Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

PICASO: Cyclic loading of wind turbine monopiles

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ABSTRACT: The PICASO project is a multi-faceted collaborative project between the University of Oxford and Ørsted that aims to develop the next generation of cyclic loading models for offshore wind turbine monopiles. The project focuses on a wide range of activities including (a) detailed development of PISA type 1D finite element models, including the application of machine learning techniques for model calibration, (b) completion of laboratory element and laboratory model testing in a wide range of soils, including monotonic and cyclic loading, (c) development of new theoretical methods to capture cyclic loading within a plasticity framework (HARM), such that it can be adapted to 0D, 1D and 3D type modelling of foundations, (d) field scale testing at a clay and sand site, adopting realistic loading patterns for cyclic loading, and exploring rate effects, at two different pile diameters (1.22 m and 2.5 m), (e) translation of the research findings to design applications. This paper provides an overview of the research completed and the important findings for design practice.

Keywords: pile testing, cyclic loading, monopiles, sand

1 INTRODUCTION

The design of laterally loaded offshore wind turbine monopiles has advanced substantially over the past decade, with the industry transitioning from long-standing "*p-y*" methods to new approaches that better capture the physics of large diameter rigid piles under monotonic loading. These approaches are exemplified by the PISA design model for monotonic loading, developed from 2013 to 2018, and described in detail through the November special issue of *Géotechnique* in 2020 (Byrne, 2020). The PISA design model integrates the outputs from advanced 3D finite element (FE) modelling with simplified 1D methods, allowing rapid analysis of pile response to enable site wide optimisation of the wind turbine foundations and structures. Adopting the PISA design model leads to better assessment of SLS and ULS behaviour, leading to significant savings in monopile steel.

2 PICASO PROJECT

The PICASO project, a collaboration between the University of Oxford and Ørsted, builds on the outputs of the PISA project to address cyclic loading of piles, as this remains the significant challenge for further optimisation of pile design. Current design methods address cyclic loading through modification of the monotonic loading response, either by factoring the strength or stiffness of response, or both. This approach does not explicitly address many of the complexities that underpin cyclic loading such as; (a) number of cycles, (b) amplitude of cycles, including pseudo-random amplitudes, (c) multi-directional loading, (e) the effect of cycling on stiffness, hysteresis and accumulated movements, (d) post-cyclic capacity, and (f) realistic implementation into a structural analysis calculation. An underlying theme is the inherent assumption that cyclic loading always degrades the response of the pile (e.g. stiffness, capacity). There is, however, very limited evidence in support of this assertion, particularly for dense sands and stiff glacial clays. The PICASO project addresses these shortcomings through various work packages, described as follows.

2.1 Advanced Modelling

The PISA design model (e.g. Byrne, 2020) enabled the calibration of 1D models for monotonic laterally loaded monopiles using soil reaction curves from detailed 3D finite element analyses. Normalisation and parameterisation of the numerical soil reaction curve data across a defined parameter space (e.g., soil and foundation properties), adapts the models to site-specific conditions. This process enables rapid calculations of a monopile's monotonic response.

The PICASO project introduces a new data-driven model for monopile foundations. This retains the PISA 1D FE framework but employs machine learning (ML) models to derive soil reaction curves directly from a database generated by completed 3D FE analyses, avoiding traditional rule-based methods. The soil reaction These curves are modelled with high-fidelity piecewise spline functions that represent various shapes, including non-linear behaviours and softening effects. Additionally, the ML models capture depth-dependent variations in soil reaction curve parameters with high precision, enabling accurate calculations without relying on complex optimisation stages. The key stages in developing the data-driven model (e.g. Kamas, 2024) are summarised in Figure 1. The data-driven model is highly scalable and applicable to a wide range of soil types, similar to the PISA design models. However, it also accommodates more complex scenarios, such as calibration for layered soil profiles (e.g. Kamas *et al.*, 2025), where direct calibration is feasible, and chalk sites, which require detailed consideration of installation processes (e.g. Kamas, 2024). A formal feature selection process ensures efficient and reliable input features for training the ML models, making this approach a practical and versatile alternative to the PISA design model for complex geotechnical challenges.

