the lowest curve recorded at pile J17.

3 OBSERVATIONS DURING PILE INSTALLATION

During installation all relevant parameters were recorded, such as progress, torque at the cutting wheel, injected volumes, applied reaction force at surface, installation depth etc.

In general all piles reached the intended depth, except the first pile G15, of which the installation had to be interrupted for 24 hours. When pile installation was resumed, a maximum driving force of approximately 1000 kN was applied. Torque at the cutting wheel was minimal, nevertheless the casing could not be lowered. After a check on bearing capacity and specific pile load it was decided to pull the TBM out at 2,25 m above the intended pile tip level. From this it can be deduced that skin friction exceeds 1000 kN with the bentonite still in place.

During the injection in the gravel bed at the pile tip, a volume of one m³ was applied to all piles. The grout pressure recorded at the pump, in general, reached a pressure of approximately 8 bar. In incidental cases a pressure of 18 bar had been reached. During pumping a sudden drop in pressure was noticed at all piles, after which the pressure stabilized at the levels mentioned above. During the pile tip injection heave of the pile was never encountered. Given the applied pressure and the area of the gravelbed, it can be deduced that the pile shaft could withstand a load between 1200 kN up to 2700 kN.

4 OBSERVATIONS DURING CONSTRUCTION

During construction all relevant pile loads and pile settlements on all the ten piles were recorded, see figure 3. Pile head settlement was recorded directly on the concrete slab from the start of the construction. Actual pile load has been deduced from the applied hydraulic pressure and cylinder surface during lowering of the structure. Once lowered on the pile head, the additional spring compression was recorded during the remaining part of the construction by subtracting the slab settlement from the leg settlement. On the basis of the spring

