BAM Screw Piles 2.0: Validating Design for 'De Drie Hoefijzers' by Rapid Load Testing

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ABSTRACT

Following an amendment on the Dutch Construction Decree in 2016 design parameters for end bearing of pile foundations have been reduced by 30% on January 1st 2017. This amendment was motivated by research on load testing data of foundation piles, which showed an overestimation of end bearing and consequential compromised safety. The new situation potentially results in a considerable increase in installed lengths as well as cross-sectional areas, with possible executional, economic and environmental consequences. A piling contractor can deviate from the CPT-based design parameters by performing pile load testing. NPR7201:2017 offers the possibility to validate a preliminary design based on freely chosen (assumed) design parameters, by verifying suitability up to design load based test loads.

BAM was awarded the installation of the foundation for housing development project 'De Drie Hoefijzers' in the central train station area in Breda. Because of the presence of sensitive objects in close proximity to the project area, a pile system with low vibration installation is selected. The BAM Screw Pile 2.0 is an optimization of the CFA pile, combining easy installation with minimal relaxation of the soil around the pile tip by introducing a permanent cast steel, serrated drill bit. Experiences with the BAM Screw Pile 2.0 thus far show considerably higher capacities compared to CPT-based design for standard CFA piles. Therefore it was decided to incorporate a pile testing program to corroborate this experience and optimize the design of the foundation.

The pile load testing method selected was Rapid Load Testing (StatRapid system). Three test piles following the preliminary design with assumed higher design parameters (20 m in length with a diameter of 800 mm) were subjected to test loads ranging from 6.0 to 7.3 MN (design loads ranging from 2.8 to 3.1 MN). The piles did not exhibit soil mechanical failure and as a consequence the preliminary design was validated. Effectively the approach saved 1 km of pile length, reducing cost by €175.000, as well as a resulting reduction in CO_2 production of 80 tons.

Keywords: BAM Screw Piles 2.0, pile foundations, optimization, Rapid Load Testing (RLT)

1 INTRODUCTION

1.1 Project 'De Drie Hoefijzers'

Commissioned by developer AM, part of the Royal BAM Group, district 'De Drie Hoefijzers' (translated into 'The Three Horseshoes') east of Central Station in Breda is being re-developed, giving rise to 270 apartments and houses. The project on the grounds of the former beer brewery (founded in 1538) includes realization of apartment building 'De Hendric' named after the founder of the brewery. This complex consists of 3 blocks 5 to 9 stories high. It will comprise 124 apartments, a semi-sublevel parking garage with 187 spots as well as indoor bicycle shelter and storage facilities. The ground floor will accommodate commercial ventures like shops, bars and restaurants. The contractor is BAM Wonen. The structural design is created by BAM Advies & Engineering.

1.2 Foundation

In the early conception stages of the project, BAM Infra Funderingstechnieken has been involved for design and installation of the foundation for 'De Hendric'. In consultation with the contractor and structural design engineer, and considering all stakeholder aspects with respect to environmental influence and nuisance, a foundation solution was to be selected which is both economical and compliant with all preconditions.

The project is located near the base of the slope of an elevated bus lane and railway track as well as in close proximity to old residential areas. Damage to the bus lane, railway track and existing houses must be avoided at all cost. Therefore the installation method considered should be low in vibration and noise. The soil profile is characterized by medium dense to very dense sand layers locally interbedded with loam- and clay layers. Consequently a drilled shaft with soil removal was the obvious solution. The selected system was the BAM Screw Pile 2.0, which is a CFA with a wide stem and permanent cast steel, serrated drill bit, offering economical and executional advantages.

Fig. 1. Former brewery ‘De Drie Hoefijzers’.

Fig. 2. Artist impression ‘De Hendric’.

2 DESIGN

2.1 NEN9997-1:2016

Since January 2017 (CPT based) design calculations according to design code NEN9997-1 have been adapted for the Netherlands following amendments on the Dutch Construction Decree in 2016. Pile toe capacity has been reduced by 30% by lowering factor α_p (pile tip factor). This reduction was motivated by research on international data (CUR229, 2010) on the interpretation of load testing on deep foundations, revealing an overestimation of pile capacity determined with the previous design parameters included in the code, thus compromising the safety of the foundation. Imminent drawback of the adaptation is the consequential, in some cases considerable, increase in length of piles. The increase in length also likely has an effect on the feasibility of execution of pile installation, e.g., an increase of installation stresses could also require an increase in installed diameters. Clearly the volume of concrete (and steel) consumed for foundation works will increase proportionally. Approximately 7% of the worldwide production of CO_2 is attributed to the production of cement and therefore reducing concrete consumption is an important factor in reaching the climate goals formulated in Paris.

