Cyclic Laterally Loaded Medium Scale Field Pile Testing for the PISA Project

Byrne, Byron W. ; McAdam, Ross A.; Beuckelaers, William J.A.P.; Burd, Harvey J. ; Gavin, Kenneth; Houlsby, Guy T. ; Igoe, David John Paul; Jardine, Richard ; Martin, Chris M.; More Authors

Publication date
2020

Document Version
Final published version

Published in
Proceedings Fourth International Symposium on Frontiers in Offshore Geotechnics

Citation (APA)
Byrne, B. W., McAdam, R. A., Beuckelaers, W. J. A. P., Burd, H. J., Gavin, K., Houlsby, G. T., Igoe, D. J. P., Jardine, R., Martin, C. M., & More Authors (2020). Cyclic Laterally Loaded Medium Scale Field Pile Testing for the PISA Project. In Z. Westgate (Ed.), *Proceedings Fourth International Symposium on Frontiers in Offshore Geotechnics* (pp. 1323-1332). Article 3540

CYCLIC LATERALLY LOADED MEDIUM SCALE FIELD PILE TESTING FOR THE PISA PROJECT

Byron W. Byrne, University of Oxford, Oxford, UK, byron.byrne@eng.ox.ac.uk
Ross A. McAdam, University of Oxford, Oxford, UK, ross.mcadam@eng.ox.ac.uk
William J.A.P. Beuckelaers, Jan De Nul, Belgium, william.beuckelaers@jandenul.com
Harvey J. Burd, University of Oxford, Oxford, UK, harvey.burd@eng.ox.ac.uk
Ken Gavin, Technical University of Delft, The Netherlands, k.g.gavin@tudelft.nl
Guy T. Houlsby, University of Oxford, Oxford, UK, guy.houlsby@eng.ox.ac.uk
David J.P. Igoe, Trinity College Dublin, Dublin, Ireland, igoe@tcd.ie
Richard J. Jardine, Imperial College London, London, UK, r.jardine@imperial.ac.uk
Christopher M. Martin, University of Oxford, Oxford, UK, chris.martin@eng.ox.ac.uk
David M. Potts, Imperial College London, London, UK, d.potts@imperial.ac.uk
David M. G. Taborda, Imperial College London, London, UK, d.taborda@imperial.ac.uk
Lidija Zdravković, Imperial College London, London, UK, l.zdravkovic@imperial.ac.uk

ABSTRACT

The PISA project explored the development of improved design methods for offshore wind turbine monopile foundations. Medium scale field pile testing for the project took place at Cowden in the UK, where the soil consists of a heavily over-consolidated glacial till, and Dunkirk in France, where the soil consists of a dense marine sand. The main focus of the testing was on monotonic capacity. However, results were also obtained for cyclic loading tests on medium scale piles of two different diameters (0.762 m and 2.0 m), and a length to diameter (*L*/*D*) ratio of 5.25. The testing consisted of uniform one-way cycling on 7 separate piles across the two sites at different amplitudes, including tests of over 20000 cycles, as well as two-way cycling on one pile at each site at different amplitudes and frequencies. The one-way tests explored ratcheting phenomena and associated effects, whilst the two-way tests explored stiffness and damping at increasing load amplitudes. This paper presents a summary of the cyclic pile tests that were completed, illustrated by results from the Dunkirk site. Comparisons are made to the PISA monotonic test results, as well as to observations from model testing reported in the literature. These field measurements support the development of new cyclic modelling approaches for offshore monopile foundations.

Keywords: Cyclic Loading, Monopiles, Offshore Wind, Field Testing

INTRODUCTION

Offshore wind turbine structures have typically been founded on monopiles; very large diameter tubular piles, now typically 8 m to 10 m in diameter, with 30 m to 50 m embedment, weighing up to 1000 tonnes, and impact driven into the seafloor. The design drivers for the monopile foundation are very different from those of typical oil and gas foundations, requiring new design methods to be developed. In recognition of these challenges, the Carbon Trust's Offshore Wind Accelerator initiated the PISA project, aimed at the development of new design methodologies for offshore wind turbine monopiles. The PISA project began in August 2013, with Phase 1 covering validated design methods for the monotonic lateral capacity of monopiles embedded in either homogeneous stiff glacial clay till or homogeneous dense marine sand. Following completion of Phase 1, in May 2016, a second phase of work exploring additional homogeneous soil profiles, and then application to layered soil was undertaken. Phase 2 was completed in June 2018.

Within its range of calibration the PISA design method accurately captures the detailed monotonic monopile soil-structure interaction for each wind farm site, ensuring site-specific and turbine-specific optimisation, accounting for the complex offshore ground conditions that exist. PISA involved a wide range of connected activities: (a) numerical modelling including sophisticated three dimensional finite element analysis, (b) theoretical developments, (c) laboratory element testing, (d) site investigation and (e) a comprehensive medium scale field pile testing campaign, at a range of diameters (0.273 m, 0.762 m, 2.0m), to validate the new design method. Key outputs of the PISA design method include generic design procedures for monopiles as well as sets of bespoke design equations. The main output of the work is reported in a series of articles: Byrne *et al*. (2017, 2019, 2019b, 2020), Burd *et al*. (2019, 2020), McAdam *et al*. (2019), Taborda *et al*. (2019) and Zdravković *et al*. (2019a, 2019b). The *Géotechnique* papers are freely available on Open Access and the content is not repeated here.

