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Numerical modelling of the long-term cyclic ratcheting of monopile foundations under lateral loading

Modélisation numérique du ratcheting cyclique à long terme des fondations monopieux sous chargement latéral

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ABSTRACT: There is growing interest to utilise advanced numerical methods by industry practitioners in the prediction of the long-term response of monopile foundations under lateral cyclic loading. One framework of interest is the High Cycle Accumulation (HCA), as it can overcome the limitations of computational expense and error accumulation encountered by conventional cycle-by-cycle finite element analyses. The authors' implementation of HCA within the finite element package PLAXIS is presented with an emphasis on the framework's key components and underlying assumptions. Furthermore, by coupling HCA with a practice oriented elasto-plastic model for sands, predictions using different HCA calibration approaches are evaluated against the field measurements of a medium sized cyclic lateral pile load test from the Pile-soil analysis (PISA) joint industry project.

RÉSUMÉ: Les professionnels de l'industrie montrent un intérêt croissant pour l'utilisation de méthodes numériques avancées afin de prédire la réponse à long terme des fondations monopieux soumises à des chargements cycliques latéraux. L'Accumulation à Haute Fréquence (HCA) est une des méthodes considérées, car elle peut surmonter les limitations de coût computationnel et les problèmes d'accumulation d'erreurs rencontrées par les analyses conventionnelles par éléments finis cycle-par-cycle. L'implémentation du HCA par les auteurs dans le logiciel de calcul par éléments finis PLAXIS est présentée ici, mettant l'accent sur les composants clés de la méthode et les hypothèses sous-jacentes. De plus, en couplant le HCA avec un modèle élasto-plastique orienté vers la pratique pour les sables, on évalue les prédictions utilisant différentes approches de calibrage du HCA par rapport aux mesures sur le terrain d'un essai de charge latérale cyclique de taille moyenne réalisé lors du projet industriel conjoint Pile-soil Analysis (PISA).

Keywords: Cyclic loading; monopile; finite element analysis; high cycle accumulation; calibration.

1 INTRODUCTION

There is a growing body of research focused on numerical methods for the prediction of long-term rotation of monopile offshore foundations subjected predominantly to regular lateral cyclic loading (Achmus et al., 2009; Staubach & Wichtmann, 2020; Abadie et al., 2023). However, translating these methods from research to design practice require both rigorous validation against large scale field tests and studies on calibration sensitivity. Greater applicability will also be found for methods whose calibration intensity can be adapted to availability of site-specific data.

The High Cycle Accumulation (HCA) framework proposed by Niemunis et al. (2005) is used here to predict the accumulated rotation of the 0.76m diameter (D) lateral cyclic pile load test in Dunkirk Sand from the PISA project (Byrne et al., 2020). Single element and field scale predictions from two calibration approaches are presented.

2 THE HCA FRAMEWORK FOR SANDS

In response to the numerical difficulties of simulating the cycle-by-cycle response of thousands of loading cycles, the HCA framework for sands proposes that the magnitude and direction of stress and strain changes due to repeated loading can be characterised directly by:

- A one-cycle cyclic strain amplitude $\|\varepsilon_{ampl}\|$,
- a history variable g^A capturing the number of cycles N and evolution of $\|\varepsilon_{ampl}\|$,
- the current (average) stress state $\{\sigma\}$,

- the current (average) void ratio e, and
- a set of material dependent properties.

When using the HCA framework in conventional finite element (FE) analyses, $\|\varepsilon_{ampl}\|$ is determined at each integration point by processing the strain path undergone over one regular loading cycle (Niemunis et al., 2005).

2.1 Low-cycle sand model

The low-cycle elasto-plastic model used herein is a non-linear elastic model capable of Masing hysteresis (Taborda et al., 2016) coupled with state-parameter driven plasticity based on the Mohr-Coulomb yield criterion (Taborda et al., 2022). Implementation details are found in Taborda et al. (2023).

