Deformation mechanisms of monopiles under long-term unbalanced cyclic lateral loads

L.L.K. Hung-Lo-Sang, J. Wang
University of Nottingham Ningbo China, Ningbo, China,
liam.hunglosang@nottingham.edu.cn, juan.wang@nottingham.edu.cn

C.M. Heron, A. Pettey
University of Nottingham, Nottingham, UK,
charles.heron@nottingham.ac.uk, angus.pettey1@nottingham.ac.uk

A.M. Marshall
Formerly, University of Nottingham, Nottingham, UK

ABSTRACT: Monopiles are widely used as foundations for offshore wind turbines but are subjected to long-term cyclic lateral loading from wind and waves, which may lead to progressive displacement and stiffness degradation. Understanding the soil–pile interaction mechanisms governing this behaviour is critical for reliable serviceability design. This study investigates the deformation mechanisms of monopiles in sand subjected to unbalanced cyclic lateral loading using 1-g model testing. The results show soil flow patterns and shifts in earth pressure around the pile for different loading magnitudes, with a critical loading threshold ratio observed to influence the pile displacement and accumulation rates. Soil pressure measurements reveal characteristic depth-dependent pressure distributions, reflecting the evolving soil–pile interaction during cyclic loading. These findings provide new insights into the mechanisms governing monopile behaviour under cyclic loads and contribute to improving the long-term performance assessment of offshore wind applications.

1 INTRODUCTION

Monopiles are the most widely used foundation solution for offshore wind turbines due to their structural simplicity and cost-effectiveness. During their service life, these foundations are subjected to lateral cyclic loads from wind, waves, and tides. They face long-term serviceability challenges governed primarily by cumulative lateral displacement and stiffness degradation, rather than ultimate capacity. The *p-y* design model describes how the lateral soil resistance *p* changes as the monopile displaces laterally by *y* at a given depth *z*. State-of-the-art design approaches typically adopt monotonic soil–pile interaction models with empirical stiffness reduction for cyclic effects, such as API/DNV p–y curves or PISA-calibrated springs (API, 2014, DNVGL, 2016, Burd et al., 2020). *p-y* models do not explicitly capture long-term cyclic deformation mechanisms and may require conservative design margins when estimating serviceability over millions of cycles. This study addresses these gaps by experimentally investigating the cyclic lateral deformation mechanisms of monopiles through 1-g physical model testing. A two-stage methodology is employed to highlight contrasting deformation mechanisms, cyclic degradation patterns, and soil–structure interaction processes that govern long-term performance. The research problem is illustrated in Figure 1.

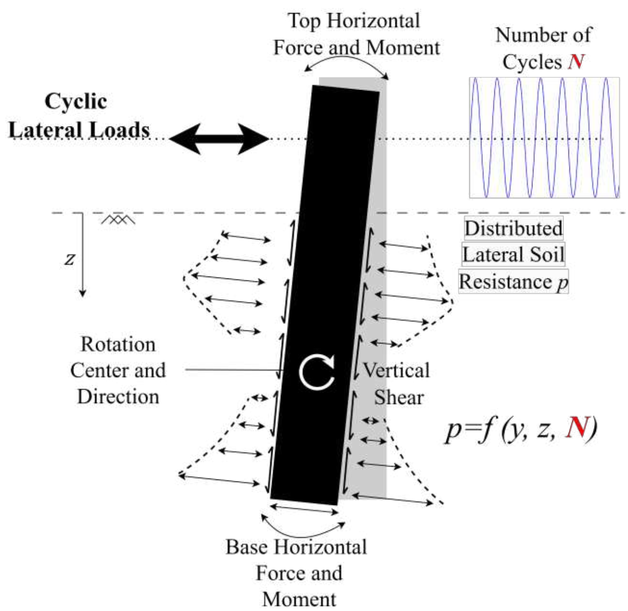

Figure 1. Illustration of the research gap: current p–y models do not account for monopile behaviour under a high number of cycles N