The (new) pile factors for CFA piles are established as α_p = 0.56 (pile tip) and α_s = 0.006 (pile shaft) including maximization to 2 MPa of the cone resistance contributing to the toe capacity above the pile toe (Koppejan method, 1952). The maximization of the cone resistance is motivated by the mode of execution for CFA piles: Upon reaching design penetration the auger is lifted slightly to open up the valve, allowing the flow of concrete. The lifting results in relaxation in the soil around the pile toe.

2.2 BAM Screw Pile 2.0

BAM Infra Funderingstechnieken optimized the CFA system by introducing a permanent cast steel, serrated drill bit, facilitating easy penetration, but more importantly, preventing relaxation of the soil near the pile toe, since immediate flow of concrete is possible. After design penetration is reached, the rebar cage is introduced into the stem after which the stem is filled with concrete. Subsequently the auger is statically retrieved allowing flow of concrete at the bottom while maintaining an overpressure. Alternatively grout or water injection at the drill bit can be applied to further increase the ease of penetration (not applied at ‘De Drie Hoefijzers’).

Load tests performed on this pile system for previous projects, Den Haag in 2017 and Hilversum in 2019, have shown that the capacity can be considerably higher compared to calculated according to NEN9997-1 for regular CFA piles.

2.3 NPR7201:2017

The Dutch code of practice for pile load testing (NPR7201) offers the possibility to test the pile system to validate higher capacity, resulting in optimization of the foundation design. Various test classes are described. In consultation with the contractor and structural design engineer it has been decided to set up a test program in compliance with class C: Validation of pile capacity for a specific location of a project. In the preliminary design pile factors can be chosen freely. Subsequently test piles (which can be working piles) are installed, followed by testing to a test load equal to a percentage of the design load. In case more piles are tested the percentage is reduced accordingly. In case all tested piles can accommodate the required test load without geotechnical failure occurring, the preliminary design is validated (no differentiation between contributions of toe and shaft will be established). Geotechnical failure for piles with soil removal is, according to NEN9997-1, arbitrarily defined at maximum pile toe displacements exceeding 20% of the equivalent pile toe diameter (160mm in this case). For load tests without direct recording of the displacement of the pile toe, this criterion is applied to the permanent set recorded at the pile head.

Class C load tests can be performed either statically or by Rapid Load Testing (RLT). RLT is a relatively easy, fast and economical method, which can be practically incorporated in the execution of the foundation works. In this case RLT is the selected test method.

2.4 Optimization foundation design

In the preliminary geotechnical design for ‘De Hendric’ the pile factors have been increased to $\alpha_p = 0.63$ and $\alpha_s = 0.075$. Furthermore the maximization of the cone resistance has been abandoned. No negative skin friction is included and shaft friction is included from a level of NAP -9 m downward. These assumptions lead to an increase of calculated capacity of 25-30% compared to regular CFA piles designed according to NEN9997-1.

By assuming the higher capacity of the pile system the foundation design resulted in 238 piles, 800 mm in diameter with a pile toe elevation of NAP -18.5 m. The piles need to support design loads F_d ranging from 2,800 to 3,500 kN. Major advantage of the higher capacity is that the number of piles could be reduced considerably as well as a reduction in size of the required pile caps. A number of pile caps could be replaced by foundation beams. Since the vertical stiffness is difficult to quantify beforehand, the structural design allows for a considerable spread in stiffness of the piles (100-200 MN/m), resulting in robustness of the design. Furthermore the selected pile diameter is able to accommodate considerable horizontal loads ($F_{d,h}$ = 90-305 kN), further adding to the suitability of the design.

3 PILE INSTALLATION

In consultation with the contractor and structural design engineer 3 working piles have been selected for testing. In preparation CPT’s have been executed at the exact locations of the test piles (figure 3). The profile at these locations can be regarded as normative for the complete site.

The test piles and all remaining working piles have been installed with a Woltman 160DR drilling rig (figure 4) with a 50 tonm rotary drill. The outer diameter of the auger equals 800 mm with a stem 560 mm in diameter. The diameter of the steel serrated drill bit equals 680 mm. The length of the piles equals 20.1 m. The rebar cage consists of 8 * Ø20 mm bars within a spiral cage over the full length of the pile. The concrete quality is C25/30 with exposure class XC2/XA2. During installation all production data (penetration, torque, pull down, rotations, speed) is automatically recorded, resulting in continuous quality control.

