GDP: A NEW TECHNOLOGY FOR GENTLE DRIVING OF (MONO)PILES

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ABSTRACT

Large monopiles with, for instance, 8 m diameter and total length of 80 m (30-40 m embedded in the ground) are commonly adopted in current offshore wind practice in suitable geotechnical conditions. Piles of such size require large impact hammers to ensure successful pile driving in a variety of soil conditions. Environmental constraints regarding underwater noise during pile installation add to the numerous challenges associated with monopile installation. It is necessary to explore alternative installation approaches, which are of less impact on the sea life (lower noise emissions) and at the same time do not compromise adequate operational performance of the foundation. To address this challenge, the Gentle Driving of Piles (GDP) JIP has been launched in the Netherlands. The experimental scope of the project includes pile installation using impact hammering, axial vibratory driving, and a novel vibratory installation method named Gentle Pile Driving, based on simultaneous application of low-frequency/axial and high-frequency/torsional vibrations. This paper overviews activities and preliminary results after the first year of project, particularly regarding the development of a new GDP vibro-hammer and the execution of 1/10-scale field tests.

Keywords: offshore wind, monopile, pile installation, vibratory driving, field testing, cyclic lateral load testing, sand, underwater noise

INTRODUCTION

Recent figures about offshore wind developments in Europe (WindEurope, 2020) report that Europe connected 502 new offshore wind turbines to the grid in 2019, bringing 3.6 GW of net additional capacity. Cumulatively, 5.047 Offshore Wind Turbines (OWTs) are now installed and grid-connected, amounting to 22.072 MW in total at the end of 2019. As for substructures and foundations, monopiles remained the most popular substructure overall, representing 81% of all installed foundations, with a total of 4.258 monopiles.

In the Netherlands, the Dutch government presented the new Climate Agreement in June 2019, containing a set of measures drawn up in consultation with various parties across the Dutch society in the joint combat against climate change. While the initial target for offshore wind energy was set at 4.5 GW of installed capacity by 2023, offshore wind farms will be installed within 2024 and 2030 with an average expansion of 1 GW per year, resulting in 11.5 GW of installed capacity by 2030.

To achieve the above goals and support innovation in the Dutch offshore wind industry, the GROW consortium was established (Growth through Research, development & demonstration in Offshore Wind – www.grow-offshorewind.nl. To date, the GROW consortium is formed by around 20 partners from the full offshore wind supply chain, with major strength arising from its ability to run focused, sequential and complementary R&D activities.

Within the GROW framework, the joint industry project Gentle Driving of Piles (GDP) was initiated in 2018. As illustrated in Fig. 1, the project is led by the TU Delft in cooperation with twelve partners, including research institutes and offshore wind developers, manufacturers, and contractors. On November 1st 2019, the GDP team hosted a demonstration day at the project site – the GDP DEMO Day. The event gave a chance to over 100 attendees to witness the successful installation of a test pile using the new GDP vibro-hammer. Media materials about the DEMO Day are publicly available at DEMO Day - link 1 and DEMO Day - link 2.

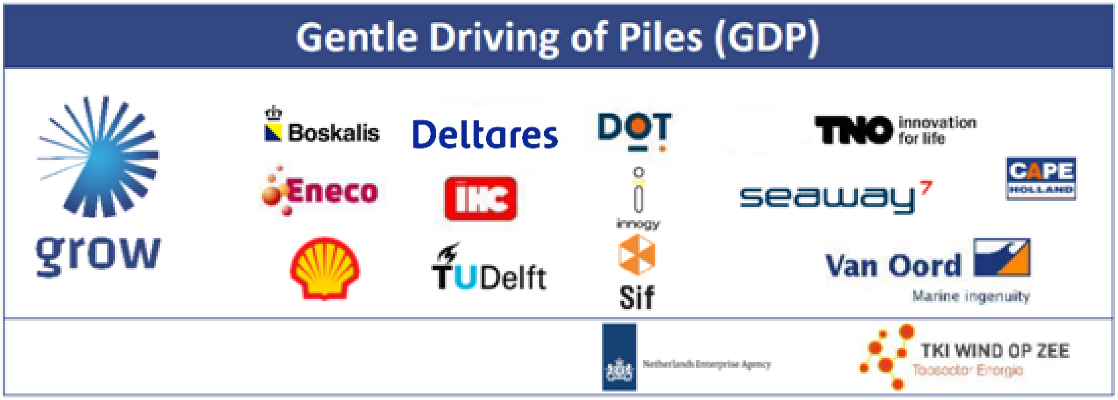

Fig. 1. The GDP consortium

Fig. 2. The GDP testing site location- A: 51, 58', 18.6" N, 4, 00', 45.3" E (left), and an aerial photo of the site during pile installation (right)

