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Towards sustainable port infrastructure by performing full-scale pile load tests

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Since most of the existing port infrastructure needs to be upgraded or replaced in the coming decades, the Port of Rotterdam Authority invests in sustainable and future proof design solutions. Together with their partners, they aim to reduce the port's CO_2 emissions by 50% in 2030 and intend to achieve a zero carbon footprint by 2050. The effective use of new and existing materials is crucial to reach these goals. However, the actual capacity of port infrastructure is generally not precisely known, given that no failures have been observed in practice and the existing berthing facilities are performing very well. In order to derive insight into the reserve capacity of these structures, unique full-scale field tests have been conducted on flexible dolphins, foundation piles and anchor piles. This paper presents the technical, commercial and environmental results of recent pile load tests performed in the port of Rotterdam. The tests have led to a significant reduction of CO_2 emissions associated with manufacturing and installing foundations, as well as reducing installation risks. Furthermore, a higher reliability level was obtained using less materials. This paper shows that in spite of the cost of performing full-scale field tests, the verification of the actual capacity of foundation piles is crucial to improve the carbon footprint of port infrastructure.

Keywords: Pile load test, Sustainable port infrastructure, Full scale field tests

Introduction

The Port of Rotterdam is Europe's largest seaport and stretches a distance of more than 40 kilometres, welcoming 30,000 seagoing vessels and 120,000 inland navigation vessels annually and handling 470 million tonnes of goods per year. An important task of the Port of Rotterdam Authority is to develop, manage and utilise the port in a sustainable way. Together with their partners they aim to reduce the port's CO_2 emissions by 50% by 2030 and to achieve a zero carbon footprint by 2050. Fig. 1 shows a typical carbon footprint of a deep-sea quay wall in Rotterdam. The carbon footprint of a quay wall is greatly impacted by the foundation piles (13%), anchors (9%) and combi wall (26%). However, the current design methods for pile foundations include a number of empirical factors and limiting resistances developed from experience in weaker soils. Therefore uncertainties exist as to their application to much stronger soils and the higher loads typically encountered in the Maasvlakte port district that is currently being developed.

In addition, many technical papers reporting field tests on piles do not provide information about the associated economic and environmental value arising from optimising pile design methods. Quantifying and sharing information about the added value is crucial in order to convince the industry of performing new full-scale field tests.

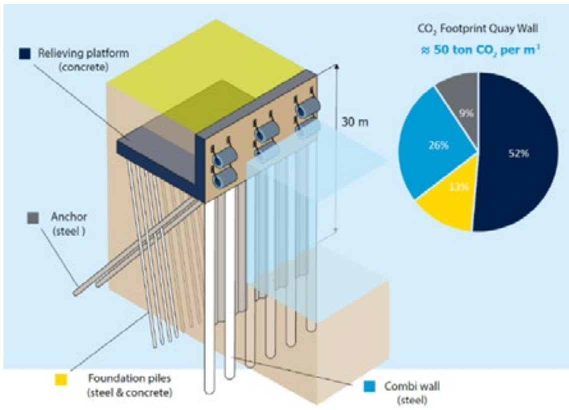

Figure 1 Typical carbon footprint for deep-sea quay wall.

This study aims to demonstrate the technical, economic and environmental value of four full-scale field test that have been conducted in the port of Rotterdam: 1) Laterally loaded steel tubular flexible dolphins in the Beneluxhaven port basin; 2) Axial capacity of precast driven concrete foundation piles in the Waalhaven port basin; 3) Axial capacity of steel MV pile anchors in the Mississippihaven port basin; 4) Axial bearing capacity of three types of foundation piles in the Amaliahaven port basin. The results of these four case studies show that, although performing full scale field tests is initially quite expensive, the verification of the actual capacity of foundation piles significantly contributes to optimise the construction costs and to improve the carbon footprint of port infrastructure.

