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Centrifuge modelling of intermediate piles subjected to multidirectional cyclic lateral loading

R. Zabatta
France Energies Marines, Plouzané, France
Gustave Eiffel University, Nantes, France

C. N. Abadie*, M. Blanc, S. Lerat, A. Jagu
Gustave Eiffel University, Nantes, France

T. Coquio
France Energies Marines, Plouzané, France

christelle.abadie@univ-eiffel.fr (corresponding author)

ABSTRACT: The expansion of offshore wind energy highlights the potential of Floating Offshore Wind Turbines (FOWTs) for deeper waters, where fixed-bottom turbines face technical and economic challenges. Shared mooring systems present a promising solution for the mass deployment of FOWTs, potentially reducing mooring costs and carbon footprint. However, shared anchoring poses increased risks of cascading failures, necessitating rigorous design considerations for complex loading scenarios, including strong multi-directional cyclic loads. This study, conducted within the MUTANC project, investigates the response of shared anchor foundations under multidirectional cyclic loading using physical modelling at the geotechnical centrifuge facility of Gustave Eiffel University. The experimental setup mimicked anchor piles shared by multiple floaters, subjecting them to complex multi-directional cyclic loading paths. One test, specifically a 'cross' test with perpendicular cyclic loads relative to a constant principal axis load, was meticulously analysed. Results reveal significant ratcheting effects under high-amplitude multidirectional two-way cyclic loading, particularly in the principal direction, where no deformation is expected from an equivalent test without the maintained load. Comparative analysis with unidirectional cyclic tests indicates that multidirectional loading increases accumulated displacements for high-amplitude cycles, underscoring the need to account for load directionality in design to minimise conservatism. These findings provide preliminary insights into the performance and design optimisation of shared anchors for floating wind applications and offer guidelines for designing monopiles to withstand multi-directional cyclic loads for bottom-fixed offshore wind applications.

Keywords: floating wind; shared anchors; multidirectional loading; ratcheting; centrifuge modelling.

1 INTRODUCTION

Offshore wind energy is rapidly expanding, with Floating Offshore Wind Turbines (FOWTs) offering a viable solution for deeper waters where fixed-bottom turbines are prohibitively large and expensive. However, floating wind farms require technological and design advancements to become commercially viable, with high capital costs for platforms and mooring systems being one of the obstacles. Shared mooring systems (e.g., Figure 1) present an innovative, cost-effective approach for deploying FOWTs in clusters, potentially reducing mooring costs by up to 16% for large-scale projects (Devin et al., 2021; Xu et al., 2024). Despite their promise, shared anchoring introduces increased mooring line loads, chain-seabed interactions, and soil cyclic effects, raising the risk of cascading failures. Further understanding of the behaviour of shared anchors, in particular to multi-directional cyclic loads, is needed to improve design and reduce capital expenditures (Lovera et al., 2025).

Published work on the understanding of shared foundations for floating wind applications has been limited and no specific design guidelines presently exist for anchors subjected to multi-directional cyclic loading (Herduin, 2019). Richards (2019) and Richards et al. (2019) present initial work on monopiles subjected to multi-directional cyclic lateral loading at height through a series of 1g test campaigns. The study reveals that the hysteretic response of the foundation under multi-directional loading closely resembles that under unidirectional cyclic loading, though with greater energy dissipation. Lovera et al. (2021) developed a model based on the *p-y* curves approach to calculate laterally loaded pile response and extended it to consider multi-directional loading. The proposed model captures the development of

