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Evaluation full-scale mooring pile load test Rotterdam

Évaluation de l'essai de chargement de pieux d'amarrage grandeur nature Rotterdam

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ABSTRACT: In the summer of 2022, a full-scale pile test was carried out in the Caland Canal on behalf of the Port of Rotterdam Authority. In this test, two large diameter mooring piles were pulled towards each other under lateral loading. The forces, displacements and strains were continuously monitored during 9 load-unload steps. The aim of the test was to gain a better insight into the load-displacement behaviour of a mooring pile during (repeated) loading, and more specifically into the fixation of the pile tip. The current design method proposed in the CROW publication Flexible Dolphins may result in mooring piles that are too long, due to the required fixation criterion in the publication. Witteveen+Bos performed the prediction and back analysis of the pile response with the use of the finite element method (FEM), the results of which are presented in this article. The results of the pile test highlight that the mooring pile may in fact be shorter with an alternative fixation criterion.

RÉSUMÉ: Au cours de l'été 2022, un essai de chargement chargement répétéde pieux grandeur nature a été réalisé dans le Canal Caland pour le compte de l'Autorité portuaire de Rotterdam. Lors de cet essai, deux pieux d'amarrage de grand diamètre ont été tirés l'un vers l'autre sous charges latérales. Les forces, déplacements et déformations ont été monitorés en permanence pendant 9 séries d'essais de chargements cycliques. L'objectif de cet essai grandeur nature est de mieux comprendre le comportement d'un pieu d'amarrage en déplacements lors d'un chargement (répété), et plus particulièrement la fixation de la pointe du pieu. La méthode de conception actuellement proposée dans la publication CROW Flexible Dolphins s'emble aboutir à des pieux trop longs, en raison du critère de fixation exigé dans la publication. Witteveen+Bos a réalisé la prédiction et la analyse réctrospective de la réaction du pieu avec la méthode des éléments finis (MEF), dont les résultats sont présentés dans cet article. Les résultats de l'essai de chargement chargement répétéde pieux démontrent que le pieu d'amarrage pourrait être plus court avec un critère de fixation alternatif.

Keywords: Mooring pile; full-scale-test; soil-structure interaction; pile design.

1 INTRODUCTION

In recent projects it has been noted that a number of design aspects included in the CROW publication Flexible Dolphins (CROW, 2018) could be improved. In particular, the degree of fixation of the mooring piles in the subsurface is a subject about which there is still a lot of uncertainty. The effect on the design outcomes can be significant.

The design method for determining the required pile length in CROW's Flexible Dolphins manual appears to be a conservative method, resulting in inefficient use of materials (piles that are too long).

The behaviour of a mooring pile under repeated loading is also uncertain. Soil reacts stiffer when reloaded, which means that in the event of a second and later mooring thrust, the displacement is smaller, and therefore also the capacity to absorb the energy of a mooring ship through pile deflection.

2 PILE DESIGN AND TEST SETUP

2.1 Pile design

The mooring piles have a diameter of 2.4 meters and are made up of sections with different optimized wall thicknesses, see Table 1.

The piles were dimensioned for energy absorption and resulting fender load (at NAP +1.7 m). In addition, the piles must be able to withstand a representative bollard load of 1500 kN, at approximately 0.5 m above the top of the pile, at NAP +6.5 m. The design value of the bollard load is 2025 kN.

The average water level is around NAP and the ground level in the channel near the mooring piles is approximately NAP -24 m. The pile tip level is NAP -42 m.

Table 1. Sections of mooring piles 81-D01 and 81-D04.

Part	Steel quality	Wall thickness [mm]	From [m NAP]	To [m NAP]
1	S355	25	+6.00	-0.75
2	X70	25	-0.75	-10.00
3	X70	30	-10.00	-12.75
4	X70	35	-12.75	-15.25
5	X70	40	-15.25	-18.25
6	X70	50	-18.25	-22.50
7	X70	55	-22.50	-34.00
8	X70	40	-34.00	-37.00
9	X70	30	-37.00	-42.00

2.2 Test setup and measurement equipment

The starting point for testing the piles was that no additional piles had to be placed for the test. For the test, a tensile connection was made at NAP +6.5 m between two planned mooring piles, 81-D01 and 81-D04, see Figure 1.