2 LATERAL LOADS ON MONOPILE FOUNDATIONS IN SAND

Existing laboratory and field research have revealed that cyclic lateral loads induce soil densification, depending on density and confining pressure, with corresponding effects on secant stiffness and foundation rotation (Byrne et al., 2010, Cuéllar et al., 2012, Klinkvort and Hededal, 2013, Kirkwood and Haigh, 2014, Abadie et al., 2019). However, most studies focus either on short-term cyclic behaviour with limited cycle counts ranging from a few hundred to a few thousand, or on the lateral response of monopiles, rather than on the causes of these responses. In these studies, lateral loads are characterised by ratios called loading magnitude (ζ_b) and symmetry (ζ_c), shown in Equations 1 and 2 (Leblanc et al., 2010).

$$\zeta_b = H_{max}/H_{ult} \quad (1)$$

$$\zeta_c = H_{min}/H_{max} \quad (2)$$

where H_{max} (N) and H_{min} (N) are the maximum and minimum peak loads within one cycle, whereas H_{ult} (N) is the ultimate monotonic lateral capacity of the monopile.

Critically, the combined influence of the loading characteristics on soil flow mechanisms, active/passive pressure redistribution, and shakedown thresholds remains insufficiently characterised for monopile design. Studies ranging from 1-g testing, centrifuge testing, and numerical simulations show that one-way loading (ζ_c=0) causes moderate pile displacement accumulation, but the greatest change in secant stiffness (Lin and Liao, 1999, Li et al., 2015, Qin and Guo, 2016, Abadie et al., 2019, Achmus et al., 2019, Cheng et al., 2020, Thangavel and Rathod, 2024). However, two-way unbalanced loading (0<ζ_c<-1), especially around $\zeta_c \approx$ -0.6, caused the highest pile displacement accumulation with moderate change in secant stiffness. In contrast, two-way balanced (ζ_c=-1) loading caused small pile displacement accumulation and change in secant stiffness (Byrne et al., 2010, Nicolai et al., 2017, Frick and Achmus, 2020). This study, therefore, focuses on unbalanced loading, which results in the greatest accumulation of pile displacement.

3 METHODOLOGY

3.1 Experimental setup

Lateral cyclic loads were applied to the pile using a servo-actuated system with closed-loop force control to reproduce prescribed load histories. The monopile was instrumented with miniature pressure sensors along the embedded depth. The sensors were calibrated and used to directly measure soil pressure acting on the monopile. Post-test digital image correlation using GeoPIV-RG was undertaken to track soil deformation. The tests were carried out in two groups, full-model and half-model testing, with the model split in half for the latter, as shown in Figure 2.

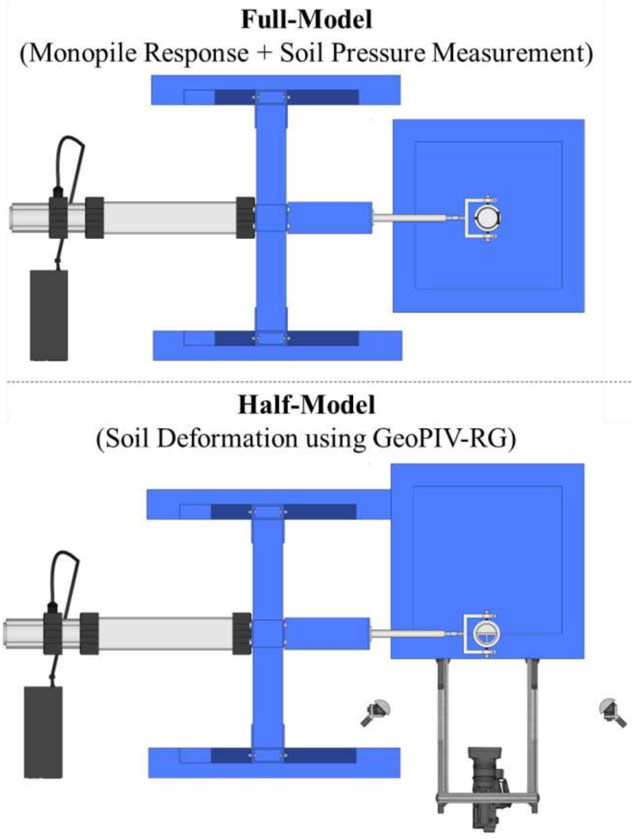

Figure 2. Loading rig configurations

3.2 Monopile properties

The monopile considered was a rigid model with a geometric scale ratio of 1:50. The prototype has a diameter of 4 m, a wall thickness of 180 mm, an embedment depth of 18 m, and a loading eccentricity of 21.5 m. The model rigidity was matched with the prototype using the pile relative stiffness (K_{rs}) proposed by Poulos (1971) and shown in Equation 3. The monopile properties are detailed in Table 1.