THE GDP PROJECT

The main objective of the GDP project is to develop a novel technique for Gentle Pile Driving (GPD) that simultaneously improves drivability, reduces noise emission, and preserves satisfactory geotechnical/structural performance during operations. Underwater noise is known to be harmful for the marine environment, as well as costly to mitigate (Tsouvalas, 2015; Tsouvalas & Metrikine, 2016). Overall, the GDP research runs across four, interrelated work packages (WPs), and encompasses the following activities:

1. Development of a new vibro-hammer for GDP pile driving;
2. Field experimental campaign, including "medium-scale" installation tests with different driving methods and post-installation, cyclic/dynamic pile loading experiments;
3. Numerical modelling of pile drivability with the GDP method at different levels of complexity; from simplified dynamic modelling of pile driving with lumped soil-structure interaction to advanced large-deformation analysis of pile driving in a soil continuum via the Material Point Method (MPM);
4. Numerical modelling of acoustic emissions during GDP driving;
5. Numerical modelling of geotechnical pile performance after installation, inspired by the outcomes of the above-mentioned loading field tests.

Activities related to items 1-2 have been finalised in December 2019, whereas items 3-5 are associated with longer term PhD projects at TU Delft with support from all GDP partners. The remainder of this paper is exclusively devoted to experimental field activities (items 1-2) carried out at the Maasvlakte 2 site, Port of Rotterdam (The Netherlands) – see Fig. 2.

DEVELOPMENT OF THE GDP VIBRO-HAMMER

The GDP technique targets pile driving that reduces both soil resistance during installation and the accompanying noise emission. To this end, a new GDP vibro-hammer was developed to combine low-frequency/axial and high-frequency/torsional vibrations. As torsional/shear waves cannot propagate through water, it is expected that noise levels in seawater will be significantly reduced. Additionally, noise associated with the coupled axial-radial vibrations of the pile can also be mitigated very effectively through the input excitation mechanism – in contrast to other pile driving techniques (Tsouvalas & Metrikine, 2016). Torsional vibrations also help to reduce radial pile expansion caused by Poisson effects, which is expected to contribute to smoother pile penetration into the ground.
Joint work of TU Delft and CAPE Holland BV produced the GDP vibro-hammer shown in Fig. 3. Given the project emphasis on the benefits of torsional vibrations, the design of the GDP shaker revolved around achieving high torsional frequencies in the range from 50 to 80 Hz. Torsional vibration in the GDP shaker is generated through high-speed rotation of eccentric masses generating a pair of forces in opposite directions. The offset between rotating masses and pile rotation axis produces a torque at the pile head. A similar principle is also used to generate low-frequency axial vibrations. Other points of attention in the design of the GDP hammer were: (i) shaker-to-pile load transfer, finally implemented through a bolted connection (Fig. 3-right); (ii) decoupling of axial and torsional vibrations.

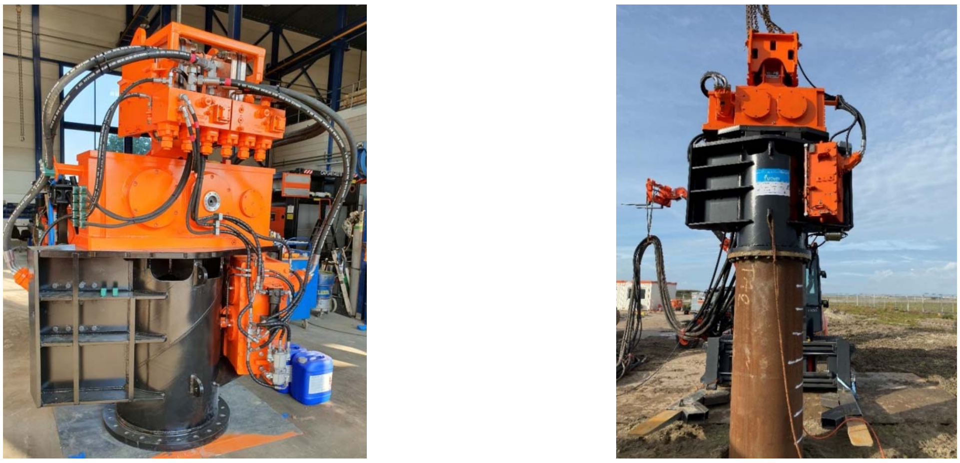

Fig. 3. The GDP vibro-hammer (left) and its deployment at the GDP site (right)

EXPERIMENTAL CAMPAIGN AT THE PROJECT SITE

This section overviews site characterisation and field testing activities at the Maasvlakte 2 site.