At the simplest level, design for cyclic loading involves a factoring of the monotonic capacity – see for example Reese *et al.* (1974), or Murchison and O'Neill (1984), with field testing for oil and gas applications reported by Cox *et al.* (1974) and also the work of Matlock (1970). Therefore the PISA project focused on monotonic capacity, recognizing that before any significant progress on cyclic loading could be made, it was first necessary to establish the monotonic backbone response robustly. In recognition that future work, following the PISA project, would move towards development of design methods for cyclic loading, a number of the pile load tests were focused on exploring the effects of cyclic lateral loading. In this way a database of high quality experimental measurements has been established, within a wider database that captures the detailed monotonic behaviour, and against which new or well established approaches for cyclic loading design can be tested.

This paper provides an overview of the PISA cyclic loading experiments and reports selected results to illustrate key behaviour observed. More detailed analysis of the behaviour will be reported in subsequent publications.

EXPERIMENTAL BACKGROUND

Offshore wind turbines are subject to a wide range of loading conditions, from severe storms, to long term operational loading from the rotating machinery, to impulse loads during an emergency stop situation. Although such loading is often pseudo-random, it is usual to adopt procedures that simplify the loading into packets of uniform loading. Experimental work then focuses on the effect of these uniform loads, expressing the outputs in a way that provides insight for design. This can be applied at element level or at system level for pile testing.

LeBlanc *et al*. (2010b; 2010a) set out a systematic framework for describing the cyclic lateral loading response of monopile foundations, assessing the implications for design, allowing for pseudo-random loading that occurs in reality. This framework has subsequently been adopted in investigations by a number of researchers including Abadie *et al.* (2019) and Richards *et al*. (2019), with an increasing focus on complex loading patterns.

A description of uniform cyclic loading on piles is illustrated in Fig. 1 (from LeBlanc *et al*., 2010b) where two different loading descriptors are defined. The first is the effect of load magnitude, described by:

$$\zeta_b = \frac{H_{max}}{H_{capacity}} \qquad [1]$$

which is the ratio of the maximum load applied in the uniform cycling to the pile capacity. Clearly the higher this ratio, the more onerous the cyclic loading on the pile response is likely to be. There is a question of whether there is a minimum threshold below which there is no effect of the cyclic loading. A second descriptor defines the bias of the loading by:

$$\zeta_c = \frac{H_{min}}{H_{max}} \qquad [2]$$

which is the ratio of the minimum load to the maximum load in the uniform cycling. One-way loading is given by a ratio of 0 and two-way loading by a ratio of -1. The nature of the pile response depends significantly on this ratio.

Fig. 2 illustrates typical pile responses for one-way and two-way loading, as these are the typical loading patterns applied in experimental work. If the pile is cycled with a bias and to zero load, then the usual observation is that the pile begins to ratchet (move) in the direction of the load bias. This is reflected in an incremental plastic displacement during each cycle, but of reducing magnitude for each subsequent cycle. This type of behaviour has been observed by many researchers, with either a power law or logarithmic relationship between the accumulated plastic displacement and cycle number being reported (*e.g.* LeBlanc *et al.* 2010). Fig. 2(b) also illustrates behaviour under two-way loading, where there may be very limited accumulated plastic displacement, with a hysteretic loop in load-displacement space possibly involving hardening (stiff soils) or softening as illustrated (soft soils). Of interest in both cases is the stiffness of the response, and the area of the hysteresis loop shape, which relates to energy loss (damping), as these are significant determinants of the dynamic response of the wind turbine.