2.2 Laboratory Testing

Element-scale testing has been conducted on materials from the Cowden clay and Cuxhaven sand test sites to support medium-scale field testing. The tests aimed to provide calibration data for soil constitutive models adopted in numerical calculations. Bender element and resonant column tests were carried out to determine small-strain stiffness, threshold shear strains, and degradation parameters, as a part of the characterisation of the elastic soil behaviour. Triaxial and direct simple shear tests were also performed to examine medium-to-large strain soil behaviour and derive intrinsic geotechnical properties of the material.

In addition to the calibration for numerical models, a comprehensive cyclic loading element testing campaign was undertaken for both materials using the variable dynamic direct cyclic simple shear apparatus. Monotonic tests were conducted to provide normalisation data for the cyclic loading behaviour. Key phenomena studied include ratcheting behaviour, defined as incremental strain accumulation under

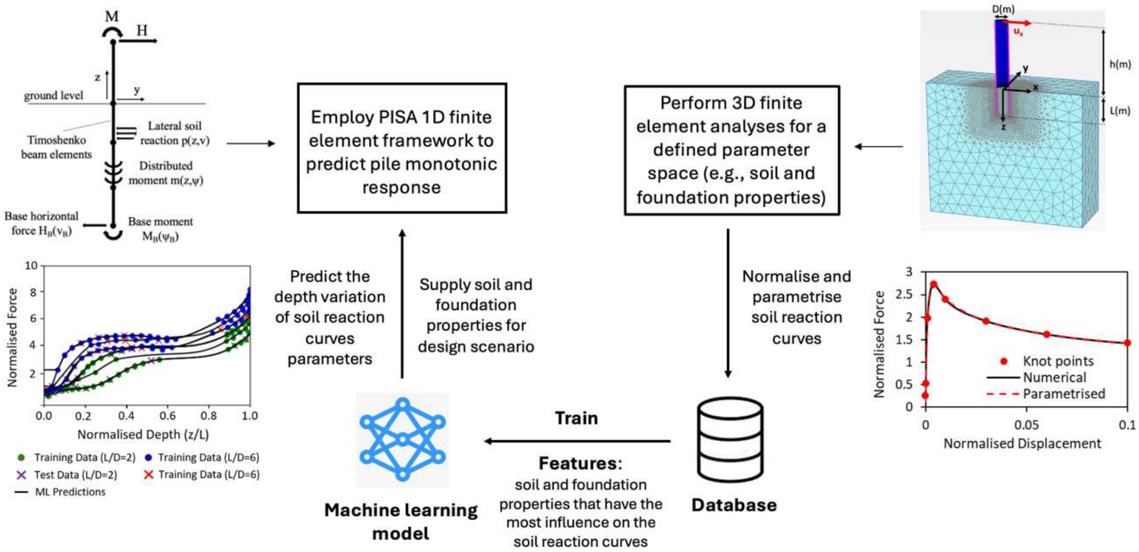

Figure 1: Illustration of the key stages involved in developing a data-driven model for predicting the monotonic response of laterally loaded monopile foundations. The data-driven model computes the pile's backbone curve and associated soil reaction curves, which can be used to calibrate the parameters of the 0D and 1D formulations of HARM (Hyperplastic Accelerated Ratcheting Model), as presented in Section 2.3.2.

cyclic loading; the soil's cyclic response, characterised by stiffness reduction in clay; and cyclic improvement, observed as densification and stiffness enhancement in sand. These aspects are critical for understanding and modelling soil response under cyclic loading in offshore environments.