Site investigation and ground monitoring

The experimental campaign began in June 2019 with the execution of 25 CPTu tests (cone penetration tests with pore water pressure measurement) at the GDP testing site. These preliminary tests were performed to support the selection of best test locations. The 25 CPTu's were performed in an area of 56 x 56 m^2 with a spacing of 12.5 m, down to a depth of 10 m. To identify the depth of the ground water table, four dissipation tests were performed for the corner CPTu's – each test lasted 1 hour to enable the attainment of hydraulic steady state. Topographic information and dissipation test results were combined to infer phreatic levels in the range of 3.5-4.3 m below the ground surface at the considered locations.
A second site investigation phase began in August 2019. Additional site tests (four CPTu's, four SCPTu's, and four hydro-profiling tests with mini-pump tests) were executed near the

selected pile locations. 6-inch diameter boreholes were excavated for soil sampling and ground instrumentation purposes. Overall, the analysis of cone penetration data revealed a sandy site (high cone tip resistance and low sleeve friction) with decreasing relative density profile (i.e., dense sand overlaying medium-dense/loose soil). Relevant profiles of cone resistance (q_c) and relative density (Dr) are reported in Fig. 4 – Dr was estimated through the empirical correlation Dr = -1.292 + 0.268·ln[(qc)(σ'_{v0})$^{-0.5}$] by Jamiolkowski et al. (2003).

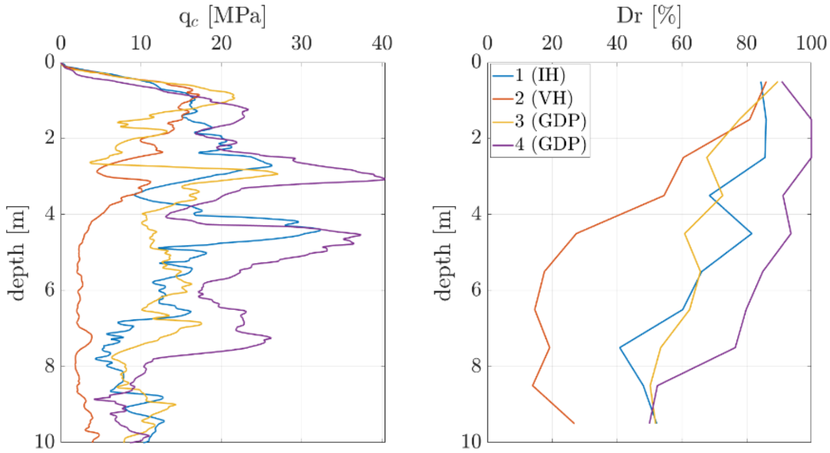

Fig. 4. SCPTu data examples: profiles of (left) cone resistance (q_c), and (right) inferred relative density (Dr)

About 80 kg of soil from the sampling boreholes were collected for laboratory testing at Deltares. The lab testing programme included tests for (1) general soil characterisation and (2) detailed study of hydro-mechanical behaviour under monotonic/cyclic loading: (i) tests for the determination of grain shape, particle size distribution (PSD) and index properties; (ii) permeability tests; (iii) monotonic direct simple shear tests; (iv) monotonic and cyclic triaxial tests; bender element tests; (v) oedometer/crushability tests; (vi) interface direct shear tests. The lab testing programme was concluded in April 2020, and will support upcoming numerical modelling activities (calibration of advanced constitutive model parameters).