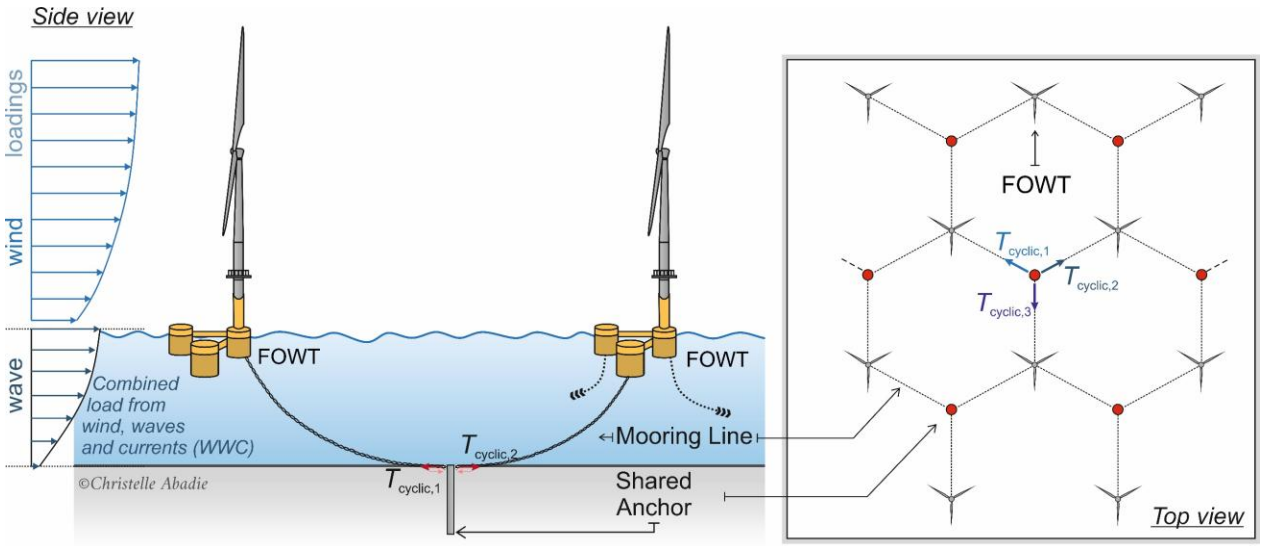

Figure 1. Principles and possible layout of floating offshore wind turbines (FOWTs) with shared anchors (Abadie, 2025)

misalignment between the loading direction and the pile's lateral displacement. However, there is limited published experimental data to validate such models. Newer contributions, motivated by the recent offshore wind expansion, extend the studies to numerical predictive tools (e.g. Finite Element Modelling, Ahmed et al., 2025; Macro-models, Richards, 2019) and other foundation types (e.g. Ifeobu et al., 2025; Soriano-Camelo et al., 2024).

This paper presents detailed experimental results of a multidirectional cyclic test conducted as part of the MUTANC project (MUTualised ANChors for offshore wind farms, 2021-2024). MUTANC investigates the feasibility of shared anchors for floating wind applications through selected work packages involving (i) advanced hydrodynamic calculations (Loveral et la., 2025) for input load estimation, (ii) geotechnical numerical modelling predictions (Ahmed et al., 2025), (iii) validation via centrifuge modelling (Zabatta et al., 2025, Figure 2) and (iv) cost analysis of the use of shared anchors. This paper focuses on one of the tests performed at the geotechnical centrifuge (CG lab) of the Gustave Eiffel University (UGE). The selected test involves a multidirectional cyclic 'cross' test and provides preliminary insights into anchor pile performances when shared by multiple floaters.