A jack was placed on top of pile 81-D04 (left), and a holding connection was attached to pile 81-D01 (right). In between, two GEWI bars Ø 57.5 mm were placed. To prevent the GEWI bars from sagging, a suspension bridge construction was created. The cylinders of the jack had a length of 2 meters, which means that both piles could be pulled towards each other up to approximately 1 meter.

During the test, the oil pressure and cylinder stroke of the jack were continuously measured. On and around both mooring piles the following measurement equipment was installed (Figure 2):

- glass fibers were placed on the inside of the piles to measure the elongation of the steel. The glass fibers were placed on the tension side, the compression side and the two neutral sides of the tubular pile. The glass fibers measured the strains between NAP -1.5 m and NAP -41.5 m;
- a SAAF (Shape Accel Array Field) inclinometer was placed on the outside of both piles, see Figure 2, which measured the deflection of the piles. The top of the SAAF was at NAP +4 m and extended to the pile tip at NAP -42 m.
- two reflectors were placed on the tube of the SAAF to measure the displacements with a total station, which was located onshore. Additionally, at the top of the pile two reflectors were placed, see Figure 2;
- the pore pressures were monitored in the subsurface sand layers at a distance of 5 m from both piles (in the pulling direction). The pore pressure meters were placed at -27.0, -28.5 and -30.0 m NAP.

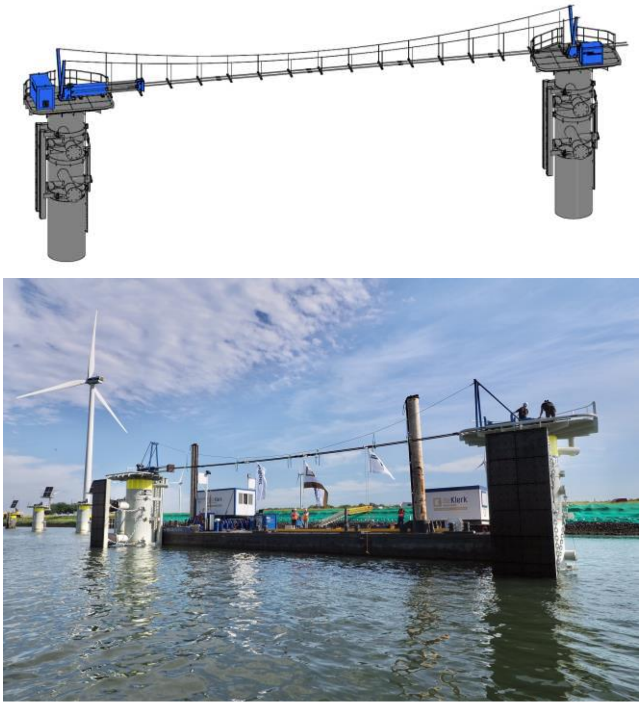

Figure 1. Test setup, pile 81-D04 (left) and 81-D01 (right).

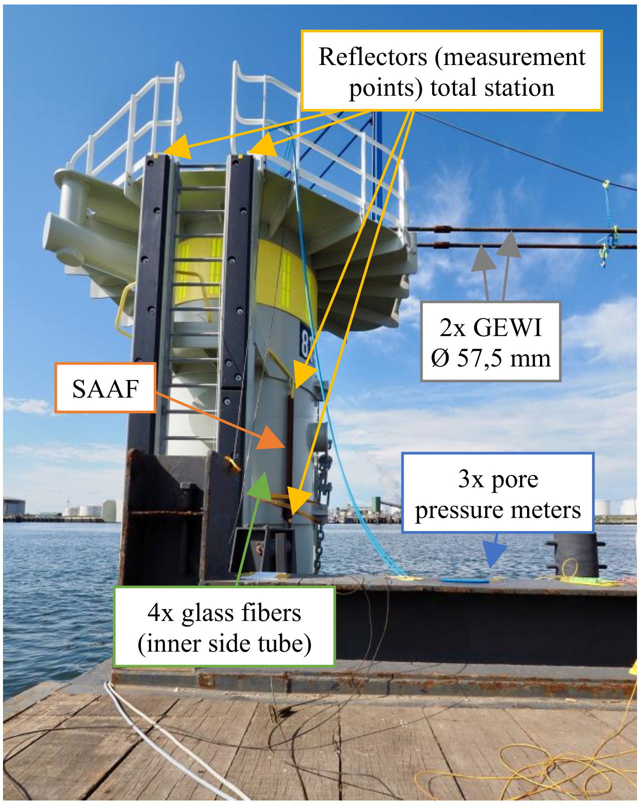

Figure 2. Measurement equipment on mooring pile 81-D04.

