Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1837

Laboratory characterisation of the cyclic simple shear behaviour of Dunkirk sand for offshore pile foundation design

Parham Reyhanianasl, **Ali Zendehdel Nobari**, Chris Brandish-Lowe, Mingnan Li, Peter Webster
Geoquip Marine, Bristol, United Kingdom, Alizendehdel.nobari@geoquip-marine.com

Tingfa Liu
School of Civil, Aerospace and Design Engineering, University of Bristol, Bristol, UK

ABSTRACT: Rigorous assessment of cyclic loading effects is crucial to the full life-cycle design of pile foundations that are employed extensively to support a wide range of onshore and offshore infrastructure. Laboratory element-scale cyclic shearing tests are routinely commissioned to characterise cyclic behaviour of geomaterials subjected to different loading and drainage conditions. This paper reports key outcomes from a laboratory undrained monotonic and cyclic simple shear testing programme on a saturated fine marine dense sand from the Dunkirk (France) site. Dunkirk sand has been studied extensively through a series of research and industrial projects dedicated to the development and validation of new design methods for axially and laterally loaded driven piles. Pre-conditioning steps of over-consolidation and drained pre-cycling were applied to simulate soil conditions and stress histories induced by driven pile installation. The results demonstrate how the number of cycles to failure, evolution of effective stress and cyclic stress-strain relationships varied systematically with the applied cyclic stress ratios. The pre-conditioned specimens exhibited substantially higher cyclic shearing resistances in comparison with the 'virgin' specimens that represent far-field in-situ soil conditions. The simple shear test results further enhance the experimental characterisation of Dunkirk sand under cyclic loading and broaden the available dataset. These outcomes provide an important basis for further analysis and advanced numerical modelling of axial and lateral cyclic pile load tests performed at the Dunkirk site. The testing scheme can be applicable for other comparable soils encountered in offshore development and design practice.

KEYWORDS: Cyclic loading; simple shear testing; pre-conditioning; fine marine sand.

1 INTRODUCTION

Cyclic loading is central to the research and engineering practice of offshore pile foundations (Jardine, 2020). The behaviour of geomaterials under *in-situ* and *in-service* conditions can be affected markedly by pile installation as well as operational and extreme loading. The capacity and cyclic characteristics of axially loaded piles depend partly on the properties of 'far-field' *in-situ* soils but most critically on the 'near-field' soil conditions adjacent to pile shaft and beneath base formed by pile driving. In contrast, laterally loaded piles mobilise large volumes of *in-situ* state soils at ultimate failure and are less susceptible to installation effects. Site- and project-specific laboratory cyclic tests that reproduce soil states and stress conditions are required routinely to derive representative cyclic design parameters (Andersen, 2015).

Cyclic simple shear (CSS) testing is one of the most commonly used methods for characterising soil's cyclic shearing behaviour, despite the method's inherent limitations in stress uniformity and stress state definition. Anderson (2015) demonstrated how cyclic interaction diagrams can be derived from routine CSS testing to enable cyclic design of offshore foundations.

Extensive research has been conducted at the Dunkirk site in Northern France to improve the understanding and prediction of driven pile behaviour in sands subjected to axial and lateral loading under both static and cyclic conditions, including the ICP testing campaigns (Jardine, 2020) and PISA joint industry project (Byrne et al., 2017). Extensive laboratory studies were undertaken by Aghakouchak (2015) and Liu (2018) to investigate Dunkirk sand's stress–strain relationships, small-strain stiffness, anisotropy, drained and undrained cyclic loading behaviour through advanced triaxial and hollow cylinder apparatus (HCA) tests. The experiment outcomes have enabled advanced numerical modelling of the PISA monotonic and cyclic pile tests by Taborda et al. (2020) and Tantivangphaisal et al. (2025).

Limited simple shear testing (DSS/CSS) has been reported on Dunkirk sand. This study aims to close this gap by undertaking two series of CSS tests on (i) normally consolidated 'virgin' specimens representing *in-situ* states and (ii) pre-conditioned specimens designed to replicate and incorporate installation effects of driven piles, supplemented by benchmarking DSS tests. Comparison between these test series reveals how over-consolidation and pre-cycling influence Dunkirk sand's number of cycles to failure, evolution of effective stress, cyclic stress-strain relationships and other characteristics.