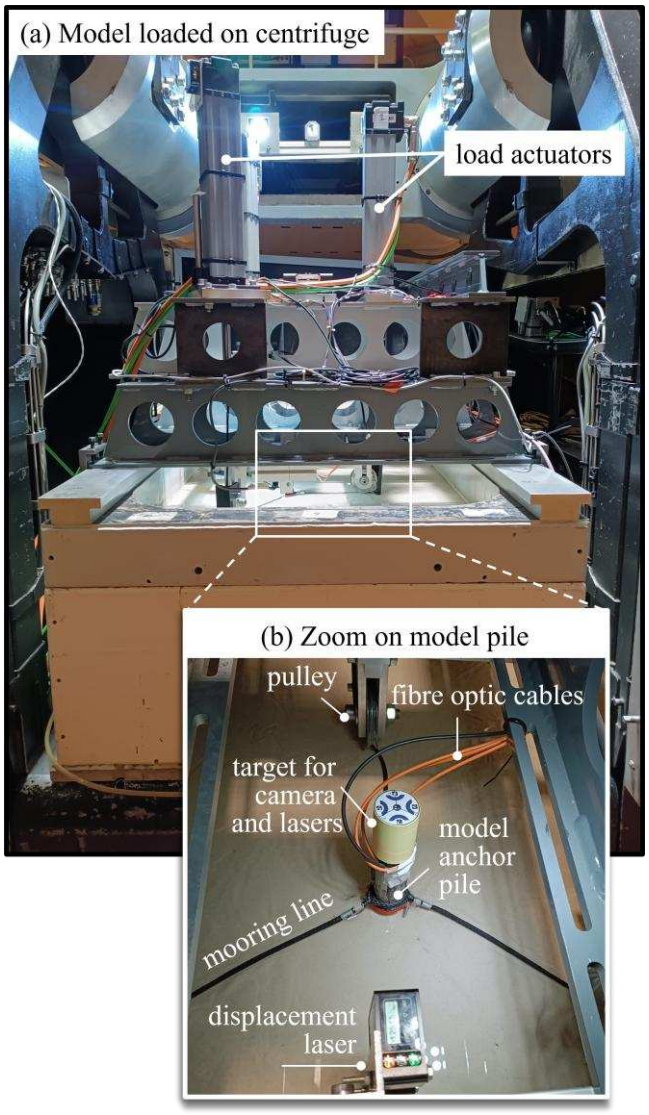

Figure 2. MUTANC experimental test setup. (a): View of the support frame with the load actuators installed in the centrifuge nacelle. (b): Detailed view of the anchor pile

2 EXPERIMENTAL METHOD

2.1 Test set-up

The UGE geotechnical centrifuge facility in Nantes features a 5.5-meter radius beam and can conduct experiments at a maximum acceleration of 100 times Earth's gravity. MUTANC tests are performed at an

acceleration level of N = 83.3 using the experimental setup presented in Zabatta et al. (2024, 2025).

This setup, shown in Figure 2a, involves three technical fibre rope cables inclined at 120° from each other and attached to the anchor (Figure 2b). Each cable passes through a pulley to maintain horizontal tension and is connected to an actuator . The actuators apply cyclic lateral loads on the anchor pile, reproducing any multi-directional load sequence in the 2D horizontal plane. This setup also mimics the forces typically experienced by an anchor connected to three horizontal catenary mooring lines oriented 120° apart (Figure 2b) and is controlled via three electric actuators (Figure 2a) with the desired input load series. Each actuator is fitted with a laser for displacement control and a load cell for load control of the tension within each cable. A Moog test controller collects data from the displacement and load sensors, enabling both individual and simultaneous control of the actuators.

2.2 Soil sample

The sand sample was prepared in a rectangular strongbox using a sand-raining technique, which ensured homogeneity and achieved a relative density of about 80%. The model soil used was poorly graded NE34 Fontainebleau sand (El Haffar, 2018, Table 1). Scale effects were minimised by maintaining D/d_{50} > 140, exceeding the established threshold of 60 for laterally loaded slender piles.

To simulate underwater conditions, the sand was saturated by slowly injecting water through draining channels, with the water table maintained 20 mm above the sand surface, ensuring appropriate effective unit weight and aiding pile installation.

2.3 Instrumented model pile

The model anchor pile was designed following typical design methods for offshore foundations from API (2011) and the PISA method (Burd et al., 2020). The pile was made of a C45 steel material (Zabatta et al., 2024), with the final geometry reported in Table 2.

Table 1. Properties of the Fontainebleau NE34 sand.

Property	Value
C_u	1.53
d_{50} (µm)	210
$\rho_{d,min}$ (g/cm^3)	1.46
$\rho_{d,max}$(g/cm^3)	1.71
e_{max}	0.753
e_{min}	0.549

Table 2. Geometry of the anchor pile.

Symbol	Model (mm)	Prototype (m)
D (pile diameter)	30	2.5
t (pile thickness)	1.25	0.104
L (pile length)	240	20

The pile head displacement is monitored using a set of two displacement lasers: a distance laser and a circle measurement laser, which permits tracking of the shortest distance between a fixed point and a rounded object. This setup enables precise tracking of the centre of the pile in the 2D horizontal plane.

Additionally, the pile is instrumented with fibre optic sensing, located at the 4 cardinal points along the shaft of the pile. This enables the acquisition of the bending strain of the pile and the derivation of the soil reaction when the pile is subjected to multi-directional cyclic loading (Zabatta et al., 2025).

2.4 Multi-directional loading series

2.4.1 Notations

To rigorously describe the evolution of load and displacements during the test, two reference axes were defined on the 2D-plane $H_1 - H_2$ (horizontal loads on mooring lines 1 and 2, Figure 4). A *Principal axis P* is oriented at 60° equidistant from mooring lines 1 and 2 (and thus from horizontal load directions H_1 and H_2). The *Load axis L*, defined perpendicular to the principal axis, is where the varying two-way cyclic loading of the cross is applied. This is consistent with the definition used in Ifeobu et al. (2025).

Load cycles are described in terms of load magnitude and amplitude, using parameters ζ_b and ζ_c (Leblanc *et al.*, 2010):

$$\zeta_b = \frac{H_{max}}{H_R} \quad | \quad \zeta_c = \frac{H_{min}}{H_{max}} \tag{1}$$

H_{max} and H_{min} are the maximum and minimum load within a cycle respectively, and H_R is the ultimate load capacity of the anchor pile, established at 12.5 MN (prototype scale, Zabatta et al, 2024).

