Full-scale flexible dolphin pile tests

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ABSTRACT: Flexible dolphins are frequently applied structures in ports and waterways. They are used to provide both mooring and berthing facilities for inland and sea-going vessels. The guidelines for these steel tubular flexible dolphin piles were found to be incomplete. Besides, the theoretical background of the existing design methods often appeared to be based on a limited amount of prototype testing. To improve serviceability and reliability of flexible dolphins within the Port of Rotterdam full-scale pile tests were carried out in which dolphin piles were loaded by lateral loads. The main focus of this research was to obtain more insight in: a) the difference in soil resistance (and thus the pile behaviour) between rapid and slow loading; b) the effect of slopes on laterally loaded dolphins; c) performance of different geotechnical design tools. A total of eight piles were loaded in different ways while deformations of both soil and piles, stresses within the piles and pore pressure changes were recorded. It was found that the impact of the rate of loading on the dolphins was very small, that the effect of the slope was smaller than expected, and that maximum bending moments were smaller and were located much more shallow than expected. All these findings were well predicted by FEM calculations. Analytical design tools required modifications to include these beneficial results.

RÉSUMÉ : Les duc-d'Albe sont des constructions qui sont souvent utilisées dans les ports et les cours d'eau. Ils sont utilisés comme emplacement pour amarrer les navires. Les directives pour le projet des pilotis n'étaient pas encore complètes. De plus, la motivation théorique des méthodes existantes de conception était souvent basée sur un nombre limité de tests . Pour augmenter l'utilité et la fiabilité des duc-d'Albe du port de Rotterdam, des essais ont été faits où les pilotis ont été soumis à des forces horizontales. Le but des essais était de mieux comprendre : a) la différence dans la résistance du sol (et du coup la réaction du pilotis) quand la force subie est changée lentement et rapidement ; b) l'effet du talus sur les pilotis soumis aux forces horizontales ; c) les résultats de différents modèles de calcul géotechnique. Au total, huit pilotis ont été chargés de différentes manières pendant que la déformation des pilotis et du sol, les tensions de l'acier et les pressions de l'eau ont été mesurées. Les essais ont montré que la rapidité de la pression n'a pas beaucoup d'effet. Les effets des talus étaient plus petits que supposé et que les moments de flexion maximale étaient plus petits et moins profonds qu'attendu. Tous ces résultats ont été prédits correctement grâce aux calculs MÉF. Les modèles mathématiques analytiques avaient besoin de modifications pour inclure ces résultats favorables.

KEYWORDS: Flexible dolphins, full-scale tests, Port of Rotterdam, Plaxis, horizontal loads, sustainable

1 INTRODUCTION

Flexible dolphins are frequently used by ships for berthing purposes in ports and waterways all over the world. These dolphins are used during berthing itself (breasting dolphins) and for fastening the lines (mooring dolphins). The material costs of these steel tubular piles account for a significant part of project expenses, so design choices (like modelling and design philosophy applied) have a large influence on the business case. Because of the large number of dolphins in the Netherlands, the lack of specific guidelines for designing flexible dolphins in the Eurocode including Dutch National Annex is remarkable. Besides, large differences in design approaches exist among international design guidelines. These differences often lead to very different design results.

The Port of Rotterdam facilitated full scale field tests in cooperation with other companies in order to gain more insight in the behaviour of dolphins. This was a major challenge because such a test had not been performed in Rotterdam before. About 5000 flexible dolphins are currently used in the port of Rotterdam and about 15% of these dolphins is owned by the Port of Rotterdam. It was expected that the tests could result in a material reduction. But to implement these optimizations first the real behaviour of the piles had to be determined.

This paper describes the full scale tests on flexible dolphins and specifically deals with the soil mechanical behaviour and its consequences for the design approach:

- Comparison among the current (geotechnical) calculation methods and measurement based validation;
- Effects of load duration on the behaviour of sandy soils (dynamic behaviour and undrained behaviour);
- Influence of underwater slopes on the lateral soil resistance and soil stiffness.