The testing program also investigated the effects of cyclic loading amplitude, ζ_b, loading asymmetry, ζ_c (Leblanc *et al.*, 2010) and multidirectional loading, replicating complex offshore loading scenarios. These results contribute to the development of cyclic contour diagrams, an approach adopted for integrating cyclic effects into foundation design frameworks. Such diagrams are typically represented on a graphical plane, shown in Figure 2. Additionally, for Cuxhaven sand, the influence of drainage conditions on cyclic behaviour was evaluated to develop current understanding of the mechanisms that influence cyclic soil behaviour under the limiting drained and undrained conditions. Outcomes from the multi-directional loading tests on Cowden clay and Cuxhaven sand are set out in Qiu *et al.* (2023), Qiu (2023), Wen *et al.* (2025) and Wen (2025).

Laboratory floor (1g) model scale testing, using the equipment in Figure 3, has been carried out in both clay and dry sand by Wu (2022) and dry and saturated sands by Keane and Byrne (2023, 2025), extending previous work by Leblanc et al. (2010), Abadie (2015) and Richards (2019). Pile movement, during cyclic lateral loading, is monitored through three linear displacement transducers (LDTs). Loading can be applied through two linear roller-screw actuators which can be adjusted to different eccentricities above ground-level. The equipment is controlled using National Instruments hardware and LabVIEW software.

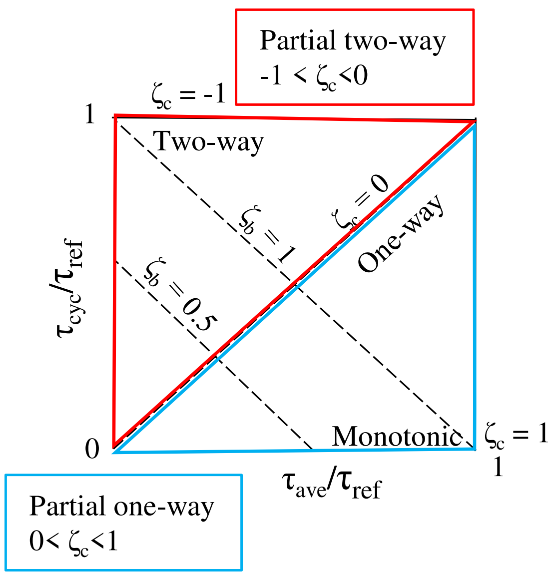

Figure 2: Graphical representation of cyclic amplitude and asymmetry.

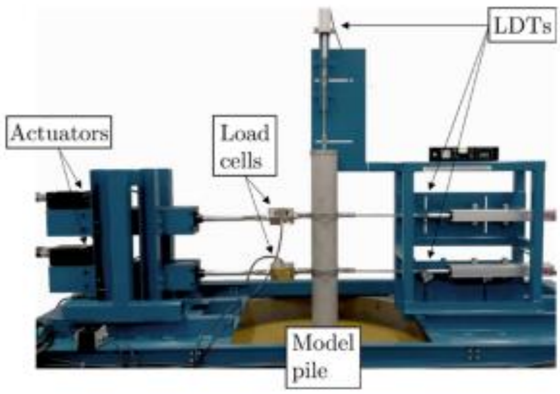

Figure 3: Experimental apparatus, Wu et al., 2020.

Wu (2022) employed the loading rig (Figure 3), in situ, at the Cowden site, to test the glacial stiff clay tills, focusing on rate effects (monotonic and cyclic loading), varied load eccentricity and different unidirectional load amplitudes. Keane and Byrne (2023, 2025) described monopile tests in dry and saturated sands, with the latter requiring careful consideration of scaling for drainage, through modification of the viscosity of the pore fluid, the particle size of the model soil, and the size of the model pile. Rate effects are characterised for both monotonic and cyclic loading, demonstrating that monotonic capacity enhancement for piles in dense sands is likely.

Separately, Malhotra and Byrne (2023) have developed new laboratory equipment to explore the accumulated displacement response of scale model pile segments to cyclic loading, under a variety of vertical stresses, as a means of calibrating design models for site specific soil conditions.

2.3 Theoretical Developments

Theoretical work has focused on development of models to predict the monotonic and cyclic response of monopiles under lateral loading. The project has adopted three-dimensional 3DFE methods and simplified approaches, encompassing both macro-element models (0D) and beam models (1D).