2.4.2 Selected load sequence

The load sequence studied in this paper consists of a 'Cross' test (Figure 3, see also Ifeobu et al., 2025): the pile is first pulled in the principal direction (60°) to a selected value of ζ_b; and then groups of cycles are applied in the perpendicular direction on a straight line (-30°), so that cycles extremes reach an "opening" of +/- 45° from the principal axis. A load offset of about 0.7 MN (at prototype scale) was applied on the principal axis at all type to ensure tension within the mooring line and facilitate better control of the load sequence. Two series of cycles were performed:

- 1008 cycles along the load axes with an opening of +/- 45° while maintaining a constant principal load of $H_P = 0.2 \times H_R = 2.5$ MN;

- 25 cycles along the load axes with an opening of +/- 45° while maintaining a constant principal load of $H_P = 0.6 \times H_R = 7.5$ MN.

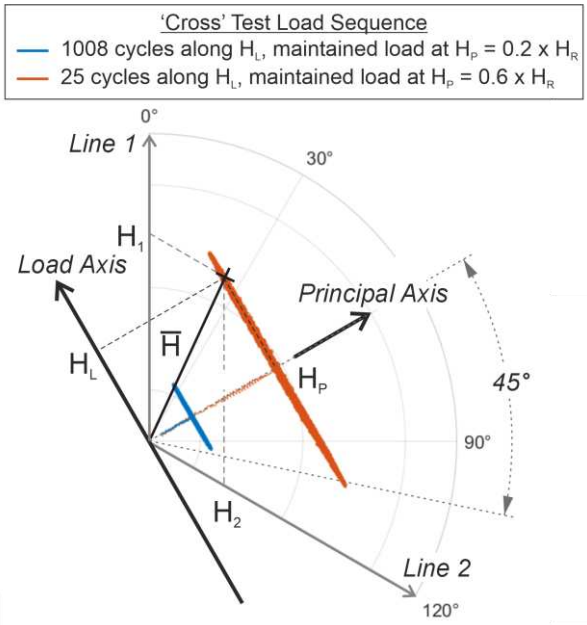

Figure 3. Force rose for the 'Cross' test; definition of axes notations (Principal P, Load L, Lines 1, and 2)

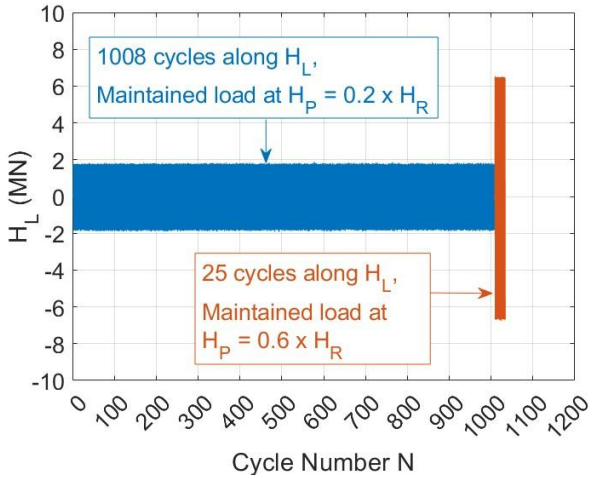

Figure 4: Evolution of H_L with cycle number

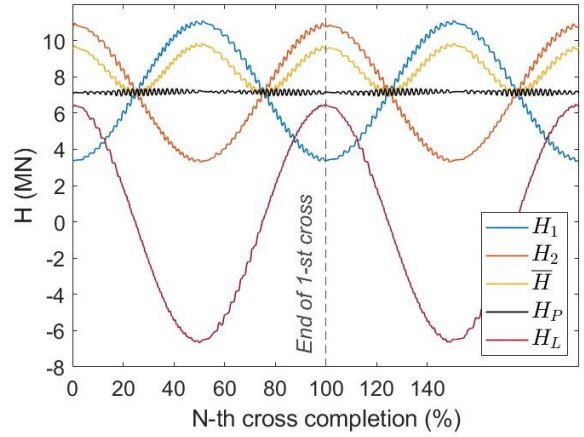

Figure 5: Components of loading for 'Cross' sequence

These cycles correspond to a two-way cyclic loading with a maintained load on the principal axis, typically not studied in published cyclic loading work on piles (e.g. Leblanc et al., 2010, Abadie et al., 2019). Figure 4 shows the evolution of horizontal load projected on the load axis with the number of cycles, illustrating 2-way loading (where $\zeta_c = -1$). Figure 5 shows the evolution of all projected loads during the completion of one 'Cross' cycle path at $\zeta_b = 0.6$.