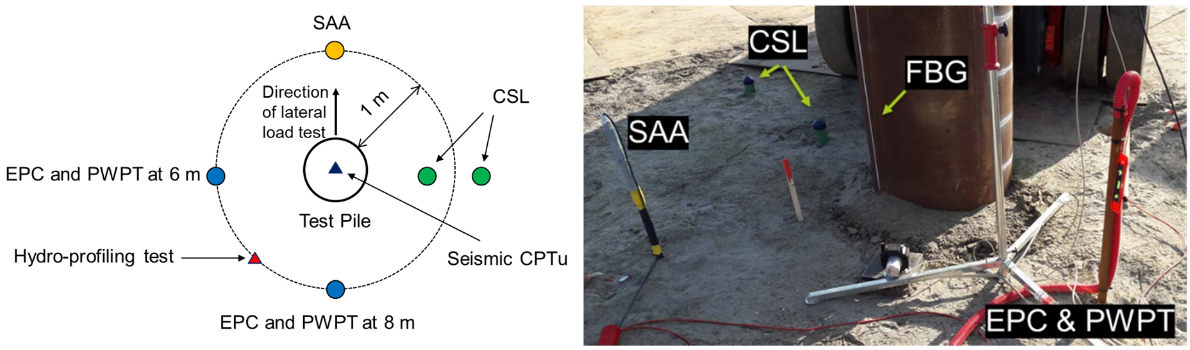

Fig. 5. Location of in-situ tests and ground monitoring sensors around an instrumented pile

To inspect the response of the soil before/during/after pile installation, a ground monitoring plan was set up. The following sensors/tests were installed/performed using boreholes drilled around instrumented test piles (see Fig. 5 and next sub-section):

- Shape Accel Array (SAA) with the length of 10 m (measured from the ground surface) to measure soil displacements;
- Earth Pressure Cell (EPC) and pore water pressure transducer (PWPT) at 6 m and 8 m depth to measure total horizontal soil stresses and excess pore water pressures;
- Cross-hole Sonic Logging (CSL) tests (up to 10 m depth) before and after pile installation to quantify the effect of pile installation.

Overall, the sandy nature and inhomogeneity of the GDP site is representative of possible offshore conditions in the (Dutch) North Sea. However, the depth of the phreatic level (about 4 m below ground surface) implies the presence of an unsaturated upper layer, which is not representative of marine environments.

Pile installation tests

Nine tubular steel piles were driven 8 m below the ground surface in October/November 2019, one as reaction pile for lateral load tests and eight as actual testing piles. The reaction pile featured length, diameter and wall thickness equal to 10 m, 1.6 m, and 20 mm, respectively; all other test piles were also 10 m long, but with diameter 0.76 m and wall thickness 15.9 mm. Out of the eight testing piles, four were instrumented and driven using different methods, namely standard impact hammering (one), conventional axial vibro-hammering (one), and the new GDP driving (two) – see Table 1 and Fig. 6. Opposite sides of test piles were instrumented with Fibre Bragg Grating (FBG) sensors with an offset, so as to measure longitudinal and transversal strains along the pile shaft and quantify bending moments during tests. FBG thermometers were also attached to the shaft of the four piles to record temperature variations during installation. Pile heads were also equipped with triaxial accelerometers, and a potentiometer was installed to measure the vertical displacement.

Table 1. Pile installation/instrumentation at the GDP site

Installation method	*Pile ID/instrumentation*
Impact Hammering (IH)	reaction pile/102/103 (un-instrumented), 1 (instrumented)
Vibro-Hammering (VH)	2 (instrumented)
Gentle Driving (GDP)	101/104 (un-instrumented), 3/4 (instrumented)

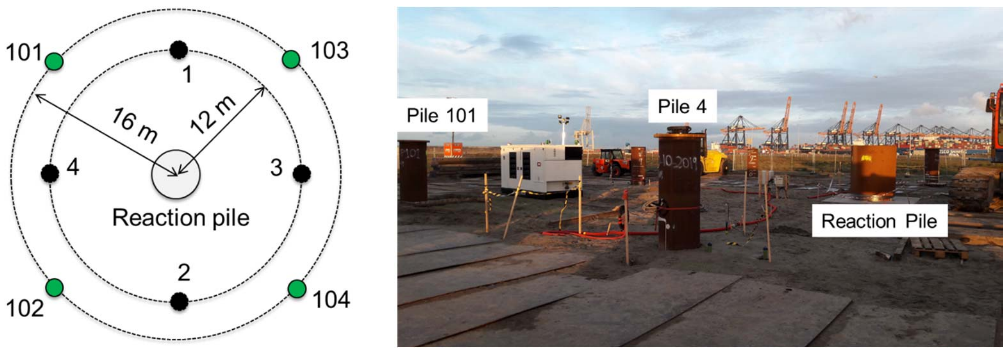

Fig. 6. Pile layout at the GDP site

Both GDP piles (3-4 in Fig. 6) were installed using axial and torsional vibration frequencies of 16 Hz and 60 Hz, respectively. Pile 2 (VH) was installed through conventional axial vibro-driving using a vibration frequency of 16 Hz for the first 3 m of penetration, then increased to 23 Hz to achieve the final 8 m target. Pile 1 (IH) was hammered into the ground with an impact rate of 70 blows per minute – with average energy per blow of about 25 kJ.
Fig. 7 illustrates the GDP time-penetration curve for pile 3 from 3.2 to 8 m below the ground surface, i.e., mainly through the water-saturated portion of the sand deposit. Recorded data indicate smooth pile installation, with about 5 m penetration achieved in slightly more than 2 minutes. Smooth GDP installation of pile 3 is further confirmed by Fig. 8:

- Fig. 8 (left-centre) show time-frequency (Stockwell) transforms of pile acceleration signals along axial/vertical (left) and transversal/horizontal (centre) directions. The two signals exhibit, steadily in time, highest amplitudes around 16 and 60 Hz, respectively, which is in agreement with the aforementioned input from the GDP vibro-hammer;

- Fig. 8 (right) illustrates the evolution in time of the pile penetration rate as obtained from numerical differentiation of the penetration curve in Fig. 7. The “more readable” red trend was obtained after low-pass filtering at 2 Hz, and confirms a fairly steady penetration rate in the range of 2.5-5 cm/s. This finding is also consistent with the Dr profile estimated near pile 3, exhibiting Dr values in a narrow range (50-70%) from 3 m to 8 m below the ground surface.

While Fig. 7-8 provide general indications about the effectiveness of the GDP method at the selected site, ongoing analysis of ground monitoring data will shed more light on the nature and impact of dynamic soil-pile interaction mechanisms.

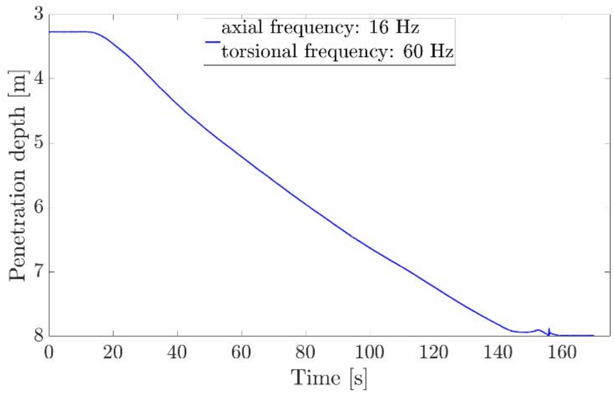

Fig. 7. Pile 3: pile penetration curve from 3.2 m to 8 m below the ground surface. Axial and torsional vibrations applied at 16 Hz and 60 Hz, respectively

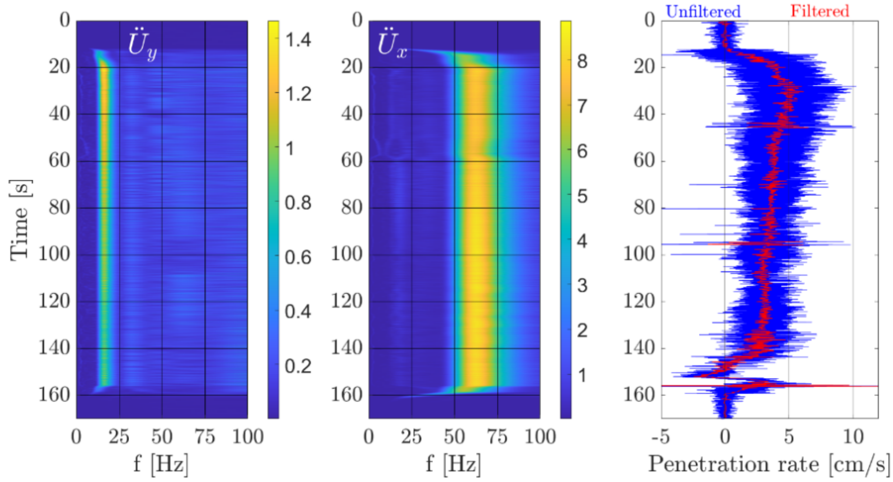

Fig. 8. Pile 3: time-frequency (Stockwell) of (left) vertical/axial and (centre) horizontal/transversal pile acceleration signals; (right) time evolution of pile penetration rate

Pile load tests – cyclic/dynamic lateral loading

After pile installation, lateral cyclic/dynamic load tests were performed to study the relationship between driving method and post-installation pile behaviour – a topic currently of high interest within the offshore wind community (Heins, et al., 2018; Anusic, et al., 2019; Jardine, 2019). For this purpose, the loading frame sketched in Fig. 9 (left), consisting of two anchoring rings linked through a connecting beam, was developed. For each load test, one of the two rings was set around the stiff reaction pile (designed to displace as little as possible), while the other around the test pile to be laterally loaded; a jacking system was devised for controlled pulling of the test pile. The load application point for each pile was approximately 1 m above the ground; pile lateral displacement was monitored at the level of ground surface.