2.3 Loading scheme and displacement predictions

Prior to the test, finite element calculations were made using Plaxis 3D to predict the deformation of the mooring piles and to determine an acceptable loading schedule: it was necessary to prevent the piles from becoming too permanently tilted after testing.

The calculated pile head displacement was just over one meter, the residual displacement of the pile head after unloading was just over 0.3 m. In consultation with the Port of Rotterdam Authority this was seen as acceptable.

3 SUBSOIL CONDITIONS

The subsoil consists mainly of sand, see Table 2:

- up to approximately NAP -30 m: loose to moderately packed sand;
- up to approximately NAP -36 m (very) dense packed sand;
- up to approximately NAP -45 m: moderately packed sand (silty);
- below NAP -45 m: loose to moderately packed sand.

The soil layers were modelled with the Hardening Soil model with small-strain stiffness (HSs) (Bentley, 2022). Lab testing on sand samples was performed (triaxial tests with unloading-reloading step for varying relative density and oedometer tests). The procedure for obtaining the final parameter set consisted of the following steps:

1. determine the initial HSs parameter set based on empirical relationships between the cone resistance of CPT's, the relative density and the HSs parameters as described in Lengkeek (2022) and Brinkgreve et.al. (2010);
2. model the pile test in Plaxis 3D with the parameter set obtained from step 1;
3. determine the average strain and mobilized shear stress during the last loading step of the pile test. This is done for each soil layer;
4. use the Soil Test module (Bentley, 2022) to simulate a triaxial test on a soil type with the parameter set obtained in step 1 and compare with the results of the laboratory research;
5. iteratively adjust the HSs parameter set from step 1 to achieve the best fit with the results of the triaxial tests. This fit is performed in the range of strain as determined in step 3.

The final parameter set is presented in Table 3. An example of the fit of the Plaxis Soil Test with the triaxial test is shown in Figure 3.

Table 2. Stratification at mooring piles (top of layer in [m NAP]) and Re being the relative density of the sand [%]

Id	Layer	81-D01	81-D04	Re [%]
1	Sand 1	-24.25	-24.7	65
2	Sand 2	-30.0	-32.0	95
3	Sand 3	-37.5	-36.0	80
4	Sand 4	-45.0	-44.0	60

Table 3. Geotechnical parameters for HSs material model (expected values), see Bentley (2022) for parameter explanation.

Id	γ / γ_{sat} [kN/m^3]	c' [kN/m^2]	φ' [°]	ψ [°]	E_{50}^{ref} / E_{oed}^{ref} / E_{ur}^{ref} [MN/m^2]	$\gamma_{0.7}$ $\cdot 10^{-4}$[-]	G_0^{ref} [MN/m^2]	m [-]	K_0^{nc} [-]	POP [kN/m^2]
1	18.7 / 20.1	0	39.8	9.6	65 / 78 / 130	5.0	80	0.4875	0.4510	65
2	19.9 / 21.1	0	44.0	24.0	80 / 65 / 160	5.0	80	0.4031	0.4499	100
3	19.2 / 20.8	0	39.5	15.5	54.8 / 58.5 / 164	1.3	137	0.4688	0.4423	39
4	18.2 / 20.0	0	37.2	4.44	33.6 / 33.9 / 101	1.6	97	0.5500	0.4379	30