2 TEST MATERIAL, APPARATUS AND PROGRAMME

2.1 *Material*

The material employed in this study was a fine-grained marine sand sampled at the Dunkirk site that was investigated extensively by Liu (2018) through monotonic and cyclic triaxial tests. The limiting minimum and maximum void ratios (e_{min} and e_{max}) were determined as 0.52 and 0.85, respectively, following the NGI/GEOLABS recommended methods (Knudsen et al., 2020). Table 1 summarises the material's particle size characteristics and key index properties.

2.2 *Equipment*

Monotonic and cyclic direct simple shear tests were performed by an Electromechanical Dynamic Cyclic Simple Shear Device (EMDCSS) manufactured by GDS Instruments. Vertical and horizontal loads were applied by electro-mechanical actuators and axial displacements measured by both external LVDTs (Linear Variable Differential Transformers) and high-resolution encoders to offer data redundancy and control verification. The EMDCSS system allows for small and large strain monotonic and cyclic testing under drained and undrained (constant volume) conditions with cycling frequencies up to 5 Hz. The maximum applied loads are up to 10 kN and displacement ranges up to ±2.5 mm axially and ±10 mm in shear. The device is configurated with an extra stiff frame that reduces system compliance, as well as an active height control mechanism that can restrict volume change during undrained shearing. The soil specimen is laterally confined by low-friction Teflon-coated retaining rings of 1 mm thickness, ensuring constant sample diameter during shearing.

Table 1. Physical properties of Dunkirk sand.

Property	Value
G_s	2.65
d_{10} [μm]	112.1
d_{60} [μm]	237.5
d_{90} [μm]	321.8
e_{max}	0.85
e_{min}	0.52
C_u	2.12
C_c	1.02

2.3 *Testing setup*

Saturated specimens of 63.5 mm diameter and 20 mm height were prepared for DSS and CSS testing in accordance with ASTM (D8296-19, 2019; D6528-24, 2024). The specimens were prepared by water pluviation method which is well suited for forming dense and uniform sand samples and reproducing sand states and fabrics representative of offshore deposition environment (Aghakouchak, 2015). High saturation degrees were achieved by inundating dry sand materials of known mass with deionised water and de-airing the mixture under vacuum for 1-2 hours to remove trapped or dissolved air.

A porous disc was placed first on the EMDCSS pedestal and a latex membrane fixed around it with two O-rings. After placing Teflon-coated (shear) rings, a two-part split mould was assembled on the base pedestal to ensure full alignment of the rings during sample preparation. A low vacuum of ≈20 kPa was applied to the assembled mould to stretch the membrane and ensure smooth inner mould surfaces. The de-aired sand-water mixture was then pluviated into the mould. Gentle tapping was applied to smoothen sample surface and improve uniformity. After the sand was fully transferred into the mould and the target height of sample achieved, the pedestal was placed in the testing position of the EMDCSS device and then the specimen docked by applying a small load of around 15 N. External horizontal and axial displacement transducers were then attached.

2.4 *Testing programme*

The experimental programme consisted of 4 DSS and 10 CSS tests. Details of the specimens and testing conditions are listed in Table 2. Benchmarking DSS tests at three effective vertical stresses (σ_v') of 100, 200 and 400 kPa were performed to characterise the material's monotonic shearing behaviour. CSS tests were carried out on specimens consolidated to σ_v' = 200 kPa at a loading frequency of 0.1 Hz with cyclic shear stress amplitudes (τ_{cyc}) of 2.5, 5, 10, 15 and 20 kPa, corresponding to cyclic stress ratios (CSR = τ_{cyc}/σ_v') in the range of 1.25-10%, as summarised in Table 2. The stop criteria of cyclic loading stage were set as either after 20,000 cycles of shearing or cyclic shear strain exceeding 15%, whichever occurred first. Specimens that sustained a maximum number of cycles of 20,000 without failure were subsequently sheared monotonically to failure.