2 TESTING METHOD AND PREDICTIONS

A testing method in the Beneluxhaven has been designed in cooperation with the parties involved, comprising eight testing piles in total. These piles were distinct in terms of some variables:

- Pile configuration. A pile with a frequently used diameter of 914 mm has been tested. For economical reasons, these piles are composed of sections with varying wall thickness and steel quality. Six distinct pile compositions have been tested in total;
- Geometry. Piles are installed either in a slope or in a flat surface level;
- Sandfilling. Two piles have been filled with sand prior to testing.

The tests aimed at a better understanding of the buckling behaviour of the piles as well. Therefore, the piles were loaded only until buckling failure rather than geotechnical instability occurred. The piles are however loaded to a level in which passive mobilization over the upper few meters is distinct.

Prior to the field tests, predictions have been made by design models which are most commonly used in the current Dutch design approaches:

- Simple force-equilibrium method: Blum;
- Elasto-plastic spring model with bi-linear springs: Ménard (elastic), combined with Brinch-Hansen (plastic) (software: D-Sheet Piling with Single Pile module);
- Elasto-plastic spring model with multilinear springs: P-Y curves according to the API (software: D-Pile Group);
- Finite Element Method (Plaxis 3D; Plaxis 2D is not suitable for modeling a single pile).

The predictions are made by using CPTs, boreholes and lab results from the test locations. An example of a CPT is shown in Figure 1. The subsurface mainly consists of loose to moderate sand, interlayed by some thin layers consisting of silt and clay (pile tip level is at NAP -19 m). Contrary to real design procedures, characteristic parameter values are applied in order to predict the pile behaviour as realistic as possible.

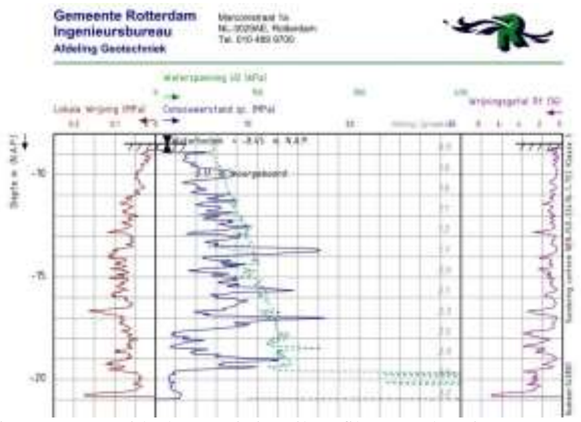

Figure 1. CPT with characteristic soil profile at test location

3 MEASUREMENTS

Three reaction piles have been installed at the test site besides the test piles in such a pattern that allows for testing all piles by using the same frame (see Figure 2). This frame was used for laterally loading the piles. A hydraulic jack was used for applying loads slowly and a crane was used for applying a short, rapid, load by cables and pulleys. The piles could be loaded inward and outward of the slope by pulling or pushing the jack respectively. The rapid pull load was exerted during time periods of 3 to 15 seconds, which represents the time period of a real berthing load. The load is applied at the pile head (at NAP +2,50 m) in all tests. The average surface level down the slope is NAP -8,0 m and the average slope gradient is 1:5.

Figure 2. Top view of the test setting with frame

A comprehensive set of measurement equipment has been installed, especially aiming at deriving the load-displacement curves of the piles, the steel stresses and the soil deformations and pore pressures in the passive wedge (see Figure 3). A team of divers assisted during the tests by visually inspecting the soil deformations near the pile (holes occurring at the back side and patterns of soil failure at the front side).