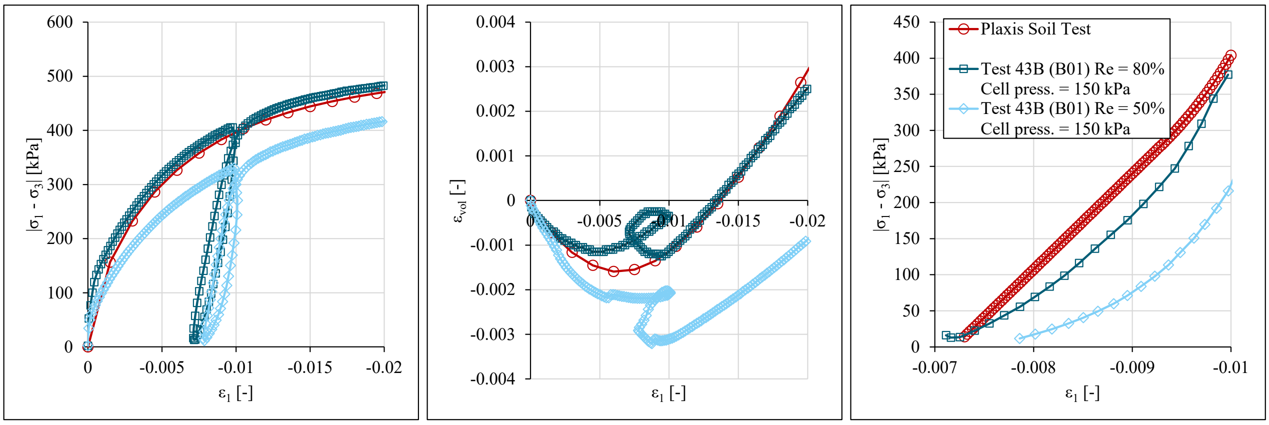

Figure 3. Comparison Plaxis soil test results and laboratory test data for sand 3.

4 BACK ANALYSIS RESULTS

4.1 Plaxis 3D modelling

The pile test was modelled in Plaxis 3D. To limit the calculation time, half of the pile was modelled with half the load on the pile. Afterwards a more extensive model was made in which, among other things, the adjacent (underwater) slope of the Caland Canal was modelled, but this turned out to have a negligible effect on the results.

The model was calculated with drained behaviour, without water over- or under-pressures. This was concluded from the pore pressure meters. These showed a consistent behaviour with the tide without deviations during the loading and unloading steps.

The calculation results of the FEM model in Plaxis 3D corresponded well with the measurement results, see Figure 4 - Figure 7. The difference in pile head displacement between the numerical analysis and the pile test was approximately 10%. The shape of the displacements matched good along the pile. The moment distribution, both under loading and unloading conditions, also corresponded well with the bending moment calculated from the strain measurements.

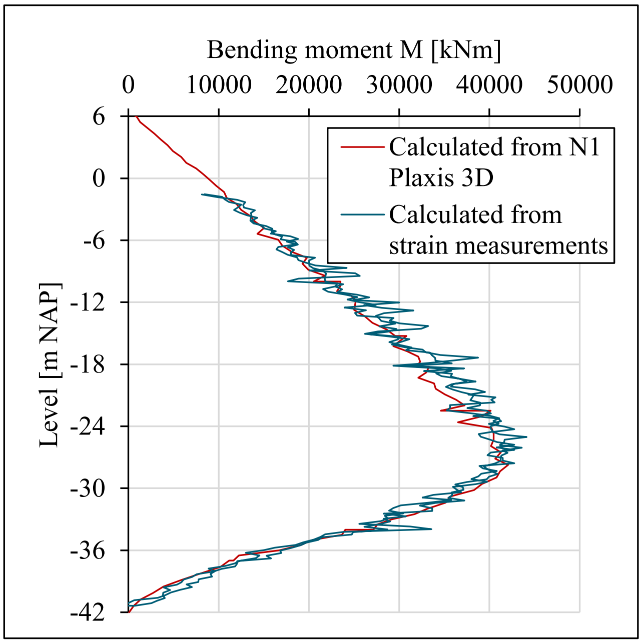

Figure 4. Bending moment mooring pile 81-D04 in loading step 8 at 1380 kN.