2.3.1 3D Modelling

The 3DFE approach was used in PICASO for two objectives: (a) to predict monopile responses by capturing the complex soil-pile interaction effects, and (b) to estimate the monotonic backbone curve for integration into the cyclic loading modelling framework being developed through PICASO. The choice of the (non-linear) soil constitutive model is central to accurate FE modelling. For monotonic behaviour, the HSsmall model (Hardening Soil model with small-strain stiffness) (Benz, 2007) was employed. This model is formulated within elasto-

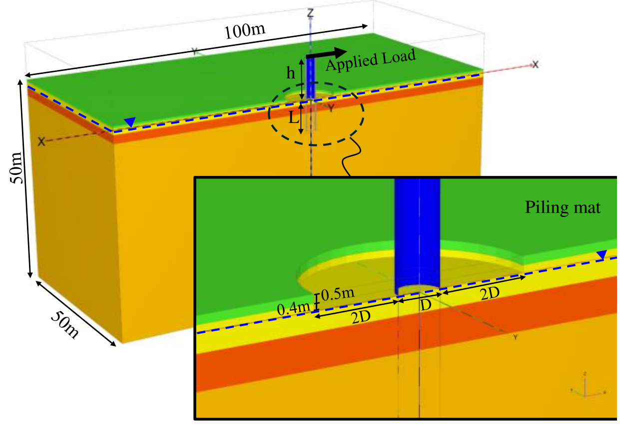

Figure 4: 3DFE model for test pile at Cuxhaven

plasticity theory adopting isotropic hardening to simulate soil behaviour from loose to dense states and soil yielding under deviatoric and compressive loading with its yield surfaces. Additionally, it captures nonlinear behaviour in triaxial states, soil stiffness stress dependency, and soil dilation under shearing.

For modelling the testing at the sand site, the HSsmall model was used to represent separate sand layers with variable relative densities. The test piles with differing geometries were simulated, allowing force-displacement relationships at a range of ground displacements to be determined.

Additionally, PICASO has seen the development of HySand, a new effective stress constitutive model for monotonic and cyclic loading of sand soils. The model is formulated within the hyperplasticity framework, a plasticity theory that rigorously obeys thermodynamic principles. The constitutive behaviour is derived entirely from two scalar potentials: the Gibbs energy function (g), which represents the system's stored energy (expressed in terms of stresses and internal variables), and the yield surface (y). HySand is formulated as a multi-surface model with N yield surfaces and non-associative plasticity, enabling it to simulate sand behaviour across varying densities and confinement pressures under both monotonic and cyclic, drained and undrained conditions using a single set of model parameters. Detailed formulations of the model in triaxial and generalized stress spaces are discussed in Simonin (2023).

Within the PICASO project, HySand was validated against a wide range of triaxial tests on different sands. Following this validation, it has been implemented as a user-subroutine in FE codes ABAQUS and PLAXIS 3D. HySand is now being applied to 3D simulations of monopiles for OWT foundations, capturing various loading scenarios under drained and partially drained conditions to support design processes (see Saberi *et al.*, 2025). Figure 4 illustrates the FE model and simulated geometry of a representative pile case.

2.3.2 0D and 1D Modelling

For 0D and 1D modelling the PICASO project focuses on augmenting the PISA design model with a new approach to cyclic loading, HARM, the Hyperplastic Accelerated Ratcheting Model (Houlsby *et al.*, 2017). In essence the PISA approach provides the underlying monotonic backbone curve, and HARM facilitates the computation of the cyclic loading effects. Formulated as an incremental model it allows computation of the response to pseudo-random loading sequences, including multi-directional effects. The model was used to provide predictions in advance of the field testing, to further calibrate parameters using the results, and to validate a new monopile cyclic loading design process with HARM at its core.