Pre-conditioning stages that involved over-consolidation and pre-cycling were applied to a suite of specimens to model the installation effects of driven piles. Similar approach was adopted in the cyclic triaxial tests on Dunkirk sand by Aghakouchak (2015) and Aghakouchak et al. (2015). The specimens were consolidated to an initial σ_v' at 800 kPa and then unloaded to 200 kPa to achieve an over-consolidation ratio (OCR) of 4. Following Augustesen et al. (2025), pre-shearing was applied with a cyclic shear stress level of 5% of the final applied effective vertical stress (i.e. 10 kPa) for 400 cycles at a frequency of 0.1 Hz, under drained and constant vertical stress (σ_v' =200 kPa) conditions. This procedure was adopted to simulate the soil states and cycling histories induced by driven pile installation. A DSS test was performed to benchmark the effects of pre-conditioning on monotonic shearing resistance. Five CSS tests were undertaken under identical shearing frequency and amplitudes to those applied on the 'virgin' specimens which did not experience any pre-conditioning.

The laboratory programme is summarised in Table 2. The test IDs follow the format: [Test Type] [Consolidation Stress]-[OCR]- [Cyclic Shear Amplitude], where the first letter denotes the test type ('D' for DSS and 'C' for CSS), followed by the applied vertical consolidation stress (in kPa), OCR and shearing amplitude. For instance, "C200-1-10" indicates a CSS test at 200 kPa consolidation stress, OCR of 1, and shearing amplitude of 10%. The test code followed by an asterisk (*) indicates that the specimen was sheared monotonically to failure after sustaining 20,000 shearing cycles.

Table 2. Summary of the DSS and CSS testing programme.

Test ID	Type	e_0	OCR	e_{0c}	CSR (%)	τ_{cyc} (kPa)
D100-1-00	DSS	0.662	1	0.630	-	-
D200-1-00	DSS	0.663	1	0.628	-	-
D400-1-00	DSS	0.672	1	0.624	-	-
D200-4-00	DSS	0.664	4	0.571	-	-
C200-1-2.5*	CSS	0.661	1	0.624	1.25	2.5
C200-1-5.0	CSS	0.655	1	0.621	2.5	5
C200-1-10	CSS	0.659	1	0.633	5	10
C200-1-15	CSS	0.657	1	0.632	7.5	15
C200-1-20	CSS	0.664	1	0.625	10	20
C200-4-2.5*	CSS	0.662	4	0.615	1.25	2.5
C200-4-5.0*	CSS	0.663	4	0.634	2.5	5
C200-4-10*	CSS	0.663	4	0.630	5	10
C200-4-15	CSS	0.654	4	0.612	7.5	15
C200-4-20	CSS	0.663	4	0.614	10	20

Notes: e_0: initial void ratio; e_{0c}: void ratio prior to undrained monotonic/cyclic shearing; all OCR = 4 specimens experienced drained pre-cycling.

3 RESULTS AND DISCUSSION

3.1 *Monotonic shearing behaviour*

Figure 1 presents the monotonic shear stress-strain response for four DSS specimens (D100-1-00, D200-1-00, D400-1-00 and D200-4-00). Peak shear stresses were reached at shear strains of <1%. Significant dilation followed as shearing continued to large strains of ≈30%. The corresponding effective stress paths are shown in Figure 2. Undrained shear strength (S_u) defined at phase transformation point (PTP) increased with increasing consolidation stress from ≈8 kPa for test D100-1-00 to 46 kPa for test D400-1-00.

The combined effects of over-consolidation and pre-cycling are evident in Figure 2, with the pre-conditioned specimen (D200-4-00) exhibiting 60% higher shear strength (≈40 kPa) than that of its counterpart D200-1-00. This specimen also exhibited markedly stiffer initial response, reflecting the combined effects of reduced void ratio (see Table 2) and enhanced soil fabric resulted from the pre-conditioning treatment.

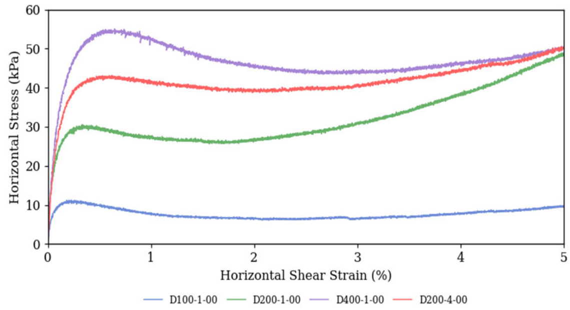

Figure 1. Shear stress–axial stress for DSS tests.