Case 1: Beneluxhaven: laterally loaded flexible dolphins

Motivation

In this full-scale test, eight flexible dolphins were tested until failure. Flexible dolphins are predominantly laterally loaded steel tubular piles that can absorb the energy of berthing vessels by deflection. However, clear design guidelines for steel tubular sand-filled tubular flexible dolphin piles were lacking. The main focus of this project was on: (i) differences in soil behaviour between static and low-dynamic loading; (ii) the behaviour of dolphins in slopes; (iii) the effects of local buckling near wall-thickness transitions and for soil-filled piles; (iv) the propagation of vibrations in sandy soils due to pile installation.

Test setup

The test programme was defined around the following main parameters: tube diameter 914 mm; pile length 21.5m; soil conditions consist of moderately dense sand with traces of silt; embedded pile length 11m. The test piles were equipped with fibre optic strain sensors and shape accel array inclinometers. Furthermore, three piezometers were installed and the displacement of the piles was measured using a total station (Roubos et al., 2014; Van der Meer et al., 2015). The deformations of the piles during the low-dynamic tests were recorded and analysed with a high speed camera.

Figure 2 Overview test setup pile load test Beneluxhaven.

In this test, static and low-dynamic tests were performed. The static tests were carried out using two hydraulic jacks with a stroke of 2.5 m and push/pull capacities of 2 × 400 kN and 2 × 1000 kN. The jacks were mounted in a purpose-made frame that rested on three reaction piles, while loading the test pile (Fig. 2). The dynamic tests were executed with a system of cables and pulleys and a crane on a floating pontoon (Roubos et al., 2014). The costs of performing this test were about €0.75m.

Results

The Beneluxhaven test resulted in novel insights into the actual behaviour of flexible dolphins. Table 1 lists the technical, economic and environmental value of this test. In summary, the test results show that it is better to select a smaller pile diameter, a thicker wall and that we need to add more steel close to the harbour bottom in order to use the materials more efficient and to prevent local buckling. This will result in an economical and a safer design solution using less construction materials. Furthermore, it is worth noting that we measured the propagation of the vibrations in the soil during pile driving. These measurements were used to optimise the amount of site investigation around a single tubular piles to mitigate the risks regarding unexploded ordnances (UXO).

Table 1 Technical, economic and environmental value Beneluxhaven test.

Value	Example
Technical	- New design guidelines for local buckling of sand-filled tubes. - New recommendations for dolphins installed in slopes. - Update of existing method for predicting the propagation of pile-installation induced vibrations.
Economic	- Project 1[a]: direct savings of €4.5m (15% of total costs). - Project 2[b]: direct savings of €0.8m (5% of total costs). - Project 3[c]: direct savings of €1m (30% of total costs). - For future dolphin projects savings up to 10-20% can be expected, approximately €5m per year. - The amount of site investigation around a single pile can be reduced by 75%. For a typical berth this results in savings of about €0.2m. - Optimisation of project planning: 2-3 months shorter.
Environmental	- Project 1[a]: direct CO_2 savings of 200 ton. - Project 2[b]: direct CO_2 savings of 50 ton. - Project 3[c]: no information available

[a]) Realisation 50 flexible dolphins for inland barges and VLCC tankers.
[b]) Realisation new jetty for Aframax tankers.
[c]) UXO site investigation Botlek port basin.

Case 2 Waalhaven: axial bearing capacity of precast concrete piles

Motivation

In 2017, the Dutch national standardization institute (NEN) released a new version of the Dutch National Annex of Eurocode 7 (NEN-EN 1997-1, 2017) and recommended reducing the pile base factors used for design of the axial static resistance by 30%. The lower pile base factors have a major impact on the dimensions of pile foundations and the associated installation risks, since longer piles would be required. This was the main reason to test four precast concrete piles as part of a quay wall project in the Waalhaven. In this test, the effect of 'pile aging' and differences between static and rapid testing have been investigated. The piles were tested over a 100 day period to (i) assess the influence of pile ageing on pile capacity and (ii) to determine if the current recommended constant pile factors used to relate Cone Penetration Test (CPT) resistance to pile base and shaft capacity in the Dutch National Annex are appropriate.