The lateral test program in Fig. 9 (right) was applied to the four instrumented piles. The loading sequence comprised stages of slow cyclic loading (0.1 Hz, 1000 cycles) combined with small-amplitude dynamic loading (cyclic load amplitude of 5 kN) at frequency increasing from 0.1 to 4 Hz (120 cycles for each frequency step, with an interval of 0.1 Hz). Load tests were performed to investigate the effects of different pile driving methods on the operational performance of single piles. Considered features of performance were permanent pile deflection (LeBlanc, et al., 2010), and lateral stiffness under different dynamic regimes (Versteijlen, et al., 2017; Kementzetzidis, et al., 2020). Particular attention was devoted to the relationship between loading history and (possible) attainment of post-installation asymptotic states. Hereafter, data recorded on pile 4 (GDP-installed) are exclusively considered (Fig. 6).

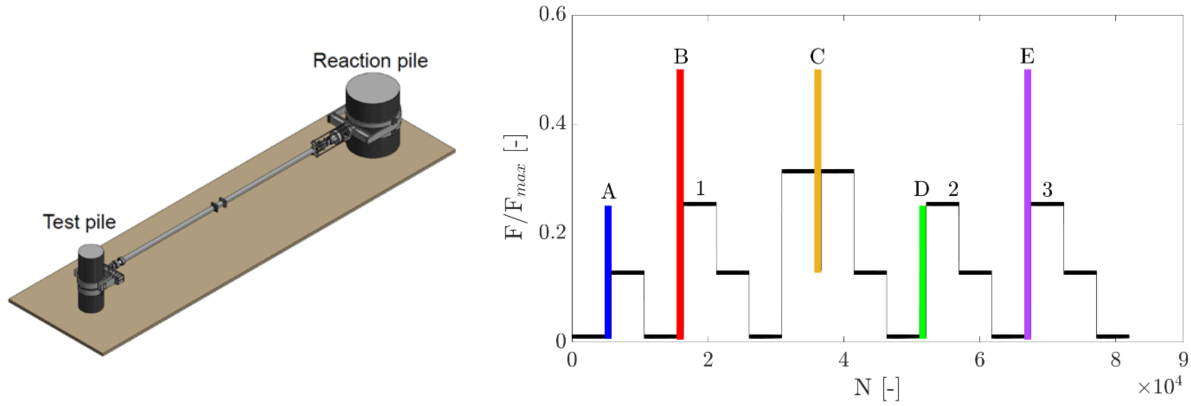

Fig. 9. Pile loading (left) set-up and (right) program. Red/blue/green force load ranges indicate slow cyclic loading stages (0.1 Hz), while black ranges denote low-amplitude dynamic stages at variable frequency (0.1-4Hz)