3 TEST RESULTS: PILE HEAD DISPLACEMENT AND RATCHETING

Figure 6a shows the evolution of the pile displacement on the 2D horizontal plane at ground level, corresponding to the force rose in Figure 3. The pile displacement at ground level (v_G) is limited around values of v_G = 0.02D caused by the 1008 cycles at ζ_b = 0.2, but there is a rapid increase at the start of the ζ_b =0.6 load sequence, reaching values beyond 0.1D.

During the first load of each cyclic sequence in the two-way cross, the displacement direction occurs at an angle near 30° from the loading axis, rather than aligning with the 0° loading direction. This causes significant displacement accumulation in the principal direction, a phenomenon not typically observed in two-way cyclic loading without a maintained load in the perpendicular (here called the principal) direction. This is highlighted in Figure 6b, where the $H - v_G$ response of the pile, projected on the principal axis, outlines the clear ratcheting effect induced by the perpendicular 2-way cyclic load. These findings are consistent with ongoing research on multi-directional cyclic loading of foundations for offshore wind applications. Similar results have been observed for piles subjected to non-perpendicular multi-directional 'cross' cyclic loading (Chalhoub et al., 2025), and to a lesser extent, for shallow foundations subjected to perpendicular 'cross' loading (Ifeobu et al., 2025). Figure 6b also demonstrates the typical result of re-joining the backbone curve on re-loads, also observed in previous published research on cyclic loading of piles (e.g. Abadie, 2015, Richards, 2019).

Ratcheting can finally be quantified through the evolution of accumulated pile displacement at ground level at the peak of the cyclic load for each N-th load cycle (e.g. Leblanc et al., 2010, Abadie, 2015).:

$$\frac{\Delta v_{G,p,N}^{max}}{v_{G,p,0}^{max}} = \frac{v_{G,p,N}^{max} - v_{G,p,0}^{max}}{v_{G,p,0}^{max}} \quad (2)$$

Equation (2) monitors the evolution of the pile displacement at ground level $v_{G,p,N}^{max}$ solely caused by cyclic loading by subtracting the plastic deformation caused by the initial monotonic load $v_{G,p,0}^{max}$ and

normalising it by this same quantity for comparison between different load packets.

The results are shown in Figure 7 and compared with the equivalent unidirectional one-way cyclic test involving 1000 cycles at ζ_b = 0.2, followed by 25 cycles at ζ_b = 0.6. The results show that multi-directionality has a limited impact on packets of small load magnitude, even for a very large number of cycles (Figure 7a). However, as anticipated from Figure 6, the impact of multi-directionality is much greater on large load magnitude (Figure 7b), even for a small number of cycles. The results from Chalhoub et al. (2025) also indicate that multi-directional loading can have a more severe impact on accumulated pile displacement, although the results shown in this paper (see Figure 6 of Chalhoub et al., 2025 for comparison) are not projected on the same axis. This result is important for future design of shared anchor piles.