The research has identified that central to the cyclic loading response is an accurate calculation for the monotonic backbone behaviour. The accumulation of displacement and rotation (i.e. ratcheting) was found to be important during cycling with a non-zero mean load. An initial calibration process for the ratcheting function is based on the sinusoidal cyclic load tests from both PICASO sites, informed by similar model and field tests previously carried out by the University of Oxford (including Leblanc *et al.*, 2010, Abadie *et al.*, 2019, Richards *et al.*, 2019, McAdam *et al.*, 2024). These test results were characterised using the methodology proposed by LeBlanc *et al.* (2010), indicating that some properties were insensitive to the different soil conditions.

The methodology developed allowed efficient calibration of the 0D model through directly linking the characterisation parameters with those in the ratcheting function (Crispin *et al.* 2025). A further procedure is under development for obtaining cyclic soil reaction curves that, when employed in a 1D beam model, result in the same pile head response. The pseudo-random storm load tests have been used to validate the calibrated model, which performed well for both the unidirectional and multi-directional tests.

2.4 Medium Scale Field Testing

The medium-scale field testing was carried out at two different sites, specifically selected to be representative of two main geological conditions found in the North Sea. The first of the two campaigns was carried out at Cowden, UK, where the soil profile consisted of clay of the Bolders Bank formation (Martin *et al.*, 2023). The location was close to the PISA site, so the PICASO site was characterised by similar geological conditions. The second campaign was undertaken at Cuxhaven, Germany, where the ground conditions consisted of silica sand within the testing depth (Byrne *et al.*, 2025).

Figure 5: View of PICASO sand site during the test P06.

A total of 24 pile tests were performed across the two testing programs, 12 at each site, including 9 medium diameter piles (D = 1.22 m) and 3 large diameter piles (D = 2.5 m). The pile sizes were different to those for PISA to facilitate development of scaling relationships. Embedment ratios L/D = 3 and load eccentricities of $e = 4D$ were constant for all tests. A significant amount of instrumentation was used during the pile tests, including linear displacement transducers (LDTs), load cells, stick-up inclinometers (SUIs), in-place inclinometers (IPIs) and fibre-optic strain and temperature gauges (FBGs). Vibrating-wire piezometers (VWPs) were installed at selected pile-testing locations (4 at Cowden and 3 at Cuxhaven) to monitor the variations of pore-water pressure during the tests. The original site surfaces at both sites were excavated to the water table, to ensure the test soils remained fully saturated. Figure 5 shows the Cuxhaven site during pile test pile P06.

The loading routines applied at the two sites cover monotonic loading, rate effects, uniform sinusoidal cyclic loading (calibration tests) and pseudo-random cyclic loading (validation tests). The pseudo-random patterns adopted simulate real load cases for an offshore turbine under various combinations of operational and environmental conditions. The cyclic phases chosen imposed a variety of amplitudes (chosen by reference to the monotonic capacity), frequencies and different biases in the directions of loading. Multi-directional random cyclic loading tests were performed to check the impact of orthogonal loads reminiscent of the wave and wind loads experienced offshore. A focus of the testing at high load magnitude was to assess the impact of cycling on the ultimate monotonic capacity. Reproducibility of the test results was evaluated by carrying out tests with identical load sequences and pile dimensions. Figure 6 shows data from Cowden and Cuxhaven, where the hysteresis loops and ratcheting are tracked as a function of continuous, medium severity, uni-directional sinusoidal one-way cyclic loading.

2.5 Application to Design

The PICASO project has focused on two typical offshore soils, to ensure the results are relevant to current wind farm design. Further work is underway to apply the key outcomes of the project to current design scenarios, as well as assessing approaches to generalise the design method to a wider range of soils. The results of this work will be elaborated in due course.