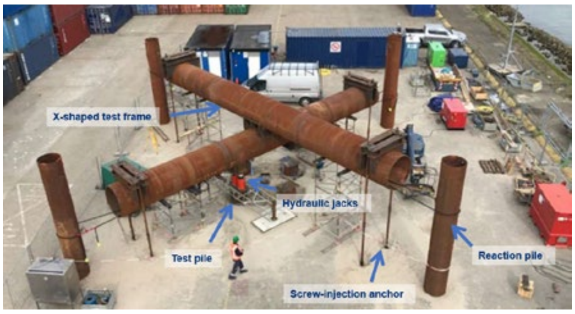

Figure 3 Overview of test setup plie load test Waalhaven

Test setup
In this test, four precast driven concrete foundation piles, 450mm x 450mm with a length of 36m, were tested until geotechnical failure. The test piles were instrumented with two types of optical fibres, Fibre Bragg Grating (FBG) and Brillouin scattering (BOFDA), along their full length, enabling detailed registration of shaft friction and base resistance. Since the optical fibres were installed during pile casting, unique insights have been acquired regarding the residual stresses in the piles after hardening and installation. An X-shaped steel test frame, consisting of two steel Ø1420 mm tubes, was chosen and has a maximum test capacity of 9,000 kN (Fig. 2). The test frame was anchored by eight 45m long screw injection anchors (Matic et al., 2019). The costs of performing this test were about €0.45m.

Results
The piles developed considerable residual loads during installation which greatly impacted the distribution of axial loads within the piles. When these residual loads are ignored the constant reduction factors for base resistance (α_p) are broadly in line with recommend values in the Dutch National Annex. However, if the residual loads are taken into account, the base reduction factor could be increased by as much as 40%. Furthermore, it was observed that the inclusion of friction fatigue effects when predicting the pile shaft capacity led to much more accurate predictions than those currently recommended in the NEN design code (Gavin et al, 2021). The results from the field tests also indicate that ageing has a much more significant effect towards the bottom of the pile. Geotechnical failure of the precast driven piles was recorded close to a test load of about 6,500 kN. Table 2 shows the technical, economic and environmental results for this project. Since the precast piles are driven about 1 meter in the deep dense sand layer, it is rather difficult to use the results of this test in other quay-wall projects.

Table 2 Technical, economic and environmental value Waalhaven test.

Value	Example
Technical	Update existing pile factors of NEN-EN 1997-1 for the Waalhaven quay-wall project (pile base factor α_p and pile shaft factor α_s).
Economic	Project 1[a]: direct savings of €0.55m (25% of the costs per foundation pile, and 5% of the total project costs).
Environmental	Project 1[a]: 25% less foundation piles.

[a]) Realisation 450m quay wall in the Waalhaven port basin.

Case 3 Mississippihaven: axially loaded MV pile anchors

Motivation
MV pile anchors consist of a steel H-shaped beam hammered in-place, whilst grout is transported through two pipes, leading towards reservoirs mounted at the pile tip. This shell of grout improves the driveability of the pile and also increases the pile's shaft friction after hardening. Since the quality of the MV piles can largely be influenced by the production process, about 2% of the MV anchors are generally tested. Most of the previous anchor tests were performed directly onto production anchors, and were not tested until geotechnical failure. Consequently, the ratio of shear resistance to the q_c value (α_t) is not precisely known and it is not clear whether the shaft friction has an upper limit (e.g. in the design method presently in use 250kPa is used as a limiting value). Furthermore, the length of the soil-retaining height of the new deep-sea quay walls increases with a vessel's draft, and so the length of the MV piles increases correspondingly. This imposes higher installation risks, especially in dense sand layers with high q_c values. In order to derive more insight into the actual capacity of the MV piles, the Port of Rotterdam Authority decided to test six MV pile anchors until failure.

Test setup
For each test pile, the strains were recorded using fibre optic sensors along the full pile length. Measures were taken to debond the pile from the surrounding soil in the active soil wedge of the quay

wall. The pile test load was limited to 95% of the yield strength of the steel beam, which was around 10,750 kN. For this test, a new steel reaction frame was constructed to transfer the axial tensile load from the test pile towards two outer reaction piles (Fig. 4). The centre-to-centre distance between the test pile and the reaction pile was approximately 6.5m. The tensile load was generated on the basis of 4 hydraulic jacks (Putteman et al, 2019).