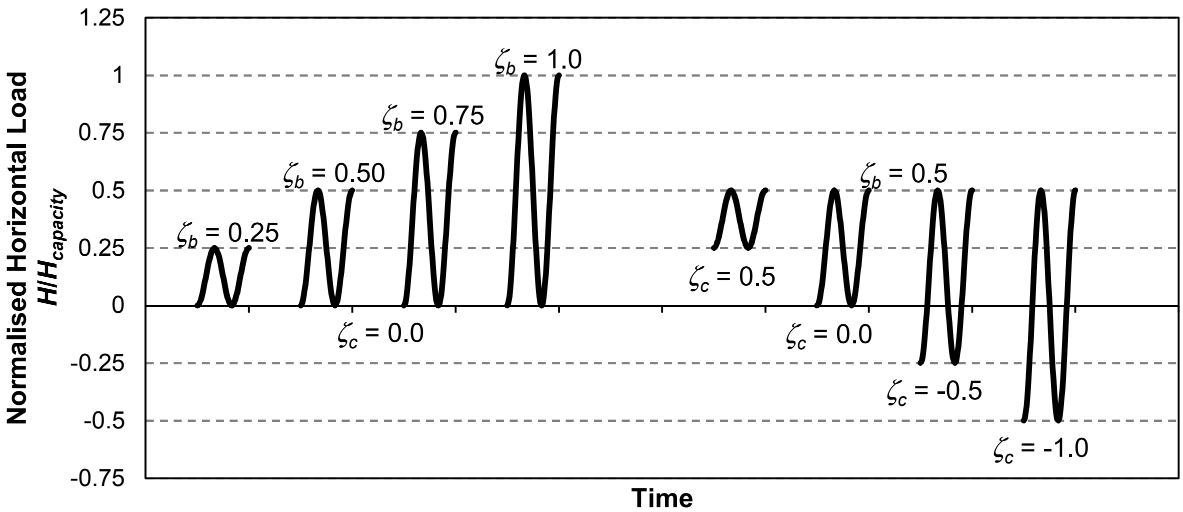
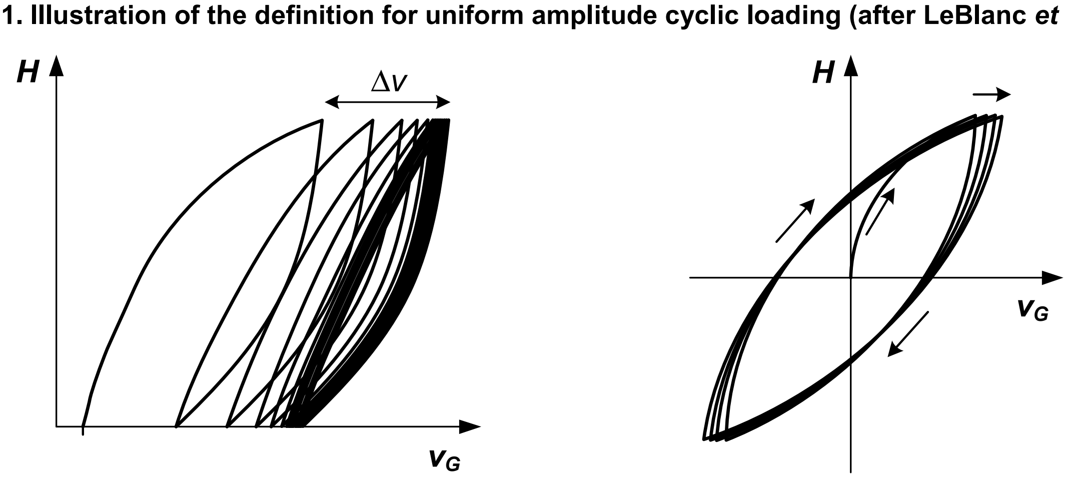


Fig. 1. Illustration of the definition for uniform amplitude cyclic loading (after LeBlanc *et al.*, 2010)



(a) One-way loading; $0 < \zeta_b \leq 1$, $\zeta_c = 0.0$ **(b) Two-way loading: $0 < \zeta_b \leq 1$, $\zeta_c = -1$**

Fig. 2. Schematic of typical cyclic response, where *H* is horizontal load, v_G is horizontal ground-level displacement and Δv is relative displacement.

There have, of course, been a number of field pile load testing programs exploring cyclic lateral loading (e.g. Cox *et al.*, 1974; Matlock, 1970). These often tend to be limited to relatively small numbers of cycles representing severe storm loading (say less than 1000 – see database information in Lin and Liao, 1999, as well as Long and Vanneste, 1994) and for piles with large *L*/*D* ratios, more relevant to oil and gas applications than offshore wind. More recent field work, such as reported by Li *et al.* (2015), has moved towards wind turbine applications. A specific focus of the PISA project cyclic tests, see Table 1, was to obtain information for at least one pile at each site under a large number of load cycles (>25000), to provide some evidence of the longer term cyclic behaviour for geometrically relevant piles at a field scale. This information will facilitate comparisons with more recent laboratory testing programs (e.g. LeBlanc *et al.*, 2010b; Klinkvort and Hededal, 2013; Bayton *et al.*, 2018), in which a wider range of loading conditions, in more tests, has been possible.

TEST PROGRAM

The PISA project field test sites were located at Cowden near Hull in the UK, and in Dunkirk in northern France. The Cowden site was comprised of a low plasticity stiff over-consolidated glacial clay till, with an undrained strength, measured in triaxial compression, increasing from about 40 kPa at the surface to about 160 kPa at 2 m depth before reducing to about 100 kPa at 4 m and then with an increasing strength with depth of approximately 6 kPa/m. The groundwater level was at about 1 m depth. The Dunkirk site consisted of a normally consolidated dense to very dense sand, with a top 3 m layer comprising 100% relative density fill material (placed during the 1970s to raise the ground level), and 75% relative density for the underlying natural sand. The ground water level was at about 5.4 m depth. The two sites were chosen for their extensive pre-existing site investigation history, including in-situ field characterisation alongside substantial suites of laboratory testing. Further site investigation, including a comprehensive CPT campaign, and laboratory characterisation was completed during PISA, to update the historical site interpretation. See Zdravković *et al.* (2019a) for the full PISA site characterisation and interpretation.