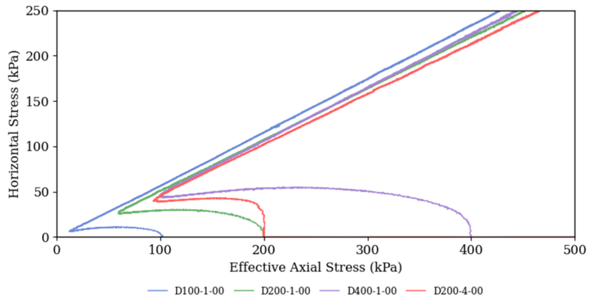

Figure 2. Effective stress paths for the DSS tests.

3.2 *Cyclic shearing response*

Figure 3 and Figure 4 illustrate the cyclic stress paths for all virgin and pre-conditioned specimens subjected to low and high cycling amplitudes, respectively. Vertical effective stresses reduced progressively as excess pore water pressure built up. Under two-way cyclic loading, typical 'butterfly-shaped' form of stress paths was observed, reflecting cyclic contraction–dilation response of saturated sands and silts in undrained condition. Axial effective stresses of the virgin specimens decayed rapidly as cycling amplitudes increased from 2.5 kPa to 20 kPa. In contrast, the pre-conditioned specimens exhibited profound improvements in cyclic resistance and delayed failure. Over-consolidation and pre-shear imparted the specimens with stronger fabric and greater tendency for dilation that suppress the building up of pore pressure and lead to enhanced cyclic resistance.

Figure 5 and Figure 6 highlight the effects of pre-conditioning on horizontal shear stress-strain responses for selected CSS tests. Under the low cyclic loading amplitude of 2.5 kPa, the stress-strain loops remained in a narrow band, indicating largely stable response with minimal stiffness degradation and negligible pore pressure generation. Increasing cyclic shear amplitudes led to accelerated shear strain developments and widen and flatten hysteresis loops for the virgin specimens. In contrast, the pre-conditioned specimens exhibited narrower stress-strain loops and maintained higher effective stresses over a greater number of cycles. Under the higher cycling amplitudes of 15-20 kPa, all specimens eventually converged toward similar failure states, although the onset of failure was delayed in the pre-conditioned specimens.

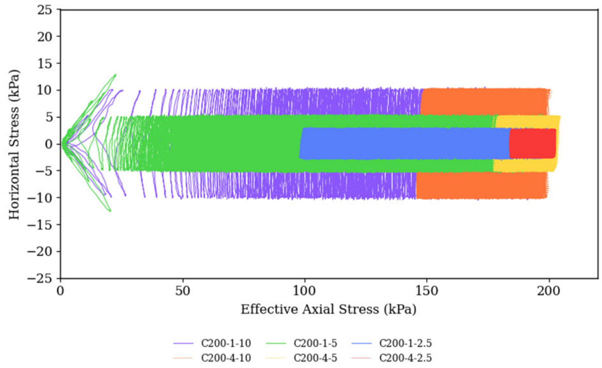

Figure 3. Cyclic stress paths for the virgin and pre-conditioned specimens at low cycling amplitudes.

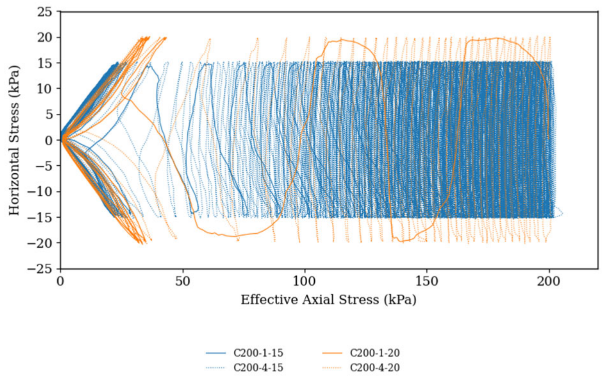

Figure 4. Cyclic stress paths for the virgin and pre-conditioned specimens at high cycling amplitudes.