3 CONCLUSIONS

This paper describes the development of a new design method for cyclic loading through the PICASO project, bringing together the results of the PISA project and the new Hyperplastic Accelerated Ratcheting Model (HARM). An overview is provided

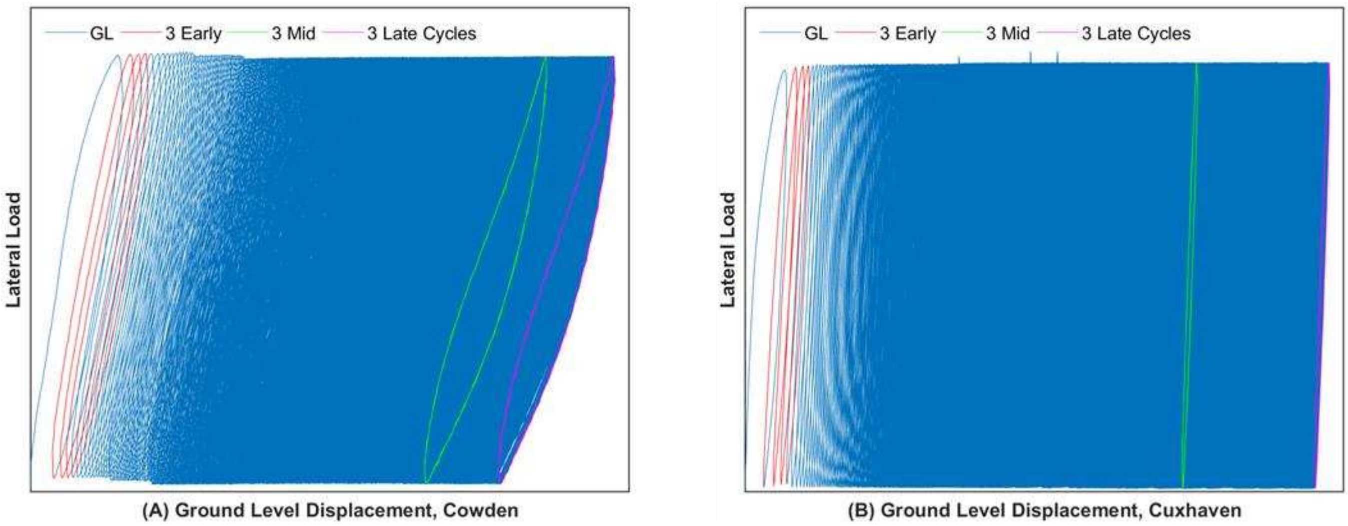

Figure 6: Lateral load vs ground level pile displacement (GL) at the two sites for unidirectional sinusoidal one-way loading. (A) 4720 cycles of medium severity at the Cowden site, figure reformatted from Martin et al. (2023). (B) 4002 cycles of medium severity at the Cuxhaven site, figure from (Byrne et al., 2025).

for each of the five work packages, highlighting important new developments that have been achieved, and signposting interested readers to recent work.

AUTHOR CONTRIBUTION STATEMENT

Byrne: Conceptualisation, Supervision, Methodology, Reviewing. **Crispin, Kamas, Keane, Nardelli, Saberi, Rasmussen & Wen:** Data curation, Formal Analysis, Writing - Original draft. **Shonberg, Soares Cunha & Vaitkune**: Resources. **All Authors**: Investigation.

ACKNOWLEDGEMENTS

The authors acknowledge the support of Ørsted in the funding for the PICASO project. The authors also acknowledge Socotec as the testing contractor for the pile testing programme. Byrne is supported by the Royal Academy of Engineering under the Research Chairs and Senior Research Fellowships scheme.

REFERENCES

Abadie, C. N. (2015). *Cyclic lateral loading of monopile foundations in cohesionless soils*. DPhil Thesis, University of Oxford.

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.

Benz, T. (2007). *Small-strain stiffness of soils and its numerical consequences*. Ph.D. thesis, University of Stuttgart, Germany.

Byrne, B.W. (2020). Editorial: Geotechnical design for offshore wind turbine monopiles. *Géotechnique*, 70(11): 943–944.

Byrne, B.W., Burd, H.J., Houlsby, G.T., *et al.* (2025). Cyclic loading of monopiles at a saturated dense sand site in Germany. *Proceedings of ISFOG 2025*, Nantes, France.

Byrne, B.W., McAdam, R.A., Burd, H.J., *et al.* (2020). Monotonic laterally loaded pile testing in a stiff glacial clay till at Cowden. *Géotechnique* 70(11): 970-985.