The pile test program was designed to provide the field evidence to verify the robustness of the PISA design model. This involved demonstrating that properly calibrated and executed three-dimensional finite element models could robustly predict the behaviour of piles in the field. To achieve this, the test program explored the monotonic pile response for a range of pile diameters and pile lengths. Three diameters of pile were tested: (a) four 0.273 m diameter piles at three different *L*/*D* ratios (5.25, 8, 10) to provide data at a small scale and to commission the testing systems, (b) eight 0.762 m diameter piles at three different *L*/*D* ratios (3, 5.25 and 10 at Cowden; 3, 5.25 and 8 at Dunkirk) to provide the main bulk of the experimental data, and, (c) two 2.0 m diameter piles at a single *L*/*D* ratio (5.25) to provide key model validation data at reasonable scale. At both sites one each of the small-diameter and medium-diameter piles were used to explore rate effects during monotonic loading.

The piles that focused on cyclic loading are indicated in Table 1, which shows five piles at Cowden and four piles at Dunkirk. One pile at each site had one-way cyclic loading applied and a second pile had two-way cyclic loading applied. The tests were specifically designed to explore the cyclic loading response features described previously (*e.g.* ratcheting, stiffness change). In addition, cyclic loading was applied following the completion of the monotonic loading test on the large piles at each site, to provide additional information, but without compromising the main focus of that specific test.

The experimental set-up for the cyclic loading tests on the 0.762 m diameter piles is shown in Fig. 3. The main loading is applied by a hydraulic actuator located 10 m above the ground, to replicate approximately the eccentricity of loading developed by wind and wave action on wind turbines. The hydraulic actuator reacts against a much larger (2.0 m) diameter reaction pile. To ensure that the hydraulic loading system is always in tension for the one-way

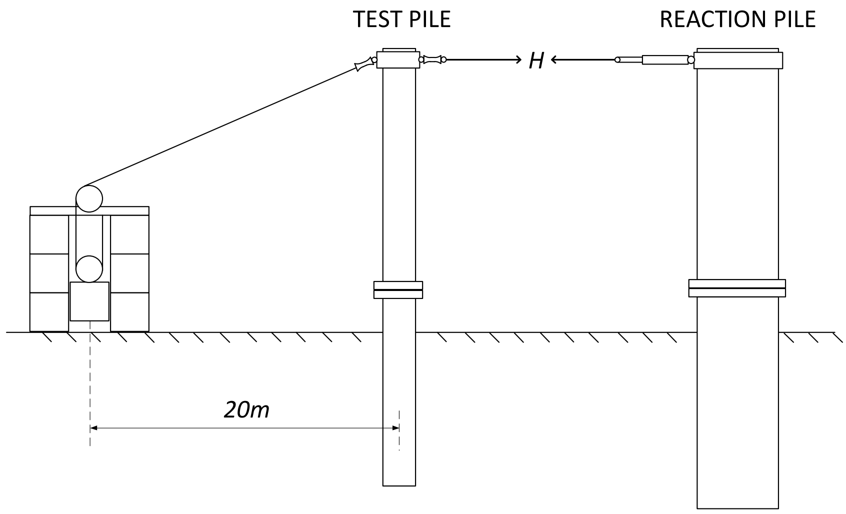


Fig. 3. Schematic of pile testing configuration (not to scale) for cyclic loading of medium diameter piles (*D* = 0.762 m)

Table 1: PISA pile tests focused on cyclic loading

Test	Type	*D* (m)	*L* (m)	*L*/*D*	*t* (mm)	*h* (m)	*h*/*D*	Number of Cycles
CM6	mon / 1w-cyc	0.762	4.01	5.26	11	9.98	13.10	55
CM5	1w-cyc	0.762	4.00	5.25	11	10.00	13.12	27650
CM7	2w-cyc	0.762	3.98	5.23	11	10.00	13.12	3868
CL1	mon / 1w-cyc	2	10.35	5.18	25	10.10	5.05	1060
CL2	mon / 1w-cyc	2	10.60	5.30	25	10.10	5.05	1060
DM2	1w-cyc / mon	0.762	3.99	5.24	14	10.00	13.12	38110
DM1	2w-cyc	0.762	3.97	5.21	14	10.02	13.15	7267
DL1	mon / 1w-cyc	2	10.61	5.30	38	9.90	4.95	588
DL2	mon / 1w-cyc	2	10.57	5.29	38	9.89	4.95	588

Note: C = Cowden; D = Dunkirk; M = medium diameter (0.762 m); L = large diameter (2.0 m); 1w-cyc = one-way cyclic loading; 2w-cyc = two-way cyclic loading; mon = monotonic loading; *L* = embedded length; *t* = wall thickness, *h* = load application height

loading, or to be able to apply two-way loading, a back-stay system with a dead load was used. Careful initialisation of the system is required to ensure that the test pile is not inadvertently loaded in one direction or the other. Although the back-stay imposes an additional vertical load to the test pile, as the back-stay inclined at about 18.8 degrees to the horizontal, it is believed that this will have only a minor effect on the lateral capacity. The system is justified on the basis of the better load control that it facilitates.

Extensive instrumentation was employed in each of the PISA tests to assess the soil-structure interaction response. The above ground instrumentation included displacement measurement systems and inclinometers, whilst below ground it included inclinometers, extensometers and fibre optic strain gauges. To deduce the pile ground displacements and rotations robustly it was necessary to develop a structural model of the test system, allowing the measured data to be merged in a principled manner, see Burd *et al*. (2019). Logging of the data at a minimum of 10 Hz ensured good definition of the full range of the cyclic loading responses, including detailed hysteretic behaviour during each cycle.