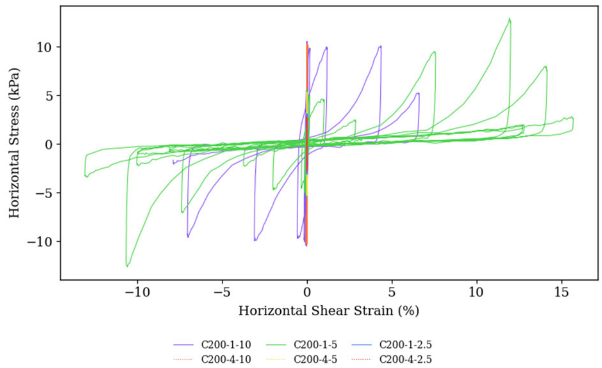

Figure 5. Effects of OCR and precycling on shear stress – shear strain curves for CSS tests at low cycling amplitudes of 2.5-10 kPa.

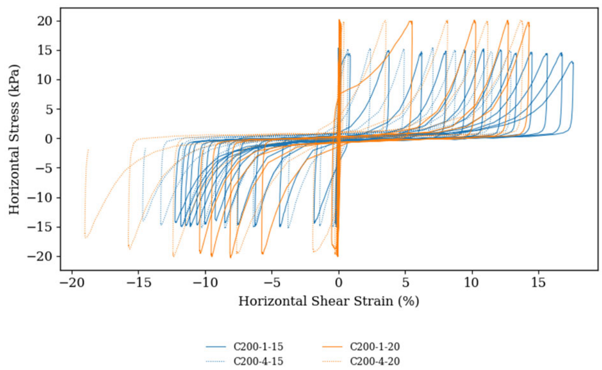

Figure 6. Effects of OCR and precycling on shear stress – shear strain curves for CSS tests at low cycling amplitudes of 15-20 kPa.

Figure 7 plots the degradation of effective axial stress against the number of cycles for all tested specimens. It is evident that the specimens underwent the pre-conditioning stages sustained larger numbers of cycles with lower rates of effective stress degradation. For cohesionless soils, excess pore water pressure (Δu) generated during undrained simple shearing can be inferred from changes in vertical stress. As in cyclic triaxial testing, pore pressure ratio (R_u) can be defined as in Equation (1) to quantify the degree of pore pressure building up with reference to initial effective stress σ_{v0}'. The number of cycles to failure was defined where R_u approached unity.

$$R_u = \frac{\Delta u}{\sigma_{v0}'} \quad (1)$$

As summarised in Table 3, the number of cycles to failure observed with the virgin specimens decreased remarkably with increasing cyclic amplitudes. The over-consolidated and pre-cycled specimens demonstrated notable improvements in cyclic resistance. Those cycled under low amplitudes sustained 20,000 cycles without failure. The most pronounced improvement was observed with C200-4-5, which exhibited a 75-fold increase in number of cycles to failure, followed by C200-4-15 with a 43-fold increase. These results confirm that the combined over-consolidation and pre-cycling effects dramatically delay the onset of failure, particularly at intermediate cycling amplitudes.

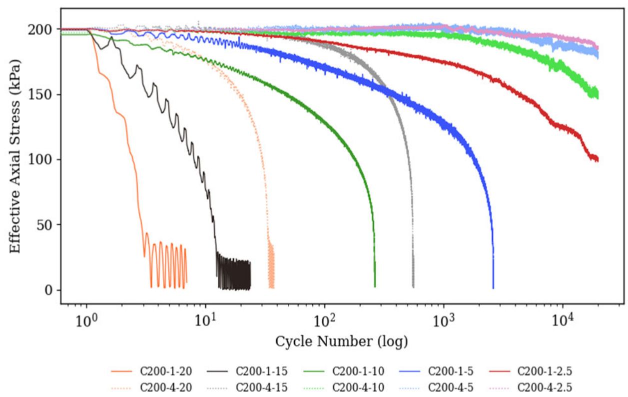

Figure 7. Evolution of effective axial stress against number of cycles to failure for all virgin and pre-conditioned specimens.

Table 3. Effects of OCR and pre-cycling on cyclic resistance.