$$K_{rs} = E_p I_P / E_s L_{em}^4 \quad (3)$$

where E_p (MPa) is the Young's modulus of the pile, I_p (m^4) is the moment of inertia of the pile section, E_s (MPa) is the Young's modulus of the soil and L_{em} (m) is the embedded pile length.

Table 1. Monopile properties

Property		Prototype	1-g Model
Type		Rigid	
Ratio		1	50
Diameter	D	4 m	80 mm
Wall thickness	t	180 mm	7 mm
Embedment depth	L_{em}	18 m	360 mm
Load eccentricity	e	21.5 m	430 mm
Slenderness ratio	L_{em}/D	4.5	
Eccentricity ratio	e/L_{em}	1.19	
Material	-	Steel	AL6061
Relative stiffness	K_{rs}	0.158	0.177

3.3 Sand properties and sample preparation

The sand used in the experiments was clean, dry, and poorly graded silica sand. Sand was poured around the monopile using an automated air pluviation device described in Hung-Lo-Sang et al. (2026). The pile was installed under wish-in-place conditions to avoid installation effects. The sand was prepared in a loose state, which is necessary in 1-g testing conditions to account for relative dilatancy effects (Bolton, 1986). The ratio of the pile diameter and mean particle size (D/D_{50}) is 160, well above the value recommended by Nunez et al. (1988) of 44 and Remaud (1999) of 60 to avoid grain-size effects. The sand properties are tabulated in Table 2.

Table 2. Sand properties

Property	Specification	
Sand Name	Henan Sand	
Relative density	26.7	%
ϕ'_{cr}	36.5	Degrees
D_{10}, D_{50}, D_{60}	0.43, 0.50, 0.56	mm
Coefficient of uniformity	1.30	-
e_{min}	0.729	-
e_{max}	1.054	-
G_s	2.65	-

3.4 Test schedule

6 tests, grouped as three pairs, were conducted in this study. Unbalanced loads with ζ_c=-0.5 at different load magnitudes were applied to the monopile for 20,000 cycles (N). The test schedule is provided in Table 3.

Table 3. Cyclic tests schedule

Test No.	Test	ζ_b	ζ_c	N
1	MPLS-F/H-MC1	0.25	-0.5	20000
2	MPLS-F/H-MC2	0.40	-0.5	20000
3	MPLS-F/H-MC3	0.55	-0.5	20000

4 RESULTS

The results demonstrate that the monopile's response to unbalanced cyclic loading is governed by the progressive mobilisation and redistribution of soil resistance along pile depth.

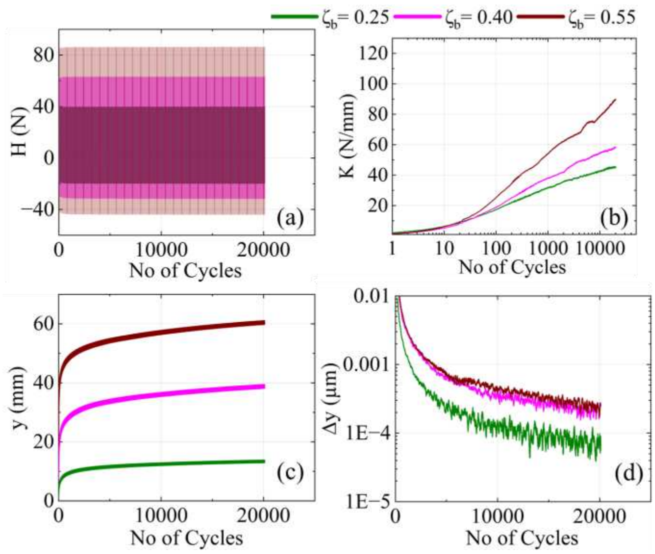

Figure 3. Monopile response under unbalanced loading of varying load magnitudes (a). load regimes, (b). stiffness evolution, (c). pile-head displacement, (d). pile-head displacement accumulation rate Vs. number of cycles