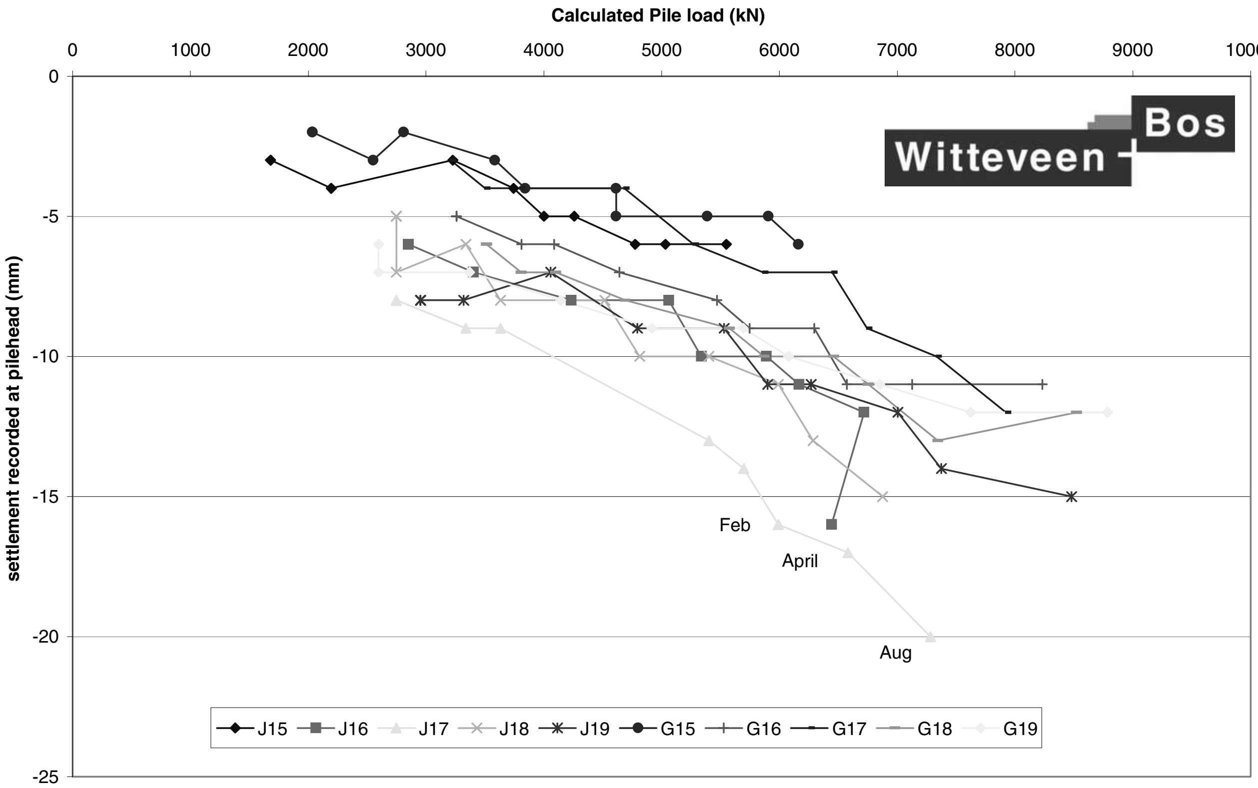

Figure 3. Load settlement curves MT-piles IBIS Amsterdam

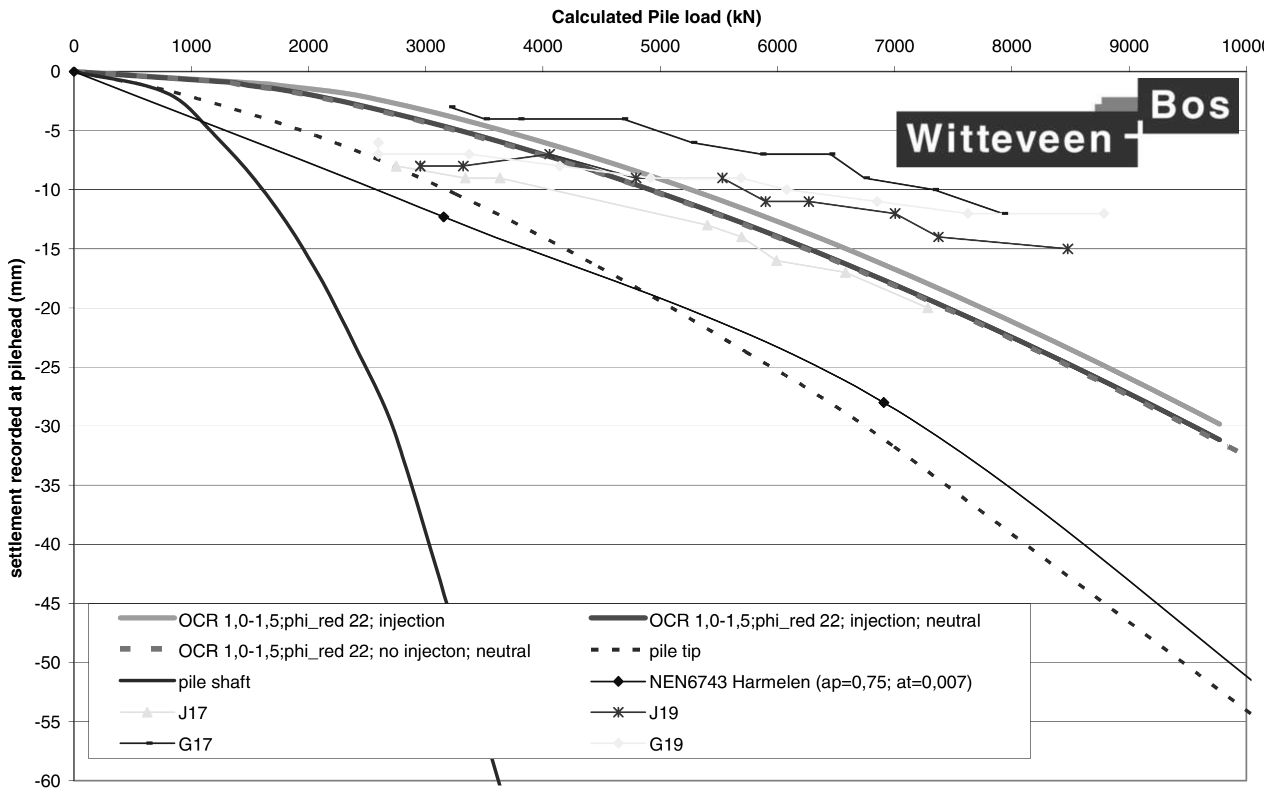

Figure 4. Recorded and predicted load settlement curves MT-piles

characteristics and the number of springs per leg, additional pile loads could be determined. The measurements were taken from August 2007 to August 2008, at completion of the structure.

Once the legs of the structure had been lowered hydraulically on the slabs at the pile heads, pile loads varied from 1600 kN up to 3500 kN and pile settlements varied from 2 up to 8 mm.

At completion of the structure, pile loads varied from 5500 kN up to 8800 kN and pile settlements varied from 6 up to 20 mm. From the curves it can be deduced that the heaviest loaded piles did not correspond with the biggest settlement. The settlement of the legs after lowering on the slabs, also influenced by spring compression, varied between 18 to 27 mm.

Based on the curves no correlation can be made between variation in pile tip level and pile response. Also the pile tip injection pressure achieved does not appear to correlate with pile settlement. The pile response varied between 360 MN/m up to more than 1000 MN/m. The load settlement curves suggest that the piles are loaded well below maximum bearing capacity.