Illustrative results are presented below for two of the Dunkirk tests to demonstrate the key features observed in the testing. As the 0.762 m diameter were embedded in soil above the water table the results provide insight into the drained cyclic response of piles in sand. Further work is needed to address pile cyclic response in saturated sand conditions.

Table 2: Load set applied to pile DM2

Load Set (LS)	Maximum Load, H_{max} (kN)	ζ_b	Number of Cycles
1	10	0.046	5100
2	20	0.093	3300
3	40	0.19	8100
4	80	0.37	11110
11	160	0.74	31

EXAMPLE ONE-WAY LOADING (ζ_c = 0)

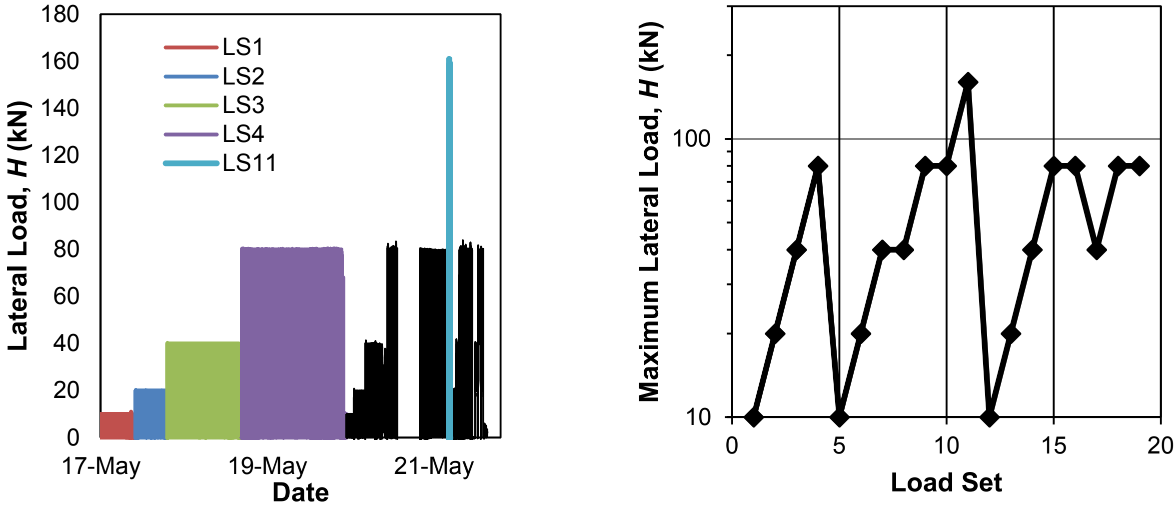
Test DM2 was focused on one-way loading, with a series of applied cycles with time illustrated on Fig. 4. Key cyclic load sets are specified in Table 2. All cyclic loading was applied at a frequency of 0.1 Hz. As is illustrated by the time history in Table 2, the initial sequences of the cyclic loading explored pile behaviour under very low relative load magnitudes. The value of ζ_b is assessed by adopting a monotonic lateral load capacity of 216 kN, the average of the values at a displacement of 0.1D reported in McAdam *et al.* (2019) for the two equivalent monotonic test piles DM4 and DM9. Normally in laboratory experimental work (*e.g.* Abadie *et al.*, 2019; Richards *et al.*, 2019) it is not possible to probe small values of ζ_b (less than about 0.20) for practical reasons; for these larger scale experiments, however, this proved possible. When it was clear that very small movements were occurring under the applied cycling, the testing moved to the next load stage. Again, experience from laboratory experiments indicates that at least 1000 cycles are needed to establish the long term accumulation behaviour (e.g. Richards *et al.*, 2019; LeBlanc *et al.*, 2010b), which provided a minimum requirement for the number of cycles. By doubling the load in each successive load set, the expectation is that the previous load history would be “erased”, so that the new load set provides additional new information about pile response.

Fig. 4(b) illustrates that, following load sets in which the load was increased (*i.e.* load sets 1 to 4) new load sets were applied at a reduced level (*i.e.* load sets 5 to 8). This enabled exploration of pile behaviour with the pile in the “elastic” region. These results are not further examined here. Load set 11 applied very significant loading to the pile, indicated by Table 2.

Fig. 5 illustrates the load displacement response observed in the cyclic test, by comparison with equivalent geometry monotonic pile tests DM4 and DM9. As expected, the pile gradually ratchets in the direction of the load bias, with the degree of ratcheting apparently a function of ζ_b. Even under the very significant loading of load set 11, the ratcheting displacements appear to reduce consistently with cycle number. Fig. 5(b) demonstrates that even under the smaller loads there is some marginal ratcheting, albeit at fairly low levels. Fig. 5(b) also indicates that a power law approach to describing the ratcheting may be