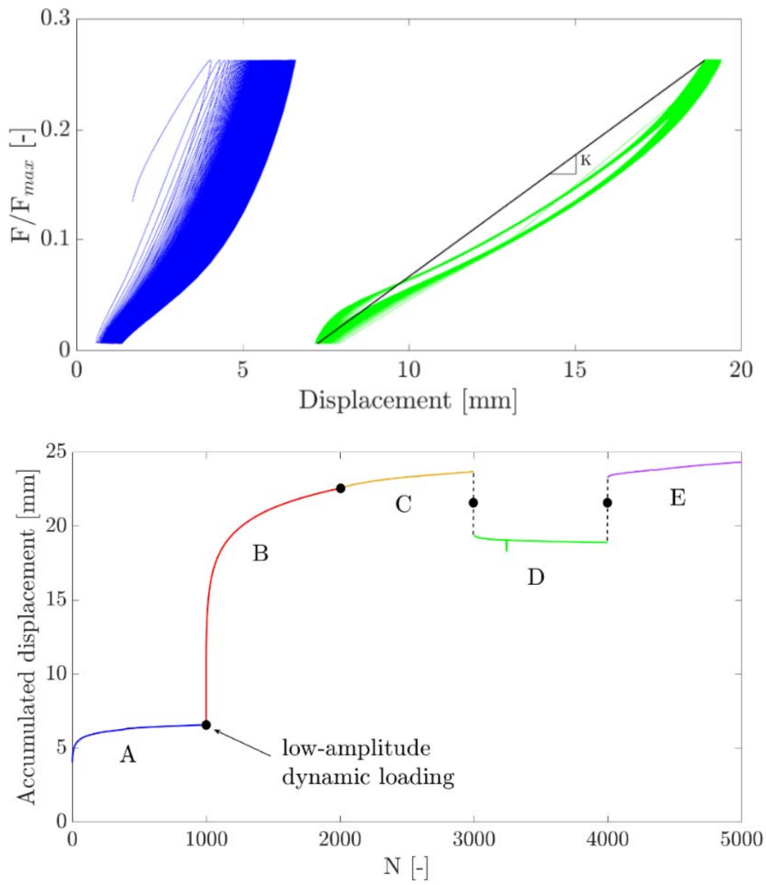

Fig. 10. Pile 4: (top) load-displacement lateral response associated with two slow cyclic loading stages; (bottom) accumulation of lateral deflection during slow cyclic loading. Line colours and labels are consistent with Fig. 9 (right)

Fig. 10 (top) displays for pile 4 (Fig. 6) typical results in terms of lateral load-displacement for the cyclic loading phases A and D in Fig. 9 (right) (load values are normalised by the estimated lateral pile capacity F_{max}). Unsurprisingly, the shape of all loading loops is affected by soil-pile gapping, as testified by obvious stiffness regains in the vicinity of maximum and minimum force values. Gapping is promoted by "apparent cohesion" in the upper unsaturated sand, as already noted, for instance, by Li, et al. (2015). Nevertheless, displacement accumulation trends (*ratcheting response*) over the cyclic loading phases A-E in Fig. 9 (right) appear in good agreement with existing physical modelling literature (Li, et al., 2015; Abadie, et al., 2018; Truong, et al., 2018; LeBlanc, et al., 2010):

- significant ratcheting is recorded when a given cyclic load amplitude, larger than previously applied, is imposed for the first time (i.e., under "virgin" cyclic loading);
- low/negligible displacement accumulation occurs upon reducing the cyclic amplitude;
- moderate variations in the average load level (*load bias*) do not cause drastic differences in ratcheting rate if the maximum load is unaltered (cf., phases B and C);

The loading program in Fig. 9 also gave also an opportunity to explore whether intermediate stages of small vibrations (black phases in Fig. 9) have an effect on pile ratcheting during major loading events – such as, in reality, storm waves. Small-amplitude loading does not seem to impact global ratcheting trends, apparently governed by the load amplitude and sequence set for the cyclic phases A-E.