Figure 3(a) shows the load histories throughout the tests. Figure 3(b) shows that the lateral stiffness increases with the number of cycles when the applied load amplitude is kept constant throughout the tests, indicating that the soil–pile system undergoes cyclic stabilisation rather than progressive degradation. This behaviour is consistent with dilatant response under cyclic shear, where repeated loading leads to particle rearrangement and local densification, thereby increasing the effective stiffness of the surrounding soil. Figure 3(c) shows a rapid accumulation of pile head displacement during the initial cycles, followed by a gradual reduction in incremental displacement, further supporting this mechanism. Figure 3(d) shows stabilisation of displacement accumulation at higher numbers of cycles, suggesting that the soil–pile system reaches a quasi-steady state with noticeably lower accumulation at a load magnitude of ζ_b=0.25.

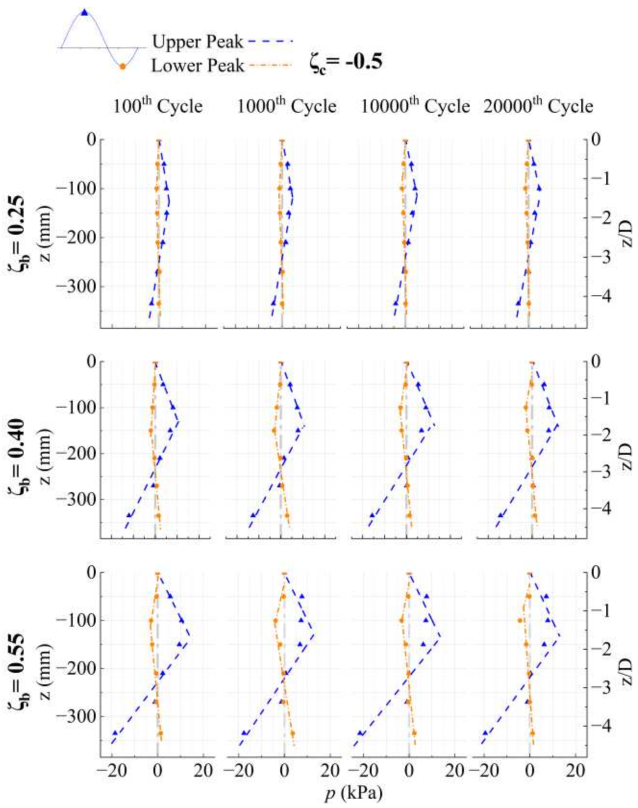

Figure 4. Soil pressure distribution at different load cycles under varying load magnitudes of unbalanced cyclic lateral loading

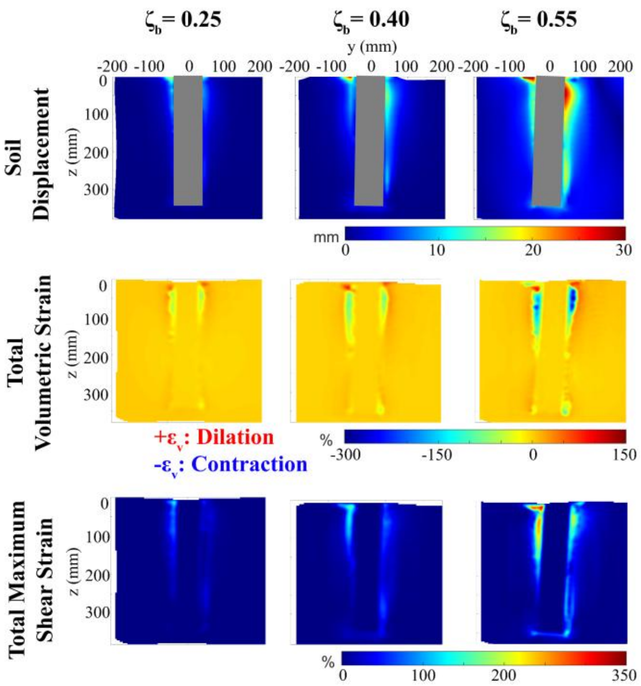

Figure 5. GeoPIV-RG plots at the 20,000th cycle under varying load magnitudes of unbalanced cyclic lateral loading