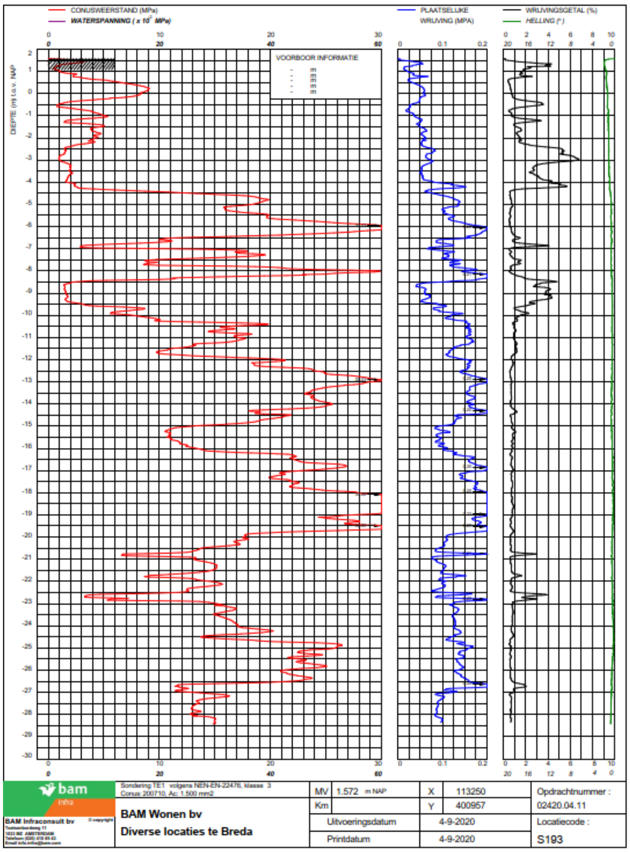

Fig. 3. Dedicated CPT test pile 193.

Fig. 4. Woltman 160DR drilling rig.

Fig. 5. Extended pile head.

Immediately after installation of the 3 test piles, the piles are extended with a steel casing filled with concrete, resulting in a pile head surface approximately 40 cm above grade (figure 5), allowing for easy testing. The installation of all 238 piles was completed within 8 weeks.

After installation three additional CPT's have been executed directly adjacent to each test pile to quantify the installation effects. The initial and 3 additional CPT's for pile 193 are presented in figure 6. It can be seen that the reduction in cone resistance above the toe is limited (slight reduction in the interval NAP -12,5m/-17,5m). Comparable influence was displayed for all 3 test piles. Abandonment of the maximization to 2 MPa therefore seems justified.

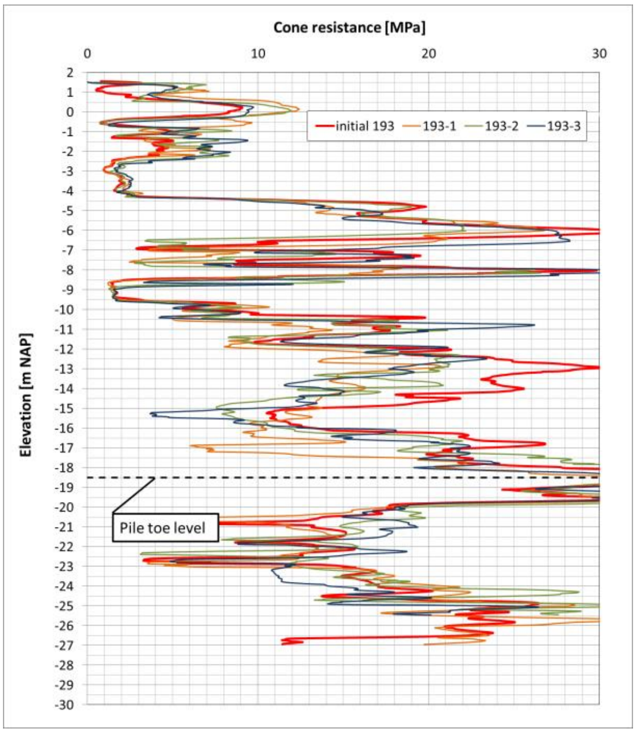

Fig. 6. Initial CPT with additional CPT's for pile 193.