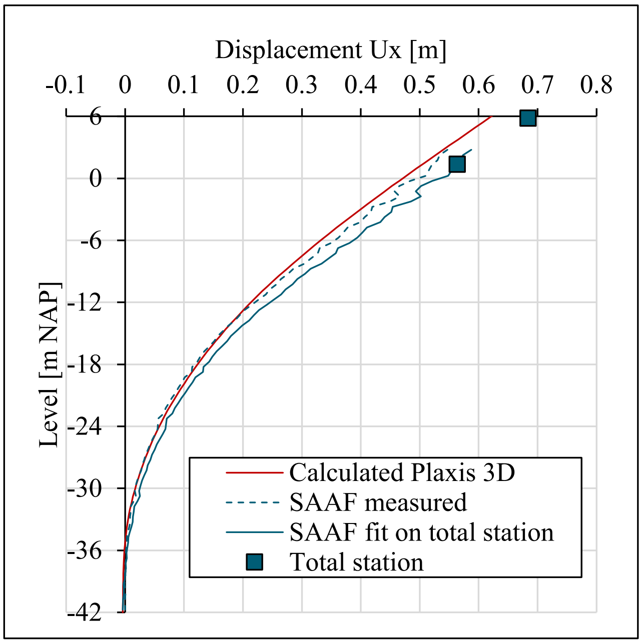

Figure 5. Displacement mooring pile 81-D04 in loading step 8 at 1380 kN.

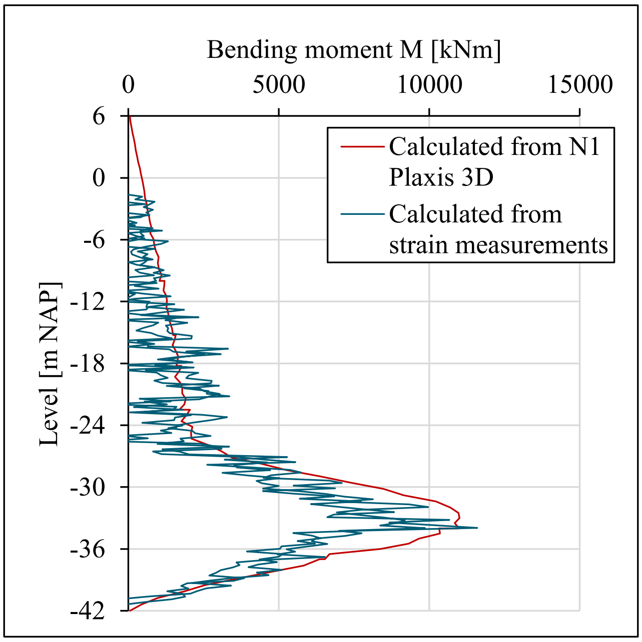

Figure 6. Bending moment mooring pile 81-D04 unloaded after loading step 8 (approximately 70 kN).

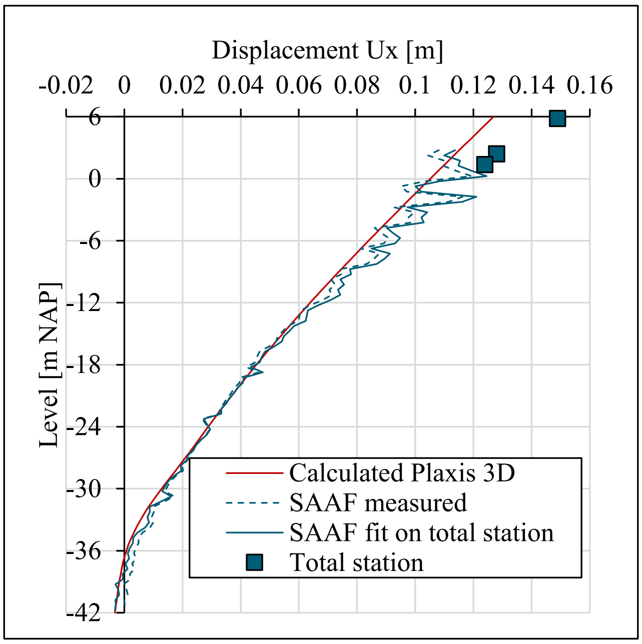

Figure 7. Displacement mooring pile 81-D04 unloaded after loading step 8 (approximately 70 kN).

The differences at the pile head of approximately 10% can be explained by uncertainties in the back analysis, including:

- the actual force on the pile. The forces from the jack pressure proved to be insufficiently reliable, the modelled force was derived from the strain measurements on the pile;
- strength and stiffness of the subsoil. Despite the extensive in-situ and lab testing, there was uncertainty in the fact that the sand samples were built in the lab at a certain relative density. Although the relative density was determined as best as possible based on lab testing and empirical correlations from CPT's, there is always a certain bandwidth. In addition to the relative density, other aspects such as stress history and structure were not represented by the remoulded sand samples.