The soil pressure and displacement fields shown in Figures 4 and 5 provide further insight into the mechanisms controlling the observed response. Under unbalanced loading conditions, the soil reaction becomes highly asymmetric, with passive resistance progressively mobilised in front of the monopile while the active side remains relatively weak. A higher load magnitude significantly enlarges the zone of soil deformation and promotes the development of localised shear zones that extend deeper along the pile shaft. The volumetric strain fields indicate dilation on the passive side and contraction on the active side, highlighting the importance of cyclic shear-induced volumetric changes in governing the evolution of soil resistance. As the load magnitude increases, both the magnitude and depth of mobilised soil reaction increase, suggesting that a larger volume of soil contributes to resisting the applied loads. These observations emphasise that, under unbalanced cyclic loading, monopile performance is strongly controlled by the progressive development of asymmetric soil resistance and localised deformation patterns in the surrounding sand.

5 DISCUSSION AND CONCLUSIONS

The unbalanced cyclic lateral tests show a clear transition in monopile–soil behaviour with load level that can be interpreted using shakedown theory (Melan, 1938, Koiter, 1960). At low load ratio (ζ_b=0.25), pile head displacement accumulates mainly during early cycles and then stabilises, while stiffness increases and asymptotes. Soil pressure profiles exhibit shallow passive build-up with little evolution beyond 1000 cycles, and the GeoPIV fields show only localised deformation and limited shear. At intermediate load level (ζ_b=0.40), stabilisation occurs later, with larger accumulated displacement, continued stiffness evolution, and deeper passive wedge development. Although displacement appears stabilised, soil mobilisation is more extensive, with continuous accumulation of displacement, consistent with behaviour near the shakedown limit. According to Melan (1938), above the limit, the structure would continuously ratchet until failure. This regime is serviceability-critical for offshore foundations because long-term tilt may approach operational limits even without ultimate failure. At high load level (ζ_b=0.55), displacement accumulates continuously, stiffness does not stabilise, passive and active pressures keep redistributing, and deep shear bands form. This corresponds to incremental collapse or ratcheting failure, indicating that the soil–pile system does not self-stabilise under continued cycling.

From an engineering perspective, these findings reinforce that monopile performance under cyclic lateral loading is governed not only by monotonic capacity but also by long-term displacement accumulation and stiffness evolution.

6 FUTURE WORK

The present study forms part of a wider research programme investigating monopile foundations under long-term lateral cyclic loads in sand using physical modelling techniques. The programme covers a range of loading characteristics. It also includes some centrifuge tests to capture soil-structure interactions under realistic stress conditions, identify scale-dependent behaviours, and complement the 1-g tests.

7 ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by the Zhejiang Natural Science Foundation (LY22E080018). The first author appreciates the full scholarship offered by the Faculty of Science and Engineering at the University of Nottingham Ningbo China (2305HFB).

REFERENCES

Abadie, C. N., Byrne, B. W. and Houlsby, G. T. (2019). Rigid pile response to cyclic lateral loading: laboratory tests. Géotechnique, 69, 863-876. https://doi.org/10.1680/jgeot.16.P.325

Achmus, M., Thieken, K., Saathoff, J.-E., Terceros, M. and Albiker, J. (2019). Un- and reloading stiffness of monopile foundations in sand. Applied Ocean Research, 84, 62-73. https://doi.org/10.1016/j.apor.2019.01.001

API. (2014). Recommended practice for planning, designing, and constructing fixed offshore platforms - Working Stress Design - API RP 2A-WSD. American Petroleum Institute Standards, 22nd Edition,

Bolton, M. (1986). The strength and dilatancy of sands. Geotechnique, 36, 65-78. https://doi.org/10.1680/geot.1986.36.1.65

Burd, H. J., Taborda, D. M. G., Zdravković, L., Abadie, C. N., Byrne, B. W., Houlsby, G. T., Gavin, K. G., Igoe, D. J. P., Jardine, R. J., Martin, C. M., McAdam, R. A., Pedro, A. M. G. and Potts, D. M. (2020). PISA design model for monopiles for offshore wind turbines: application to a marine sand. Géotechnique, 70, 1048-1066. https://doi.org/10.1680/jgeot.18.P.277

Byrne, B., Leblanc, C. and Houlsby, G. (2010). Response of stiff piles to long term cyclic loading. Geotechnique, 60, 79-90. https://doi.org/10.1680/geot.7.00196

Cheng, K., Heron, C., Prendergast, L. and Marshall, A. 2020. *Centrifuge tests of monopile foundations under one-way cyclic lateral loading*.