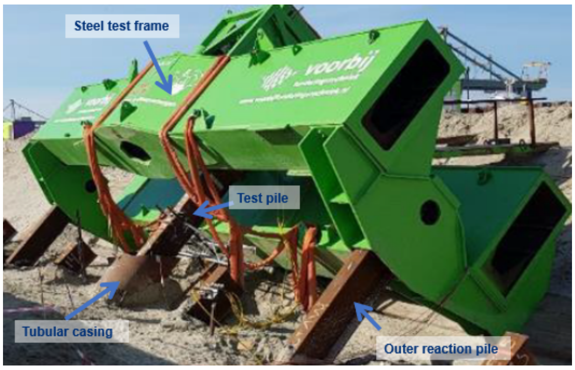

Figure 4 Overview of test setup plie load test Mississippihaven

Results

The results of this test show that the maximum measured shaft friction was about 600kPa, which indicates that there is no physical reason to limit the shaft friction to 250kPa. Furthermore, a ratio of 1.2% between shaft resistance and cone resistance (α_t) was found (Westerbeke, 2021), which is in accordance with the design method that is presently in use for screw-injection anchors (CUR 166, 2012). In addition, a new mobilisation curve for shaft friction of MV piles was developed, which is quite similar to the mobilisation curves of axial-loaded screw-injection foundation piles. This test also results in new ideas for future research, since the pile-installation data (energy per blow and grout volume) seems to be highly correlated to the bearing capacity. The idea is to develop a method to verify the in-situ capacity of MV piles. Table 3 summarizes the value of the Mississippihaven test. The results have directly been used to deepen one of the existing deep-sea quay walls with approximately 2m additional nautical depth.

Table 3 Technical, economic and environmental value Mississippihaven test

Value	Example
Technical	- Update existing CPT-based design method (shaft friction factor α_t and limiting value). - High correlation between installation parameters and bearing capacity. - New mobilisation curves for shaft friction.
Economic	- Project 1[a]: direct savings of €4.5m (capacity of existing MV anchors was 10% higher). - For future deep-sea quay walls savings of €1m per km seem possible.
Environmental	- Project 1[a]: 1 kton CO_2. - For future deep-sea quay walls savings of 0.5 kton CO_2 per km seem possible.

[a]) Deepening 1.6 km deep-sea quay wall in Maasvlakte port basin. The costs and CO_2 reduction are based on installing additional screw-injection anchors.

Case 4 Amaliahaven: axial bearing capacity foundation piles

Motivation

Similar to the Waalhaven test (Case 3), this test was performed to derive insight into the axial bearing capacity of foundation piles. However, in contrast to the situation in the Waalhaven, the test piles were installed deeper into the dense sand layer in order to (i) improve pile design by deriving project-specific pile class factors (ii) to update the national pile class factors and to investigate whether limiting q_c values are necessary for estimating base and shaft resistance. Consequently, three different pile types were tested as part of the overall testing programme for a total of eleven piles. These comprised of three driven precast concrete piles, four screw injection piles and four driven cast-in-situ (vibro) piles. An important reason for the Port of Rotterdam Authority to conduct this test was to optimise the design of a major deep-sea quay-wall project, including the installation of 2600 foundation piles.

Test setup

Axial load testing was executed on all piles through the use of a spider-shaped reaction frame attached to a series of screw-injection anchors (Fig. 5). The maximum test capacity was 25,000 kN. Strains across the full length of each foundation pile have been recorded, in addition to settlement at the pile head and the corresponding pile installation data. Six automatically controlled hydraulic jacks were used, each with a capacity of a 5,000kN. On top of each jack six calibrated load cells (dynamometers) were installed. The pile head displacement was measured relative to a reference frame. The costs of performing this test were about €2.5m.