4 TESTING PROGRAM

4.1 Rapid Load Testing

Rapid Load Testing –described in ISO22477-10, 2016– combines the advantages of Dynamic Load Testing (DLT) in terms of flexibility and economy and Static Load Testing (SLT) in terms of reliability. For mobilizing the required capacity approximately only 5 % of 'ballast' is required for RLT, whereas for SLT in excess of 100 % is required. Because the duration of application of the test load for RLT considerably exceeds the stress wave period, it is assumed that all elements in the pile are moving in the same direction. Consequently the pile moves like a rigid body minimizing the influence of stress wave phenomena. As a result interpretation of RLT data (following the Unloading Point Method) is fairly straightforward and user-independent, whereas for DLT complex and non-unique signal matching analysis is required.

The Unloading Point Method (Middendorp, 1992) makes use of the condition, that at maximum displacement during the loading event the velocity equals zero (the unloading point). As a consequence damping is zero. The load on the pile at the unloading point therefore reduces to the sum of the static resistance and the inertia component. Since the load on the pile and the acceleration of the pile are recorded directly, the static capacity can be determined (static point). When multiple load cycles are performed a hyperbola can be fitted through the static points, representing the load-displacement behavior (Rollberg, 1978). Because of the relatively high loading rate, the hyperbola is corrected by a soil dependent factor η, yielding the long term static behavior.

4.2 Determination RLT test load

The minimum test load to be applied according to NPR7201 shall be in line with equation (1):

$$F_{test;RLT} = (\kappa \times F_d + 2 \times F_{nk;d})/(\eta/\xi_{RLT}) \qquad (1)$$

κ: *product of partial factor total capacity* γ_t *and correlation factor* ξ_1
F_d: *design value external load*
$F_{nk;d}$: *design value negative skin friction*
η: *loading rate factor (0.94 for sand)*
ξ_{RLT}: *Correlation factor for RLT (1.10)*

Factor κ is dependent on the type of foundation and the number of tests to be performed (table 1). For the current project it is assumed that the structure is not capable of redistribution of the loads (non-rigid construction) and testing of 3 piles: $\kappa = 1.56$. Negative skin friction is not applicable. However in the design no shaft friction will be attributed to the layers above the reduction in cone resistance at NAP -9 m. Obviously these layers will contribute to the shaft friction during testing, consequently it will need to be incorporated in the test load.

Table 1. Factor κ NPR7201:2017.

number of test piles per project	factor κ	
	non-rigid structure	rigid structure
3	1.56	1.42
4	1.54	1.40
5	1.54	1.40
7	1.52	1.38
≥10	1.50	1.37

For the 3 dedicated CPT's the magnitude of the shaft friction $R_{s;cal}$ above NAP -9 m is calculated according to NEN9997-1. The following minimum test loads have been determined:

Table 2. Test load $F_{test;RLT}$.

pile	F_d [kN]	$R_{s;cal}$ [kN]	$F_{test;RLT}$ [kN]
193	3,109	1,327	7,267
214	2,948	462	5,954
230	2,805	1,121	6,467

According to NPR7201 the test load should be applied in no less than 5 load cycles, with approximate equal load increments.

4.3 StatRapid

Rapid Load Testing is performed by Allnamics with the system StatRapid (figure 7), which is a modular drop mass system in combination with a modular spring system and a further development of the work of Gonin et al (1984). With wave equation software AllWave-RLT predictions are performed to determine the required set-up and the drop heights corresponding to the different load cycles. For the current case a drop mass of 40 tons in combination with a spring system with a stiffness of 33.6 MN/m is selected, being able to generate test loads up to 10 MN.

Fig. 7. Rapid Load Testing system StatRapid.

4.4 Test results

All three piles have been subjected to loads in excess of the required test load, without geotechnical failure occurring at the required test load. Consequently the foundation has been validated and the preliminary design can be promoted to final design.

The average value of the vertical stiffness at characteristic load equals 129 MN/m (characteristic load divided by displacement at characteristic load), which is within the limits assumed in the design.

Table 3. Results RLT.

pile	max displ at $F_{test;RLT}$ [mm]	max mobilized load [kN]	permanent displ [mm]
193	52.1	8,243	45.5
214	59.5	8,777$^{(1)}$	144.7
230	88.3	6,487	64.9

$^{(1)}$ Considerably higher than required test load for class C.