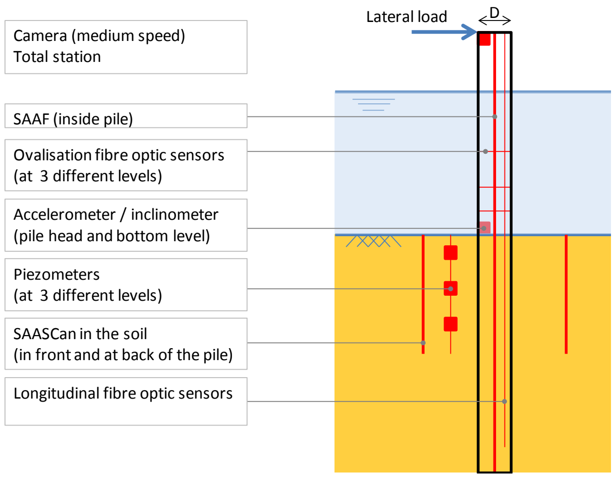

Figure 3. Installed measurement systems

4 RESULTS

4 .1 *Comparison of predictions and test results*

The comparison of the calculation models already indicated a clear difference between the predicted results. The field tests confirmed the hypothesis that the results calculated by Plaxis 3D best match the measurements. This turned out to concern not only the displacements (displacement pattern and order of magnitude) and bending moments (maximum moment and depth of the maximum), as is presented in Figure 4 and 5. In addition, also the calculated soil displacements in the passive wedge match the measurement values by the SAASCan very well (see Figure 6).

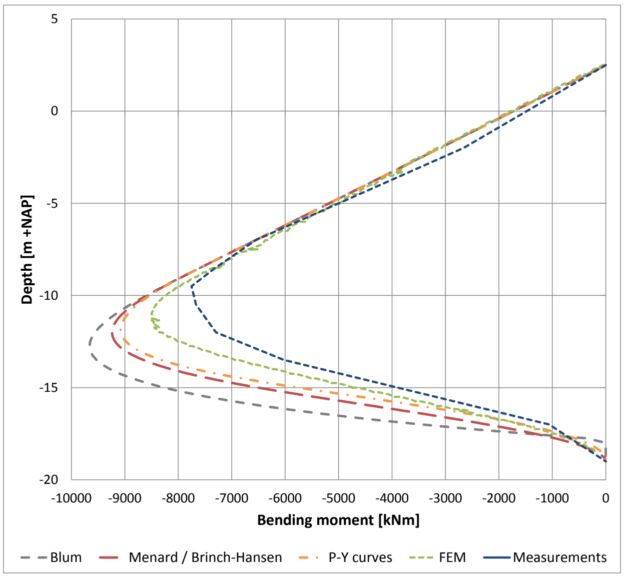

Figure 4. Bending moment distribution of the pile over the depth. Both the calculated values from the different models and the measured values are presented, corresponding to a horizontal load of 690kN.

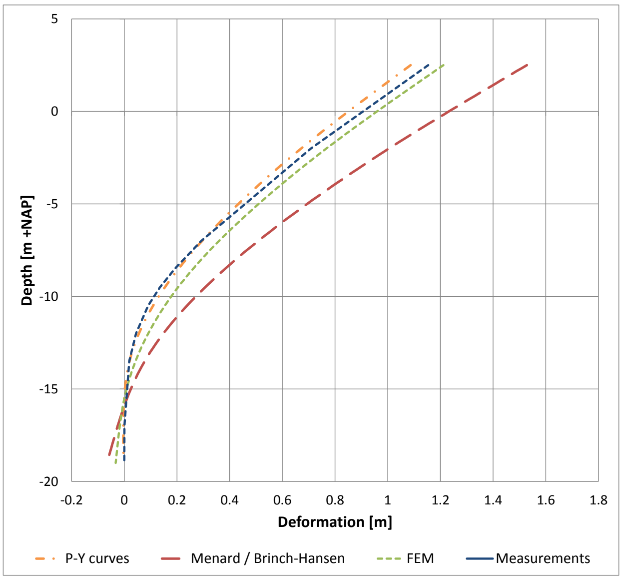

Figure 5. Displacement of the pile over the depth. Both the calculated values from the different models and the measured values are presented, corresponding to a horizontal load of 690kN.