Crispin, J.J., Houlsby, G.T., Burd, H.J. and Byrne, B.W. (2025). An improved ratcheting function for the Hyperplastic Accelerated Ratcheting Model (HARM). *Proceedings of ISFOG 2025*, Nantes, France.

Houlsby, G.T., Abadie, C.N., Beuckelaers, W.J.A.P. and Byrne, B.W. (2017). A model for nonlinear hysteretic and ratcheting behaviour. *International Journal of Solids and Structures*, 120: 67–80.

Kamas, I. (2024). *Generalised methods for the development of 1D models of monopiles for monotonic lateral loading*. DPhil Thesis, University of Oxford.

Kamas, I., Burd, H.J. and Byrne, B.W. (2025). Comparison of machine learning models in a data-driven method for design of laterally loaded monopiles embedded in layered clay sites. *Proceedings of ISFOG 2025*, Nantes, France.

Keane R. and Byrne, B.W. (2025). Rate effects of model monopiles in saturated sands. *Proceedings of ISFOG 2025*, Nantes, France.

Keane, R. and Byrne, B.W. (2023). Cyclic lateral loading of model monopiles in dry and saturated sands. *Proceedings 9th International SUT OSIG Conference*, London, UK. doi.org/10.3723/SJPN3553

LeBlanc, C., Houlsby, G.T. and Byrne, B.W. (2010). Response of stiff piles in sand to long-term cyclic lateral loading. *Géotechnique*, 60(2): 79–90.

Malhotra, S. and Byrne, B.W. (2023). A novel apparatus for lateral load testing miniature pile segments. *Proceedings of the 9th International SUT OSIG Conference*, London, UK. doi.org/10.3723/PABF5421

Martin, S.C., Buckley, R.M., McAdam, R.A., *et al.* (2023). Medium-scale field testing of laterally loaded monopiles in glacial till at Cowden. *Proceedings of the 9th International SUT OSIG Conference*, London, UK. doi.org/10.3723/PKFE5118

McAdam, R.A., Buckley, R.M., Schranz, F., *et al.* (2024). Monotonic and cyclic lateral loading of piles in low- to medium-density chalk. *Géotechnique*, Ahead of Print, doi:10.1680/jgeot.23.00484.

Qiu, Z. (2023). *Cyclic simple shear behaviour of Cowden till*. DPhil Thesis, University of Oxford.

Qiu, Z., Byrne, B. W. and Martin, C. M. (2023). Multi-directional cyclic simple shear testing of an overconsolidated glacial till. *Proceedings of the 9th International SUT OSIG Conference*, London, UK. doi.org/10.3723/DCFN5831

Richards, I. A. (2019). *Monopile foundations under complex cyclic lateral loading*. DPhil Thesis, University of Oxford.

Richards, I.A., Byrne, B.W. and Houlsby, G.T. (2020). Monopile rotation under complex cyclic lateral loading in sand. *Géotechnique*, 70(10): 916–930.

Saberi, M., Simonin, L., Houlsby, G.T. and Byrne, B.W. (2025). Three dimensional finite element simulation of monopiles for offshore wind turbines using the HySand constitutive model. *Proceedings of ISFOG 2025*, Nantes, France.

Simonin, L. (2023). *Development of an effective stress model for sand under cyclic loading in the hyperplastic framework*. DPhil thesis, University of Oxford.

Wen K. Z. (2024): *Mechanical behaviour of cohesionless soils: Implication for offshore foundations design*. DPhil Thesis, University of Oxford.

Wen, K. Z., Buckley, R. M. and Byrne, B. W. (2025). Multidirectional perpendicular cyclic behaviour of a marine sand in drained and undrained conditions. *Proceedings of ISFOG 2025*, Nantes, France.

Wu, K.-W. (2022). *Rate Effects for Monopile Foundations*. DPhil Thesis, University of Oxford.

Wu, K.-W., et al. (2020). Investigation of rate effects for monopile foundations: laboratory-scale model tests. *Proceedings of ISFOG 2020*, Austin, Texas.