Despite the uncertainties mentioned, the current FEM model in Plaxis 3D appeared to be sufficiently reliable to substantiate further conclusions with regard to unloading-reloading behaviour and the pile tip displacement (fixity check).

4.2 Unloading-reloading behaviour

One of the research questions of the test was how the mooring pile reacts as a result of repeated loading. The force-displacement diagrams as measured and calculated in Plaxis 3D are shown in Figure 8.

This figure shows that during initial (virgin) loading (or first impact), both in the test and in the modelling, the pile reacted less stiff than during unloading-reloading, which is also the expected behaviour of the subsoil. The absorbable mooring energy is therefore higher during the first mooring thrust (virgin loading). The displacement behaviour was comparable during the second and subsequent mooring thrusts (step 6 - 9 in Figure 8).

The pile test had sufficiently demonstrated that with repeated loading, the second impact already showed sufficiently representative reloading behaviour for any subsequent impacts. The resulting forces and displacements from the second mooring thrust with a serviceability limit state (SLS) mooring energy seemed sufficient to check the fixation of the mooring pile during the design of a mooring pile.

4.3 Pile tip displacement

The pile tip displacement during the pile test could not be directly derived from the SAAF measurements. To do this, the SAAF would have had to extend below the pile tip (fixed in the subsoil), but this turned out to be impracticable.

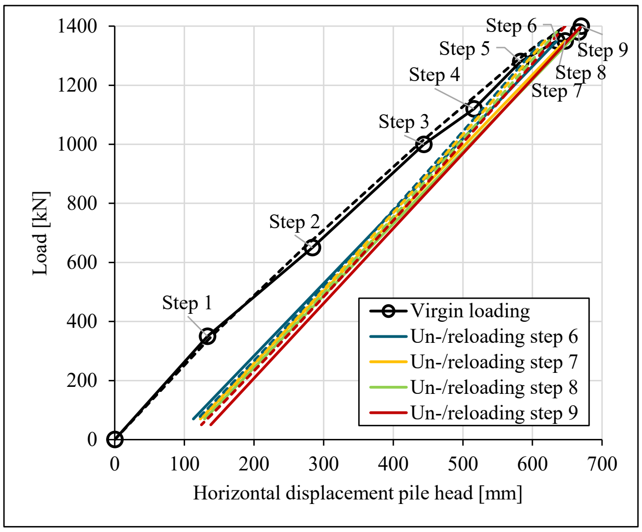

Figure 8. Load-displacement diagram with repeated unloading-reloading measured (continuous) and calculated in Plaxis 3D (dashed)

However, when the SAAF measurements were combined with the displacements from the FEM model in Plaxis 3D, see for example Figure 5, it became clear that a limited displacement of the pile tip (order of millimeters) was the most likely scenario.

5 FIXITY CHECK

5.1 Current fixity check

The purpose of the fixity check in the CROW publication 'Flexible Dolphins' is to make sure that plastic soil deformation at the pile tip does not contribute to energy absorption and/or result in permanent pile inclination (CROW, 2018).

According to the publication, it needs to be shown that the chosen embedment length has a limited effect on the displacement of the pile at the impact level. The recommended limit is 2% of extra deflection at impact level compared with an infinitely long pile. In practice, this can be done by comparison with the deflection of a longer pile by 5*D (CROW, 2018).

In practice, the current fixity check turns out to be governing for the design of the mooring pile in many cases. Especially for piles with long freestanding length, differences in deflection at impact level occurs quickly, while at the pile tip no significant deformations occur. Because calculated deformations of the pile tip are limited, also shown in the Caland Canal pile test, the current fixity check results in piles that are probably too long.

5.2 Adjusted fixity check

In the new edition of CROW Flexible Dolphins (to be published), an adjusted fixity check will be presented.

As explained above, the purpose of the fixity check is to avoid excessive plastic soil deformation. This is established by limiting the plastic deformation at the pile tip. For e.g. a spring model with PY-curves, mobilisation of the passive soil resistance σ_p should be limited to a maximum of 50% in SLS conditions.