Cycling amplitud e (kPa)	No. of Cycles to Failure (NC)	No. of Cycles to Failure (OCR4 – Pre-cycled)	Improvement Factor (times)
2.5	20000 (Not fail)	20000 (Not fail)	-
5	2634	20000 (Not fail)	>8
10	266	20000 (Not fail)	>75
15	13	557	43
20	3	34	11

4 CONCLUSIONS

Characterising geomaterial's behaviour under both *in-situ* and *in-service* conditions is crucial for the analysis and design of driven pile foundations to sustain axial and lateral offshore loading. This paper presents a laboratory monotonic and cyclic simple shear testing programme on Dunkirk sand, considering both normally consolidated 'virgin' specimens that represent *in-situ* state and pre-conditioned specimens that involve over-consolidation and pre-cycling to model driven pile installation. The main conclusions drawn from the study are summarised as follows:

- In comparison with normally consolidated state, the over-consolidation and pre-cycling stages performed on the specimens led to 60% increase in monotonic undrained shear strength along with increased shear stiffness and more gradual post-peak softening, reflecting combined effects of increased density and enhanced fabric.
- The pre-conditioned specimens showed significantly improved cyclic resistances with increased number of cycles to failure and delayed pore pressure building up.
- Pre-conditioning effects appear to be most pronounced under intermediate to high cyclic stress ratios.

The presented experiments provide valuable data for the analysis and modelling of axially and laterally loaded pile tests performed at the Dunkirk site. The testing and interpretation scheme can be applicable for other comparable soils encountered in offshore site characterisation and pile design.

5 ACKNOWLEDGEMENTS

This experimental study was undertaken as part of a strategic partnership between Geoquip Marine and the University of Bristol. The experiments were carried out in Geoquip Marine Bristol Laboratory. The authors thank gratefully the laboratory team of Geoquip Marine, particularly Mr. Edward Allan, Mr. Craig Croucher and Ms. Melissa Field.

6 REFERENCES

Aghakouchak, A., 2015. Advanced laboratory studies to explore the axial cyclic behaviour of driven piles. Imperial College London.

Aghakouchak, A., Sim, W. W., & Jardine, R. J. (2015). Stress-path laboratory tests to characterise the cyclic behaviour of piles driven in sands. *Soils and Foundations*, *55*(5), 917-928.

Andersen, K. H. (2015). Cyclic soil parameters for offshore foundation design. *Frontiers in offshore geotechnics III*, *5*(11).

ASTM D6528-24, 2024. Test Method for Consolidated Undrained Direct Simple Shear Testing of Fine Grain Soils.

ASTM D8296-19, 2019. Standard Test Method for Consolidated Undrained Cyclic Direct Simple Shear Test under Constant Volume with Load Control or Displacement Control.

Augustesen, A. H., Krogh, L., Jensen, N. B., Carrington, T., & Larsen, S. P. (2025). Investigations into end constraints and specimen conditioning in direct simple shear testing of sands. *Proceedings of 5th International Symposium on Frontiers in Offshore Geotechnics*, Nantes, France.

Byrne, B. W., McAdam, R. A., Burd, H. J., Houlsby, G. T., Martin, C. M., Beuckelaers, W. J. A. P., ... & Plummer, M. A. L. (2017). PISA: New Design Methods for Offshore Wind Turbine Monopiles. In *Offshore Site Investigation Geotechnics 8th International Conference Proceeding* (Vol. 142, No. 161, pp. 142-161). Society for Underwater Technology.

Jardine R. J. (2020). Geotechnics, Energy and Climate change: the 56th Rankine Lecture. Géotechnique 70(1):3-59.

Knudsen, S., Powell, J. J. M., Lunne, T., Thomsen, N. V., Krogh, L., & Barwise, A. (2020). Development of new robust procedures for the determination of maximum and minimum dry densities of sand. *ISFOG2020*.

Liu, T. Advanced laboratory testing for offshore pile foundations under monotonic and cyclic loading (2018). PhD thesis. Imperial College London. London, UK.

Taborda, D. M., Zdravković, L., Potts, D. M., Burd, H. J., Byrne, B. W., Gavin, K. G., ... & McAdam, R. A. (2020). Finite-element modelling of laterally loaded piles in a dense marine sand at Dunkirk. *Géotechnique*, *70*(11), 1014-1029.

Tantivangphaisal, P., Taborda, D. M. G., Kontoe, S., Liu, T., & Jardine, R. J. (2025). Numerical modelling of the long-term cyclic response of laterally loaded piles driven in sands using the high-cycle accumulation framework. Ahead of Print in *Géotechnique*, 1-17.