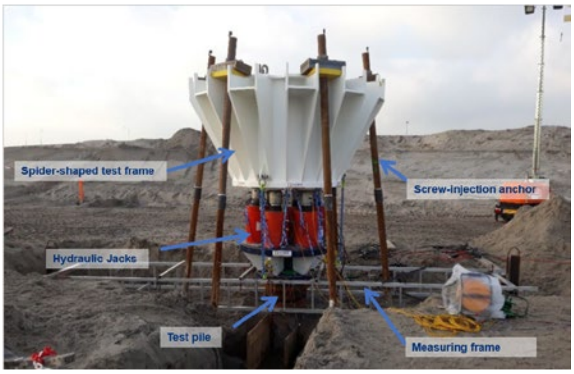

Figure 5 Overview of test setup plie load test Amaliahaven

Results

Again, it was found that the residual stresses after pile installation play a crucial role when determining pile class factors for displacement piles. No necessity for limiting q_c values was found for any of the pile systems. The axial bearing capacity of the driven precast and in-situ cast concrete piles have a higher capacity compared to the recommend design method in NEN-EN 1997-1 (2017). Unfortunately, segregation of the driven cast-in-situ piles occurred, which made it difficult to distinguish between base and shaft resistance in the very dense sand deposit. Nevertheless, the results in the shallower soil layers gave new insights into the shaft response of the pile with respect to friction fatigue. In contrast, the screw injection foundation piles showed significant softening effects, and hence new mobilisation curves were developed for these foundation piles. Furthermore, the test results are the first tests that have been accepted for implementation in the Dutch national pile load test database. Table 4 lists the technical, economic and environmental value of this test.

Table 4 Technical, economic and environmental value Amaliahaven test

Value	Example
Technical	- Update existing CPT-based design method (pile base factor α_p, pile shaft factor α_s, and limiting value). - New design method to determine bearing capacity on the basis of the q_c-averaging technique was developed.
Economic	- Project 1[a]: direct savings of €11m (30% cost reduction per foundation pile; 3.3% of total project costs) - Project 2[b]: direct savings of €4.5m. - For future deep-sea quay walls savings of about €4m per km seem possible.
Environmental	- Project 1[a]: direct savings of 8 kton CO2. - Project 2[b]: direct savings 3 kton CO2. - For future deep-sea quay walls savings of about 3.3 kton CO_2 seem possible per km.

[a]) Realisation of 3 km deep-sea quay wall in the Maasvlakte 2 port district.
[b]) Deepening 1.6 km deep-sea quay wall in Maasvlakte 1 port basin. The costs and CO_2 reduction are based on installing additional precast concrete piles.

Conclusion

The technical results of the case studies show that several novel insights regarding soil behaviour have been acquired, e.g. (i) differences between static and dynamic loading; (ii) ageing effects of soil; (iii) relation between cone resistance and bearing capacity; (iv) and the effect of vibrations in sandy soils caused by pile driving. Furthermore, the four case studies confirm that the design methods in use presently are safe, but also quite conservative. Although performing full-scale field test is fairly expensive, Table 5 shows that significant material savings were possible and that the design of port infrastructure can be optimised on the basis of full-scale field tests and also contribute to reducing installation risks.

Case	n	Costs	Realised savings		Future savings[a]	
	[-]	[m€]	[m€]	[kton CO_2]	[m€]	[kton CO_2]
1	8	0.75	6.10	0.25	6.00	0.30
2	4	0.45	0.55	0.75	n/a	n/a
3	6	0.75	4.50	1.00	3.00	1.50
4	11	2.50	15.50	11.00	12.50	10.00
Total	**29**	**4.45**	**29**	**4.45**	**29**	**4.45**

[a]) Annual savings based on the realisation of 3km deep-sea quay wall, fifty flexible dolphins and two jetties per year.

In addition to a return on investment, about 13 kton CO_2 was directly saved and approximately 10 kton each year. Just to give an indication of what this means: 1 ton CO_2 is equal to 6,000 km driving with a diesel car and has a monetary value of about €100. This results in substantial annual savings of about €1 million. The authors of this paper highly recommend that not only the technical outcomes, but also the economic and environmental value of full-scale field tests will be published, since this will help funding and support for future expensive full-scale tests, which will be needed to bridge the gap between theory and practise.

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