In FEM models it is not straightforward how to derive the mobilised soil resistance, since this is not explicitly reported. Instead, a different approach is used, based on the amount of pile displacement needed to mobilise the soil resistance. This approximation is easier to use since displacement can be derived directly from the FEM calculation results.

The proposed method is based on appendix C.3 of EN 1997-1. For different modes of wall movement, required displacement in relation to soil mobilisation is given for 100% and 50% mobilisation. For mooring piles, Figure 9 is applicable, in which v_p is the displacement to mobilise passive soil resistance σ_p and h is the height difference between point of rotation and pile tip.

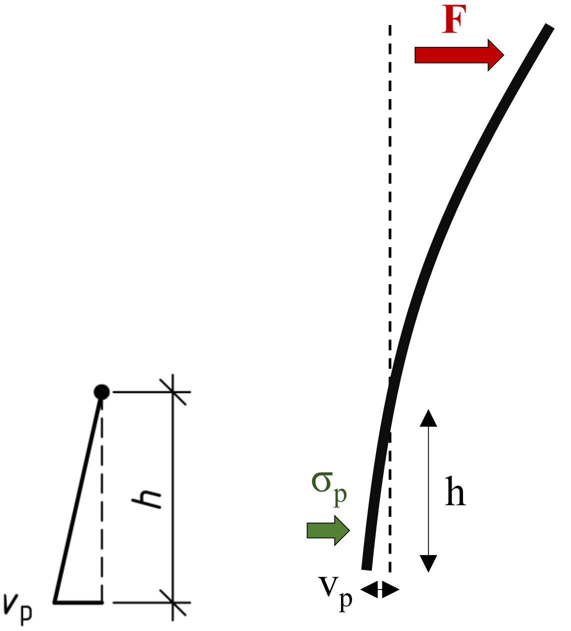

Figure 9. Mode of wall movement (left, EN 1997-1, 2005) and translation to mooring pile behaviour (right).

For ratio v_p/h, displacement criteria will be given in the updated version of CROW Flexible Dolphins, depending on the soil type the pile tip is in. The criteria are given for $0.5{\cdot}\sigma_p$, i.e. 50% passive soil resistance mobilisation, which should be evaluated in SLS conditions.

For the determination of this new fixity check, multiple benchmark calculations were evaluated. The Caland Canal pile test represented the finalisation of this study, in which the FEM model of one of the benchmark calculation was validated.

6 CONCLUSIONS

During the Caland Canal pile test, two mooring piles were repeatedly loaded to approximately 1400 kN, which is approximately 70% of the ultimate load for which the pile was dimensioned. Back analysis was performed with a FEM model in Plaxis 3D, using HSs soil parameters. A good fit was found with the measured data, leading to the following conclusions:

- the surface of the mooring post reacts less stiff during the first load compared to the second and subsequent loads, which means that the energy absorption during repeated mooring thrust is lower than during the first mooring thrust. The forces and displacement resulting from the second mooring with a SLS mooring energy seem representative and can be used to check the fixation of the mooring pile;
- the pile tip displacement of the mooring piles in the Caland Canal was limited. The validated FEM model in Plaxis 3D was used to determine which optimization of the pile was possible with the adjusted fixity check. The piles could have been 2 m shorter and the wall thickness could have been reduced in several segments. In total, a reduction of 12.7% in the required amount of steel appeared to be possible for the mooring piles in the Caland Canal.

ACKNOWLEDGEMENTS

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REFERENCES

Bentley (2022). PLAXIS 3D Reference Manual, PLAXIS CONNECT Edition V22.01.

Brinkgreve, R.B.J., Engin, E., Engin, H.K. (2010). Validation of empirical formulas to derive model parameters for sands. In: *Numerical methods in geotechnical engineering NUMGE 2010*, T. Benz, & S. Nordal (eds.), CRC Press, London, pp. 137-142. http://doi.org/10.1201/b10551-27.

CROW (2018). Flexible Dolphins

EN 1997-1:2005: Eurocode 7: Geotechnical design - part 1: General rules

Lengkeek, H.J (2022). Testing and modeling of sheet pile reinforced dikes on organic soils: Insights from the Eemdijk full-scale failure test (PhD thesis). https://doi.org/10.4233/uuid:78df5e2b-740e-4268-a821-ed0ccaae93e5. TU Delft.

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