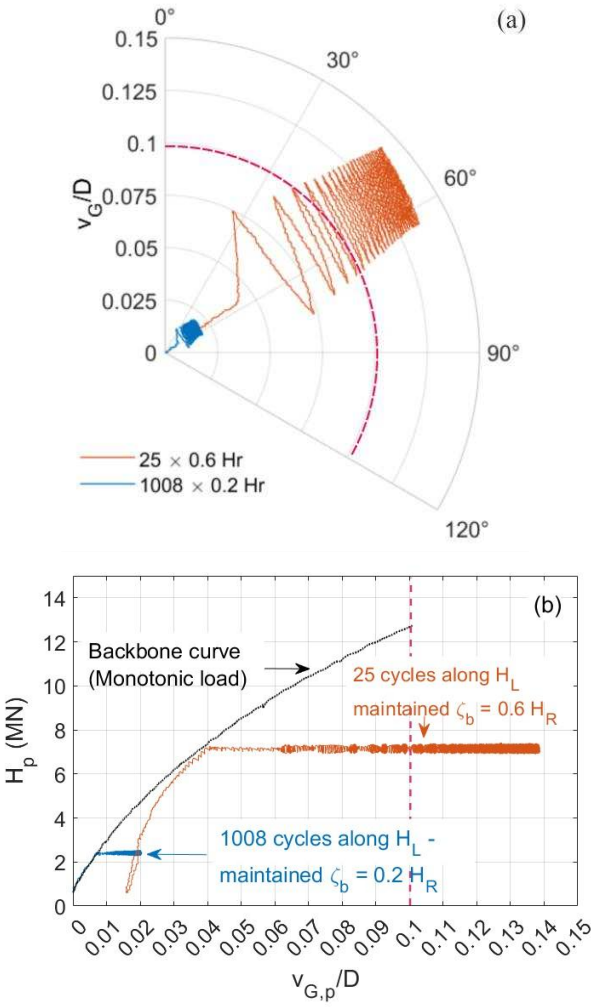

Figure 6. Overall pile response: (a) Displacement rose in the horizontal 2D plane at ground level; (b) Load-displacement response along the Principal axis

4 CONCLUSIONS

This paper presents initial experimental observations on the response of shared anchor piles to multidirectional cyclic loading. The test presented here was conducted in the Geotechnical Centrifuge at the UGE facilities in Nantes, where bespoke experimental equipment was developed to investigate the behaviour of shared anchor piles for floating wind applications.

The work focus is on the results of a 'Cross' test on a typical model anchor pile, designed using standard offshore foundation design tools. The test simulates a scenario where a constant load is maintained in one direction while cyclic loading occurs in the opposite direction. This scenario is also relevant to monopile foundations, where wind load remains relatively constant, and wave load is misaligned, producing cyclic loading on the foundation.

The results show that cyclic loading causes large accumulated displacement in the perpendicular direction, where the load is maintained, a phenomenon not typically seen for piles subjected to uni-directional 2-way loading, with no maintained load. This phenomenon can be significant for large load magnitudes and needs to be investigated further for future design practices of shared anchor piles.

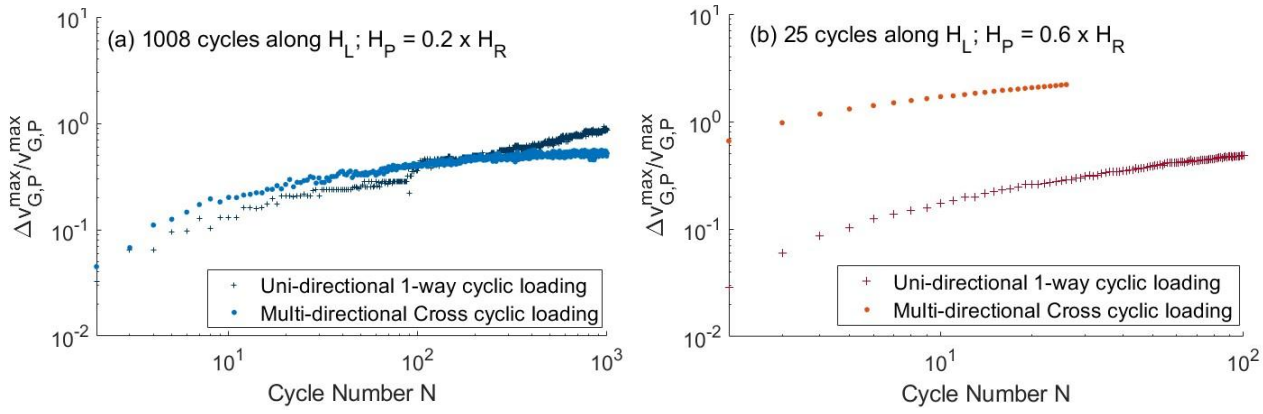

Figure 7. Accumulated pile displacement with cycle number caused by (a) Package 1 and (b) Package 2

AUTHOR CONTRIBUTION STATEMENT

R. Zabatta: Data curation, Formal Analysis, Writing-Original draft. **C. N. Abadie**: Conceptualization, Methodology, Supervision, Reviewing and Editing. **M. Blanc**: Conceptualization, Methodology, Supervision, Reviewing and Editing. **S. Lerat**: Conceptualization. **A. Jagu**: Conceptualization. **T. Coquio**: Supervision, Funding acquisition

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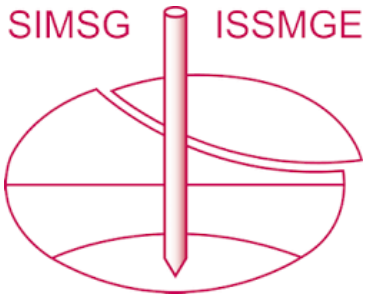

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