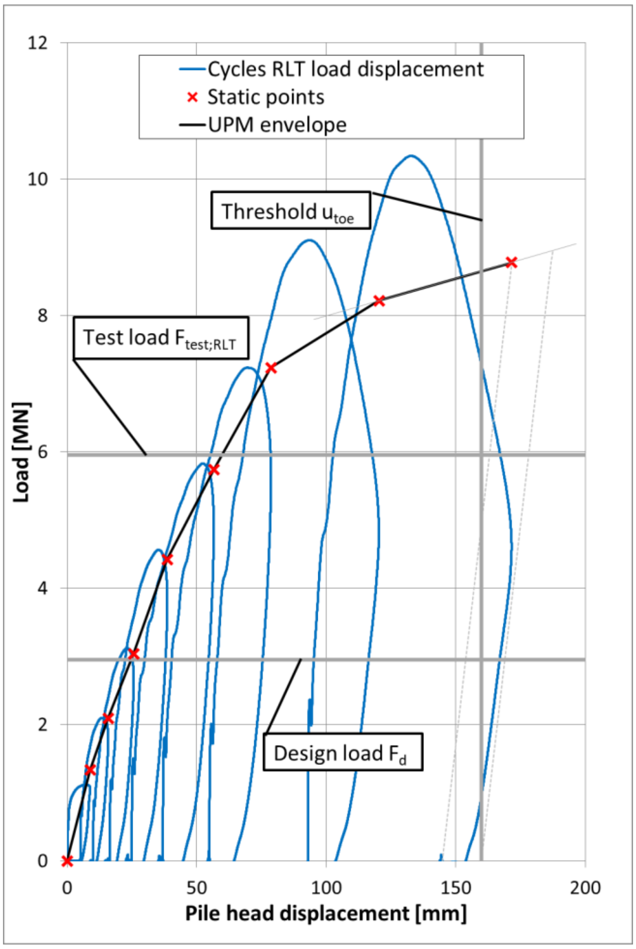

Fig. 8. Load-displacement pile 214.

Since the required test load was low for pile 214 compared to piles 193 and 230, and surplus testing range in terms of capability of the StatRapid device was available (possible test loads up to 10 MN), it was decided to continue testing until geotechnical failure occurred. As a result the test can be promoted to class B (section 4.5) according to NPR7201. Strictly speaking the criterion for geotechnical failure (permanent displacement exceeding 160 mm) was not quite reached, however, judging from the load-displacement behavior (Fig. 8), the pile is clearly failing. With slight extrapolation the failure load $R_{c;ic;t}$ for pile 214 can be determined at 8.95 MN.

4.5 Class B NPR7201:2017

Class B tests are defined as: Determination of pile capacity for a specific location of a project. The difference is that the result offers the possibility to re-evaluate the design load per pile, i.e., the amount of required piles could possibly be reduced (no differentiation between contributions of toe and shaft will be established). In general this implies class B testing is preferably performed during a pilot phase. Nevertheless the evaluation is elaborated here for reference.

The capacity of pile 214 can be determined as:

$$R_{c;m;g} = \eta \times R_{c;ic;t}/\xi_{RLT} - R_{s;cal} \qquad (2)$$

According to NEN9997-1 this test result can now be converted to a design capacity following:

$$R_{c;k} = min\left\{\frac{(R_{c;m})_{average}}{\xi_1}; \frac{(R_{c;m})_{min}}{\xi_2}\right\} \qquad (3)$$

$$R_{c;d} = R_{c;k}/\gamma_t \qquad (4)$$

Characteristic value $R_{c;k}$ is linked to the test result through correlation factors ξ_1 and ξ_2 (both 1.39 considering 1 pile tested for a non-rigid construction) and $R_{c;d}$ is linked to the characteristic value through a resistance factor γ_t (1.15 for CFA). The design capacity $R_{c;d}$ is now determined at 4.5 MN, which is considerably higher (152 %) than the design load applicable to this pile. This result also confirms the validation according to class C.

5 CONCLUSIONS

Implementing a pile testing program resulted in a considerable reduction in installed length and, as a consequence cost, time and raw materials for this project. By assuming improved capacity in the preliminary design phase and validating these assumptions with class C testing during the early stages of foundation installation, the associated cost is amply covered by the savings compared to following a design in line with NEN9997-1 for standard CFA piles. Effectively the approach resulted in a reduction in the number of piles with approximately 25% equivalent to 1 km length or 500 m^3 of concrete. In terms of cost the optimization resulted in saving €175,000 for the foundation piles alone. In this day and age saving 80 tons of CO_2 production should also not be left unmentioned.

Furthermore considerable savings have been achieved, both in terms of cost and use of raw materials, by reducing the size of pile caps and replacing several pile caps by foundation beams.

The results also show that further optimization and additional savings could be achieved by setting up a pilot testing program following class B, ahead of finalizing the design.

This showcase should convince and persuade developers and designers, that considerable savings can be achieved by implementing pile testing in their projects.

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