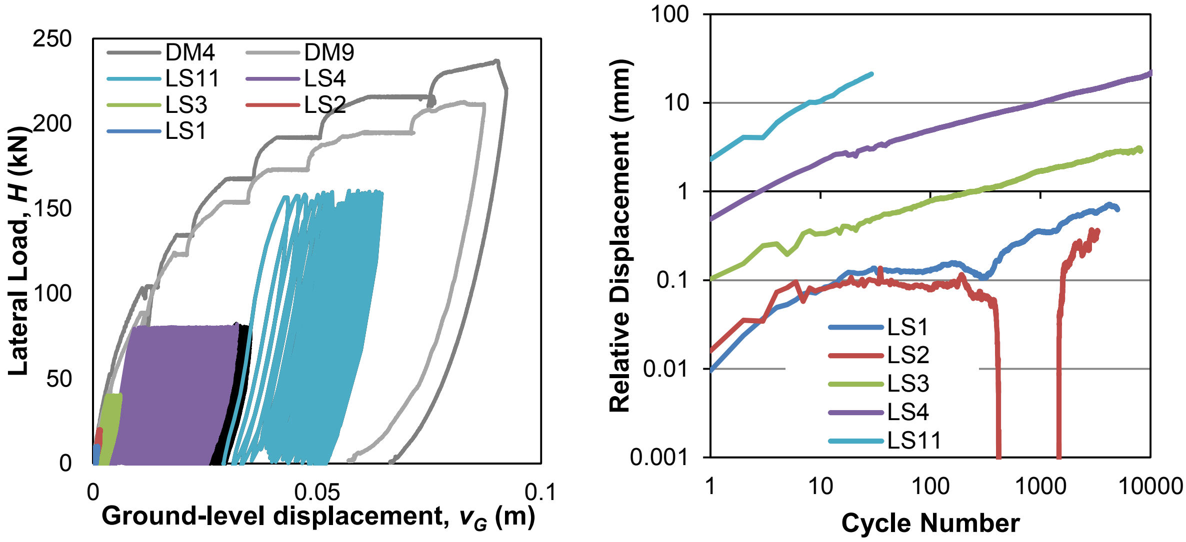
Table 3: Load set applied to pile DM1

Load Set (LS)	Maximum Load H_{max} (kN)	ζ_b	Frequency (Hz)	N
1-2	0.2	0.00093	0.0167 - 0.1	126
3-4	0.5	0.0023	0.0167 - 0.1	139
5-6	1	0.0046	0.0167 - 0.1	118
7-8	2	0.0093	0.0167 - 0.1	114
9-26	4	0.018	0.0167 - 1	701
16-17	6	0.028	0.0167 - 0.1	117
18-25	10	0.046	0.0167 - 1	829
26-27	15	0.069	0.0167 - 0.1	102
28-35	20	0.093	0.0167 - 1	991



(a) Time history (b) Load sets (note logarithmic scale)

Fig. 4. Loads applied to one way cyclic test DM2



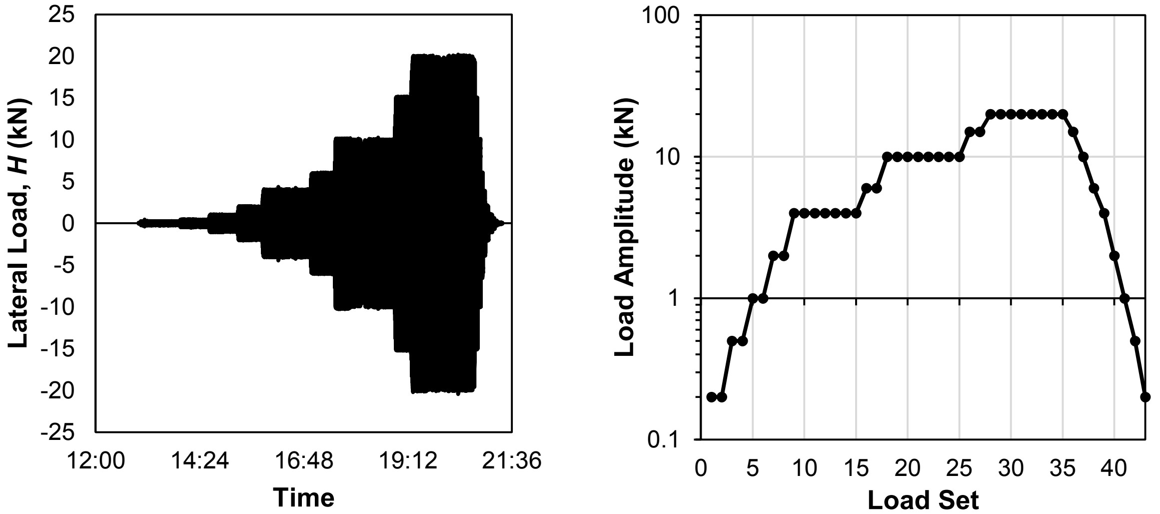
(a) Load displacement response compared to monotonic tests DM4 and DM9 (b) Accumulated relative displacements for each significant cyclic load stage

Fig. 5. Results for one-way cyclic test DM2

suitable, consistent with laboratory experimental work (e.g. LeBlanc *et al.*, 2010b). Further analysis is given in Beuckelaers *et al.* (2020).