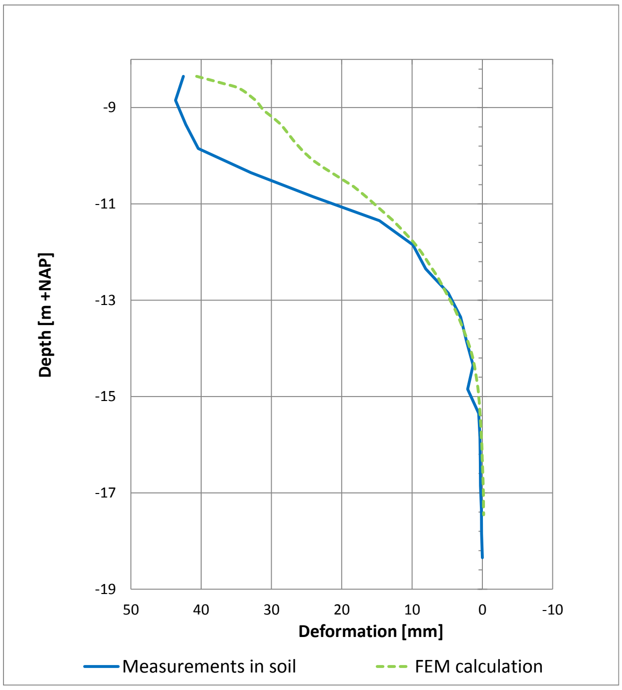

Figure 6. Soil displacement at the passive side of the pile. Both the calculated values (FEM calculation) and the measured values by the SAASCan at a distance of 1,0m from the pile are presented.

Apparently, mainly the soil resistance in the upper layers is underestimated, especially when using the several analytical models. It is remarked that displacements calculated by P-Y curves do well match the measurement values, but the bending moments do not. Besides, the test results indicate that the calculated bending moments by Plaxis 3D are still quite high as well. Not only the indirectly measured bending moments over depth (by tensile stress sensors) but also the position of buckling in the pile indicate that the maximum bending moment occurs at a higher position than resulted from calculations. The exceedance of the maximum bending moment during the field tests often occurred at about 1 to 1.5 meters below the surface level, which is at a higher position than the position of maximum bending moment resulting from Plaxis 3D.

4.2 *Undrained soil behaviour*

The sandy soil was expected to react stiffer during a short load as a consequence of undrained behaviour, especially in the upper layers. Highly differing results appeared from the predictions by the available models for describing this mechanism (P-Y curves (undrained) and FEM).

The field tests showed some undrained response in the piezometers (see Figure 7) but the sand did not react significantly stiffer during a rapid load increase (load applied in 1 to 3 seconds) compared to a static load (load applied slowly in more than 15 minutes). Due to variations in the measured pore pressures it was not possible to derive a clear conclusion on the undrained behaviour of the sandy soil.

The total effects of a rapid load increase (typical for berthing conditions) on the deformations and bending moments of the pile over depth appear to be very limited. This finding does well match the difference between drained and undrained calculations in FEM (which turned out to be very limited), but it does not match the differences between drained and undrained calculations using P-Y curves (from which a large influence on the displacements resulted).