In February 2008, 80% of the permanent pile load had been applied. In April 2008 the load increased to 90%. In August 2008 the permanent pile load had been reached. The last three readings of the curves in figure 3 and 4 present the results of these three stages. Given the recorded load settlement curves with fairly constant k values and the elapsed time, significant consolidation in underlying Amsterdam Eem Clay does not seem likely. Oedometer tests on this Clay also indicate an Over Consolidation Ratio (OCR) of approximately 1.5. Rough estimates indicate a load increase on this layer by 10% at an initial effective stress level of 300 kPa at the top of this layer. Back ground settlement, caused by natural long term compression of Eem Clay below the pile tip, did not affect the readings. In general the back ground settlement is limited to 1 to 2 mm per year on Amsterdam historical wooden pile foundations. (Cook et al. 2007).

5 FINITE ELEMENT MODELLING

Despite the observations, calculations, soil investigations and monitoring during installation, which all contributed to the confidence in pile performance, the pile behavior itself could not be fully explained. Also an ultimate bearing capacity could not be deduced from the load settlement curves. Given the available soil investigation from the IBIS project and the adjacent North South line metro extension, another method for analysis could be applied: Finite Element Modelling (FEM). Main purpose of the model was to determine the effects from pile installation on pile behaviour and determine a maximum bearing capacity.

The model was created in FEM software Plaxis, version 8.6. Within the program the axial symmetric model has been used. Soil parameters were obtained from North South line experience, (North/Southline Consultants. 2000) soil strata has been deducted from the specific CPT tests on site. Within the soil model, hardening soil has been selected.

The various stages in pile installation have been modelled, starting with the casing at maximum depth with the tip being unsupported. The next stage involved the filling of the casing with the concrete mixture over the first ten meters (one truck load of 15 m^3), with hydrostatic concrete pressure at the pile tip. The third stage involved the load of the total weight of the pile. In the fourth stage an excess pore pressure of 8 bar has been applied in the gravel bed. In the fifth stage the excess pore pressure has been removed, leaving a hardened grout entity at the pile tip. In the last stage the pile load has been applied and increased by an automated multiplier over the following calculations, thus creating a load settlement curve. The effect of the excavation with the TBM and the shaft injection with bentonite and later on grout has been modelled by applying an interface between the casing and the surrounding soil.

During the optimization of the model, soil parameters were not changed. The initial model showed too much settlement. After the introduction of the stage with the 10 m hydrostatic concrete mixture, the results improved considerably. Final adjustments were the increase of the OCR of the sandlayer from 1 to 1.5 and the interface which had been increased from an angle of internal friction of 15 degrees to an angle of 22 degrees (see figure 4).

From the calculations it was recognized that the loss on effective soil stress is limited to the direct vicinity of the pile tip. Approximately one diameter below the pile tip 50% reduction occurred, which coincided with analytical models (Maclean 2006). After the 10 m concrete mixture had been poured in the casing almost 50% of the initial stress at the pile tip has been regained, due to the weight of the mixture. The effect of the pile tip injection is limited, since it is believed that the pressure will dissipate before hardening of the grout.

Given the limited reduction of effective soil stress after completion of the pile, another model has been created by skipping all the intermediate pile installation stages. This so called neutral pile consists of a pile installed without loss on effective soil stress, but with the interface and grout entity at the pile tip (see figure 4, neutral). Using this model, calculations with and without pile tip injection have been made.

The FEM results from staged modelled pile and the neutral modelled pile seem to correlate well. The effect of the pile tip injection appears insignificant. The limited loss on effective soil stress explains the direct pile response. From the models it can be concluded that at a pile head settlement of 50 mm at a pile load of 13000 kN pile failure still has not occurred.

6 CONCLUSION

Based on the monitoring, analysis and FEM the following conclusion have been made:

1. The predicted load settlement curve proves to be conservative.
2. The good pile performance can be explained by the limited loss on effective soil stress. The effect of the unsupported pile tip is limited to one diameter below the pile tip and the filling with concrete mixture restores approximately 50% of initial effective stress at the pile tip. The skin friction is also contributing to a direct pile response.
3. The applied pile tip injection appears less effective, given the loss on pressure and the limited pressure achieved.
4. Ultimate bearing capacity has not been determined. Based on the monitoring and FEM results, pile failure does not appear to be imminent.
5. Time-dependent behavior has not been recognized in the load settlement curves.

7 RECOMMENDATIONS

CPT tests inside and outside the casing could be included in the Monitoring Program. Also pile tip settlement could be recorded by using a tell tale to the pile tip as well as pore pressure measurement during injection of the pile tip.

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