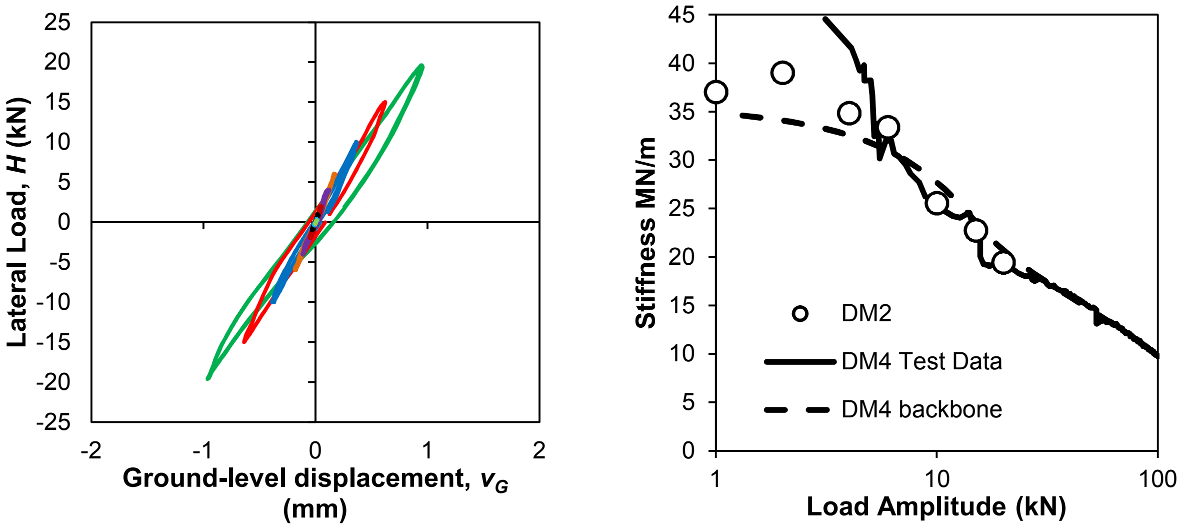
EXAMPLE TWO-WAY LOADING (ζ_c = -1)

Test DM1 focused on two-way loading, with a distribution of applied cycles with time as shown on Fig. 6. This represents the first day of testing; there was a second day with additional cycles applied to the pile. For this first day of testing, cyclic loading was applied at increasing load levels as indicated by the data in Table 3. At the different load levels the cycling was applied at different frequencies, usually with periods of 10 s and 60 s, though at load levels 4 kN, 10 kN and 20 kN cycles were also applied at higher frequencies. Once sufficient data were gathered at one load level, the cycling moved to the next load level. A minimum of 100 cycles was adopted. Clearly, given the loads applied, careful attention to detail in applying the initial loading (through off-setting the back-stay system) was needed to ensure that the pile was not overloaded in one direction or the other. After load stage 35, cycles of decreasing amplitude were applied to the pile as indicated in Fig. 6(b); these are not further examined here.



(a) Time history (b) Load Sets (note logarithmic scale)

Fig. 6. Variation of load amplitude applied to pile DM1 (Day 1 of testing)



(a) Load displacement response (b) Interpreted peak to peak stiffness

Fig. 7. Foundation response of for DM1 for Load Sets 6, 8, 15, 17, 25, 27 and 35. Plotted on (b) is the secant stiffness for DM4.

Fig. 7 shows the load-displacement results for the first 35 load stages. It is clear that a symmetric response is observed, and there appears to be some reduction in stiffness with increase in load level. This is further identified in Fig. 7(b) which plots the peak-to-peak stiffness for the load stages above 1. This is compared to the secant stiffness for monotonic test DM4, from both the test result and idealised backbone response from McAdam *et al.* (2019). Even at small loads, there is a very good correlation between the two independent sets of results, indicating that the monotonic response and the cyclic response are closely aligned at these load levels. This match between monotonic and cyclic test results has significant implications for the development of theoretical models and design methods.

CONCLUSIONS

An overview of the PISA project cyclic pile testing has been given, illustrated by two tests completed at the Dunkirk site in northern France. A one-way loading test, comprising constant amplitude cycles of increasing amplitude, showed behaviour similar to that observed in laboratory model testing. In particular a ratcheting response was observed, with the accumulation of plastic displacement reducing with each cycle number, following a power law relationship. Even cycling at very low amplitudes produced some ratcheting. Two-way cyclic loading produced symmetric load-displacement responses, with stiffness reducing with load amplitude level, as expected. The peak-to-peak stiffness compared favourably to the secant stiffness taken from an equivalent monotonic test. These results provide evidence that can be used as a comparator for the development of new models for pile cyclic loading design.

ACKNOWLEDGMENTS

The PISA Project was funded by the UK Department for Energy and Climate Change (DECC) and the PISA Industry Partners under the umbrella of the Offshore Wind Accelerator (OWA) program which was designed and is led by the Carbon Trust. The Authors acknowledge financial and technical support from the project partners: Alstom Wind, Ørsted (formerly DONG Energy), E.ON, EDF, Equinor (formerly Statoil), innogy, SPR (formerly Iberdrola), SSE, Statkraft, Van Oord and Vattenfall. The Authors acknowledge gratefully the work of Socotec UK Ltd (formerly ESG) as the main contractor for the design and execution of the field testing program. Byrne is supported by the Royal Academy of Engineering under the Research Chairs and Senior Research Fellowships scheme.