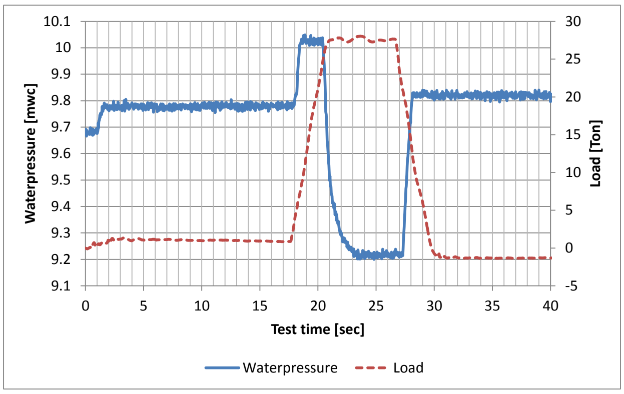

Figure 7. Measured waterpressure during rapid load test

4 .3 *Influence of the slope*

The calculations with FEM do well match the test results on quantifying the influence of the slope. This was expected because modeling an entire slope in Plaxis 3D is straightforward. Instead, adjustments of either the geometry (equivalent increased or reduced surface level) or the soil parameters (equivalent friction angle) are necessary for discounting the influence of the slope in the analytical calculation models. An equivalent increase or reduction of the surface level is usually applied in design approaches because adjustments of soil parameters is much less straightforward, as a consequence of the Eurocode prescription of discounting by partial factors.

A load inward of the slope is modeled by an increased surface lever, whereas a load outward of the slope is modeled by a reduced surface level. The configuration of modeling such an adjustment is determined from estimations of the zone of influence of the passive wedge next to the pile, the slope gradient and the soil profile. The predictions by FEM demonstrated that the influence of the slope is smaller than appeared from (conservatively determined) manual adjustments in analytical models. This is confirmed by the field tests.

The test results and additional analyses in Plaxis 3D have been used for deriving curves concerning the typical soil characteristics in Rotterdam from which the applicable equivalent increase or reduction of the surface level can be obtained, based on the slope gradient and the soil type in the upper few meters. These curves, however, are not generally applicable and are therefore only adopted by the "design approach dolphins" of the Port of Rotterdam.

5 CONCLUSION

The results of the field tests have provided a better understanding of modelling the soil mechanical behaviour of laterally loaded "flexible dolphins". All currently available analytical models overestimate the bending moments in the piles. The FEM calculation (Plaxis 3D) corresponds better, though it still slightly overestimates bending moments. Underestimated lateral soil pressures in the upper layers seem to be the main cause for this. These results do not give rise to exclusion of (one of) the current models, though the characteristics of the load need to be well concerned. After all, stiff soil behaviour during berthing is unfavorable (energy absorption), whereas it favours mooring.

Rapid loads have a negligible effect on the behaviour of "flexible dolphins" compared to slow loads. Undrained behaviour of sand does occur during a typical short load, but this results in only a marginally modified pile design. Bending moments and displacements decrease only very little by this undrained behaviour. The modifications of P-Y curves regarding undrained behaviour of sand (in D-Pile Group) provide pile displacements which heavily deviate from the field tests. Based on the field test results, using this module for designing "flexible dolphins" is therefore not recommended.

The effect of the slope is less than appears from the manually adjusted analytical models which are commonly used, although it is accurately modeled in FEM calculations (Plaxis 3D). Necessary adjustments in the analytical models corresponding to several slope gradients have been determined for the typical soil characteristics in Rotterdam.

On top of the geotechnical conclusions as presented in this article, the determination of a new integrated design approach and the derivation of new calculation methods for preventing buckling of steel tubular piles have eventually succeeded. Besides, new insights have been obtained, and safer designs requiring less material proved possible. Too much steel was installed in the deeper subsurface in the past, whereas the buckling appears to occur only just above or just below the subsurface because of the stiffer pile-soil interactions. The material can therefore be distributed much more efficient over the length of the pile, resulting in a material cost saving of about 15%. Important remarks regarding this material saving:

- The ability of installing the tubular piles (i.e. sufficient wall thickness) can be normative for the design. This topic has not been explored in this article.
- The encountered stiffer soil behaviour can result in a more unfavorable pile load during berthing because of the reduced energy absorption.

6 ACKNOWLEDGEMENTS

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