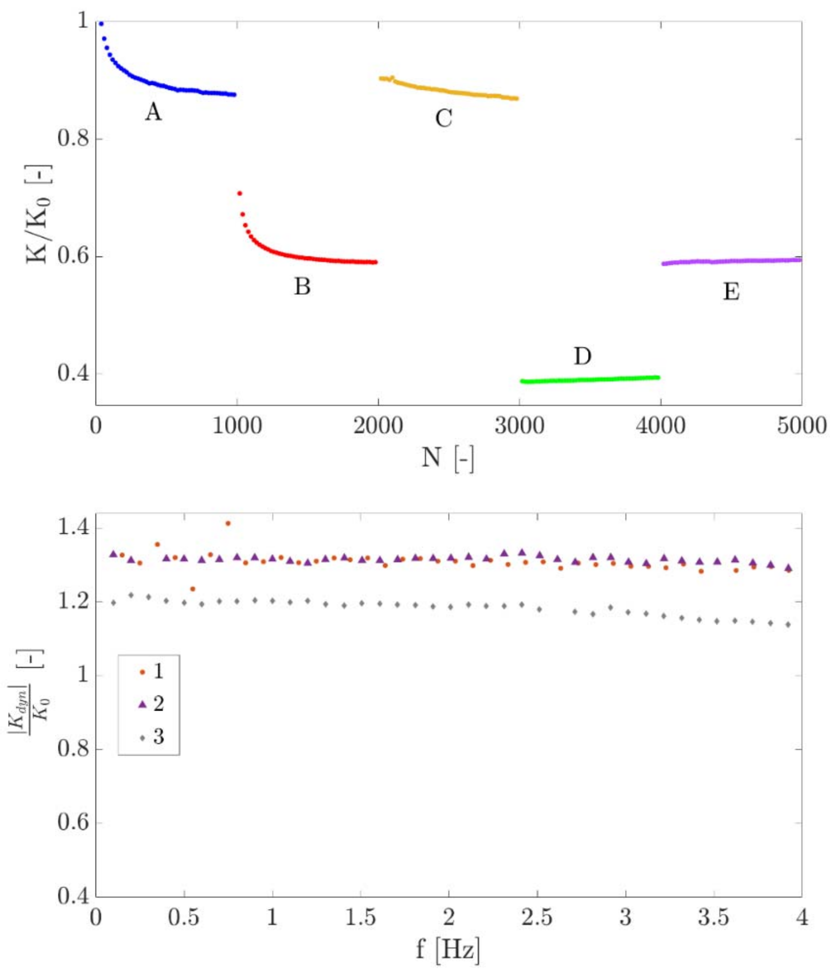

Fig. 11. Pile 4: evolution of secant cyclic stiffness during (top) slow cyclic loading (vs number of cycles), and (bottom) small-amplitude dynamic loading (vs loading frequency). Line labels are consistent with Fig. 9 (right)

Particularly relevant to the structural analysis of wind turbines is the global stiffness of the soil-foundation system. Fig. 11 provides useful insight for pile 4 regarding:

- Fig. 11 (top): the cyclic lateral stiffness K obtained from slow cyclic phases A-E. K is a secant stiffness defined as in Fig. 10 (top), and normalised (for confidentiality) with respect to the post-installation value K_0;
- Fig. 11 (bottom): (the absolute value of) the dynamic stiffness K_{dyn} associated with small vibrations during the loading phases 1, 2, and 3 in Fig. 9 (right). is also normalized with respect to K_0.

It is interesting to observe in Fig. 11 (top) how $K/K_0 - N$ trends are decreasing in phases A-B-C and increasing in phases D-E. Although only further analysis will lead to conclusive statements, it would seem as though the first three decreasing trends are markedly influenced by the mechanics of soil-pile gapping. Indeed, similar reduction in cyclic/secant stiffness has not been observed in other small-scale tests in dry or saturated sand, and would probably not occur offshore in presence of a cohesionless seabed. Conversely, phases D-E exhibit more typical stiffening trends, most likely associated with sand densification around the pile in presence of a gap already fully developed.
As for the dynamic stiffness K_{dyn}, Fig. 11 (bottom) hints the following inferences – concerning small vibrations around the average load bias (phases 1, 2, and 3 in Fig. 9):

- small vibrations mobilise a lateral stiffness larger than during strong cyclic loading, with limited influence of the major loading sequence after full gap development (i.e., after phase B). It is also worth noting that, due to the gap being wider than the small-vibration deflection range, K_{dyn} relates mostly to soil-pile interaction in “full contact” below the gap depth;
- although implicitly embedded in K_{dyn}, inertial effects do not seem to play a role for loading frequencies < 2.5 Hz. Slight frequency-dependence is observable around 3-4 Hz, with a gradual decrease in dynamic stiffness similar to what reported/explained by Kementzetzidis, et al. (2020) for a full-scale, impact-hammered monopile.

Further analysis of soil/pile sensor data will allow deeper grasp of geotechnical mechanisms and their impact on pile response, including comparison among piles installed with different methods. Such analysis will be accompanied by advanced 3D FE modelling accounting for non-linear, hydro-mechanical sand behaviour (Kementzetzidis, et al., 2019; Pisanò, 2019).

CONCLUDING REMARKS

GDP is a recent research initiative born in the Netherlands within the GROW offshore wind consortium, with public-private funding from a Dutch national grant and industry partners. The main goal of the project is to develop a new technology for “gentle pile driving”, combining axial and torsional vibrations to reduce noise emissions while enabling smooth pile installation that does not compromise post-installation performance.
The first year of the project was mainly dedicated to the experimental campaign at Maasvlakte 2, a reclaimed sandy site located at the Port of Rotterdam in the Netherlands. After detailed site investigation, pile installation took place using three different methods, namely impact hammering, axial vibro-driving, and the new GDP vibro-driving. Thorough ground monitoring was set up around four instrumented test piles, to obtain information relevant to grasping soil-structure interaction mechanisms during pile installation.
Following pile installation, cyclic/dynamic lateral load tests were also performed to investigate the relationship between installation conditions and post-installation performance of the test piles. The dataset collected through pile instrumentation and ground monitoring is allowing to interpret relevant features of performance, e.g., evolution of small-strain lateral stiffness, and permanent pile tilt as a consequence of cyclic soil ratcheting.
To date, field activities have generally proven the GDP technology capable of efficient pile driving in sandy soil. Preliminary analysis of post-installation test results shows no signs of poor soil performance during GDP installation. Interested readers are referred to upcoming publications for detailed analysis and modelling of GDP field data.

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