REFERENCES

Abadie, C.N., Byrne, B.W. and Houlsby, G.T. 2019. Rigid pile response to cyclic lateral loading: laboratory tests. *Géotechnique* 69 10: 863-876.

Bayton, S.M., Black, J.A. and Klinkvort, R. T. 2018. Centrifuge modelling of long term cyclic lateral loading on monopiles. *Proceedings of ICPMG 2018* pp. 689–694, London

Beuckelaers, W.J.A.P., Burd, H.J., Houlsby, G.T., McAdam, R.A. and Byrne, B.W. 2020. A generalised Winkler model for the hysteretic and ratcheting behaviour of monopiles in clay and sand. *Proceedings of ISFOG 2020*, Austin, Texas.

Burd, H.J., Beuckelaers, W.J.A.P., Byrne, B.W., *et al.* 2019. New data analysis methods for instrumented medium scale monopile field tests. *Géotechnique,* doi.org/10.1680/jgeot.18.PISA.002

Burd, H.J., Taborda, D.M.G., Zdravkovic, L., *et al.* 2020. PISA design model for monopiles for offshore wind turbines: Application to a marine sand. *Géotechnique,* doi.org/10.1680/jgeot.18.p.277

Byrne, B.W., Burd, H.J., Zdravkovic, L., *et al.* 2019. PISA design methods for offshore wind turbine monopiles. *Offshore Technology Conference*, Houston, Texas.

Byrne, B.W., McAdam, R.A., Burd, H.J., *et al.* 2019b. Monotonic laterally loaded pile testing in a stiff glacial clay till at Cowden. *Géotechnique,* doi.org/10.1680/jgeot.18.PISA.003

Byrne, B.W., Houlsby, G.T., Burd, H.J., *et al.* 2020. PISA design model for monopiles for offshore wind turbines: Application to a stiff glacial clay till. *Géotechnique*, doi.org/10.1680/jgeot.18.p.255

Byrne, B.W., McAdam, R.A., Burd, H.J., *et al.* 2017. PISA: New design method for offshore wind turbine monopiles. *SUT OSIG 8th International Conference*, London, UK.

Cox, W.R., Reese, L.C. and Grubbs, B.R. 1974. Field testing of laterally loaded piles in sand. *Proceedings Offshore Technology Conference* Paper 2079, Houston, Texas.

Klinkvort, R.T., and Hededal, O. 2013. Lateral response of monopile supporting an offshore wind turbine. *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering* 166 2: 147–158, https://doi.org/10.1680/geng.12.00033

Leblanc, C., Byrne, B.W. and Houlsby, G.T. 2010a. Response of stiff piles to random two-way lateral loading. *Géotechnique* 60 9: 715-721.

Leblanc, C., Houlsby, G.T. and Byrne, B.W. 2010b. Response of stiff piles to long term cyclic loading. *Géotechnique* 60 2: 79-90.

Li, W., Igoe, D.J.P. and Gavin, K. 2015. Field tests to investigate the cyclic response of monopiles in sand. *Proceedings of the Institution of Civil Engineers–Geotechnical Engineering* 1685: 407–421, http://dx.doi.org/10.1680/jgeen.14.00104

Lin, S.-S. and Liao, J.-C. 1999. Permanent strains of piles in sand due to cyclic lateral loads. *ASCE Journal of Geotechnical and Geoenvironmental Engineering* 125 9: 798-802

Long, J.H. and Vanneste, G. 1994. Effects of cyclic lateral loads on piles in sand. *ASCE Journal of Geotechnical Engineering* 120 1: 225-244

Matlock, H. 1970. Correlations for design of laterally loaded piles in soft clay. *Proceedings Offshore Technology Conference* Paper 1204, Houston, Texas

McAdam, R.A., Byrne, B.W., Houlsby, G.T., *et al.* 2019. Monotonic laterally loaded pile testing in a dense marine sand at Dunkirk. *Géotechnique*, doi.org/10.1680/jgeot.18.PISA.004

Murchison, J. M. and O'Neill, M. W. 1984. Evaluation of p–y relationships in cohesionless soils. *Proceedings of the ASCE symposium on analysis and design of pile foundations*, San Francisco, pp. 174–191.

Richards, I.A., Byrne, B.W. and Houlsby, G.T. 2019. Monopile rotation under complex cyclic lateral loading in sand. *Géotechnique*, doi.org/10.1680/jgeot.18.p.302

Reese, L.C., Cox, W.R. and Koop, F.D. 1974. Analysis of laterally loaded piles in sand. *Proceedings Offshore Technology Conference* Paper 2080, Houston, Texas.

Taborda, D.M.G., Zdravković, Potts, D.M., *et al.* 2019. Finite element modelling of laterally loaded piles in a dense marine sand at Dunkirk. *Géotechnique*, doi.org/10.1680/jgeot.18.PISA.006

Zdravković, L., Jardine, R.J., Taborda D.M.G., *et al.* 2019a. Ground characterisation for PISA pile testing and analysis. *Géotechnique*, doi.org/10.1680/jgeot.18.PISA.001

Zdravković, L., Taborda, D.M.G., Potts, D.M., *et al.* 2019b. Finite element modelling of laterally loaded piles in a stiff glacial clay till at Cowden. *Géotechnique*, doi.org/10.1680/jgeot.18.PISA.005