Cuéllar, P., Georgi, S., Baeßler, M. and Rücker, W. (2012). On the quasi-static granular convective flow and sand densification around pile foundations under cyclic lateral loading. Granular Matter, 14, 11-25. https://doi.org/10.1007/s10035-011-0305-0

DNVGL. (2016). DNVGL-ST-0427: Design of offshore wind turbine structures. DNVGL Standards,

Frick, D. and Achmus, M. (2020). An experimental study on the parameters affecting the cyclic lateral response of monopiles for offshore wind turbines in sand. Soils and Foundations, 60, 1570-1587. https://doi.org/10.1016/j.sandf.2020.10.004

Hung-Lo-Sang, L. L. K., Wang, J., Heron, C. M., Pettey, A. and Marshall, A. M. (2026). An automatic sand pourer for the preparation of loose and dense samples for physical modelling. *Proceedings of the 11th International Conference on Physical Modelling in Geotechnics (ICPMG 2026).* Zurich, Switzerland.

Kirkwood, P. and Haigh, S. 2014. *Centrifuge testing of monopiles subject to cyclic lateral loading*. https://doi.org/10.1016/S1350-4789(14)70093-5

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, 147-158. https://doi.org/10.1680/geng.12.00033

Koiter, W. T. 1960. *General theorems for elasto-plastic solids*, North Holland Publishing Co.

Leblanc, C., Byrne, B. W. and Houlsby, G. T. (2010). Response of stiff piles to random two-way lateral loading. Géotechnique, 60, 715-721. https://doi.org/10.1680/geot.09.T.011

Li, W., Igoe, D. and Gavin, K. (2015). Field tests to investigate the cyclic response of monopiles in sand. Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, 168, 407-421. https://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. Journal of Geotechnical and Geoenvironmental Engineering - J GEOTECH GEOENVIRON ENG, 125, https://doi.org/10.1061/(ASCE)1090-0241(1999)125:9(798)

Melan, E. (1938). Der spannungszustand eines hencky-Mises schen kontinuums bei verandlicher belastung. The stress state of a Hencky-Mises continuum under variable load (in German). Sitzungsberichte der Akedemie Wissenschaften Wien, Vol. 147, p. 73.

Nicolai, G., Ibsen, L. B., O'Loughlin, C. D. and White, D. J. (2017). Quantifying the increase in lateral capacity of monopiles in sand due to cyclic loading. Géotechnique Letters, 7, 245-252. https://doi.org/10.1680/jgele.16.00187

Nunez, I., Hoadley, P., Randolph, M. and Hulett, J. Driving and tension loading of piles in sand on a centrifuge. Centrifuge, 1988. 353-362.

Poulos, H. G. (1971). Behavior of Laterally Loaded Piles: I-Single Piles. Journal of the Soil Mechanics and Foundations Division, 97, 711-731. https://doi.org/10.1061/JSFEAQ.0001592

Qin, H. and Guo, W. D. (2016). Response of static and cyclic laterally loaded rigid piles in sand. Marine

Georesources & Geotechnology, 34, 138-153. https://doi.org/10.1080/1064119X.2014.979961

Remaud, D. 1999. *Pieux sous charges latérales: étude expérimentale de l'effet de groupe. Piles under lateral loads: experimental study of the group effect (in French).* Ecole Doctorale Sciences pour l'Ingenieur de Nantes; Centrale Nantes. https://doi.org/10.5150/jngcgc.1998.038-R

Thangavel, J. and Rathod, D. (2024). Behaviour of a Laterally Loaded Rigid Pile Subjected to One-Way Cyclic Loading. Geotechnical and Geological Engineering, 42, 1-21. https://doi.org/10.1007/s10706-024-02822-4