2.2 High-cycle framework implementation

The incremental HCA stress-strain relation is:

$$\{\Delta\sigma\} = \left[D_{HCA}^{ela}\right]\{\Delta\varepsilon^{ela}\} \qquad (1)$$

$$\{\Delta\varepsilon^{ela}\} = \{\Delta\varepsilon^{t}\} - \{\Delta\varepsilon^{acc}\} - \{\Delta\varepsilon^{p}\} \qquad (2)$$

$$\{\Delta\varepsilon^{acc}\} = \left\{\frac{\partial\varepsilon^{acc}}{\partial N}\right\}\Delta N \qquad (3)$$

where $\{\Delta\sigma\}$ is the local stress step, $\Delta\varepsilon^{ela}$, $\Delta\varepsilon^{t}$, $\Delta\varepsilon^{p}$, $\Delta\varepsilon^{acc}$ are respectively the elastic, total, plastic and accumulated strain steps. $\left[D_{HCA}^{ela}\right]$ is the HCA isotropic elastic stiffness matrix described by K_{HCA} and ν_{HCA}, and is dependent on e and mean effective stress (p'):

$$K_{HCA} = K_{HCA}^{ref} \cdot f_K(e) \cdot \left(\frac{p'}{100}\right)^{m_{K,HCA}} \qquad (4)$$

where K_{HCA}^{ref} and $m_{K,HCA}$ are material parameters and $f_K(e) = (1.63 - e)^2/(1 + e)$ follows Wichtmann et al. (2013) as modified from Hardin & Richart (1963).

The plastic strain step is determined via standard elasto-plastic integration employing the low-cycle model yield surface and plastic potential, using a modified total strain step $\{\Delta\varepsilon^{t}\} - \{\Delta\varepsilon^{acc}\}$.

The empirical function from Wichtmann (2016) driving the prediction of the average strain change due to an increment of stress cycles (and vice-versa) is formed of a direction $\{\vec{m}\}$ and a scalar magnitude:

$$\left\{\frac{\partial\varepsilon^{acc}}{\partial N}\right\} = \{\vec{m}\} \cdot \frac{\partial f_N}{\partial N} f_{ampl} f_e f_p f_Y \qquad (5)$$

where $\{\vec{m}\}$ is the unit norm of the Modified Cam Clay surface, whose size (and hence the accumulation direction) is described by a single material parameter ϕ_{HCA}. The magnitude is dependent on 9 material parameters: ϕ_{HCA}, and C_{ampl}, C_e, e_{max}, C_p, C_Y, C_{N1}, C_{N2}, C_{N3}, three state variables e, g^A and $\|\varepsilon_{ampl}\|$, and the current stress state represented by invariants p', J and θ with $\eta = J/p'$ (where J is the deviatoric stress invariant and θ the Lode-angle). The f-factors are:

$$\frac{\partial f_N}{\partial N} = C_{N1}C_{N2}\, exp\frac{-g^A}{f_{ampl}C_{N1}} + C_{N1}C_{N3} \quad (6)$$

$$f_{ampl} = \left[min\left(\frac{\|\varepsilon_{ampl}\|}{10^{-4}}, 10\right)\right]^{C_{ampl}} \qquad (7)$$

$$f_e = \left(\frac{C_e - e}{C_e - e_{max}}\right)^2 \cdot \frac{1 + e_{max}}{1 + e} \qquad (8)$$

$$f_p = exp\left(-C_p\left(\frac{p'}{100} - 1\right)\right) \qquad (9)$$

$$f_Y = exp(C_Y \cdot Y) \qquad (10)$$

where Y is a measure of stress ratio normalised by the Matsuoka-Nakai yield surface defined using ϕ_{HCA}.

$$Y = \left[\frac{9 - 3\eta^2}{1 - \eta^2 + \frac{8\sqrt{3}}{9}\eta^3\left(\sin^3\theta - \frac{3}{4}\sin\theta\right)} - 9\right]/[8\, tan^2\, \phi_{HCA}].$$

g^A initialises as 0 assuming no pre-cycling; its evolution incorporates the combined effect of ΔN and strain amplitude magnitude via f_{ampl} as follows:

$$\Delta g^A = \Delta N f_{ampl} C_{N1} C_{N2}\, exp\frac{-g^A}{f_{ampl}C_{N1}} \qquad (11)$$

2.3 Implementation in PLAXIS

A user-defined soil model (UDSM) “flag” allows different integration behaviour using the same UDSM at different phases: (1) Low-cycle, no record, (2) Low-cycle, strain recorded, (3) Strain processed or ‘HCA initialisation’ and (4) HCA accumulation.

A two-stage modified-Euler with automatic sub-stepping and error control integration algorithm is used during (4). Given an incoming total strain step $\{\delta\varepsilon^{t}\}$, a forward $\{\delta\varepsilon^{acc}\}_1$ and a backward $\{\delta\varepsilon^{acc}\}_2$ accumulation step is first calculated using equations (3) and (5) to (11). Intermediate forward and backward stresses are then calculated, and their average and difference are used as the initial error control measure. After a suitable sub-step size is determined, a ‘modified’ total strain sub-step $\{\delta\varepsilon^{t}\} - \frac{\{\delta\varepsilon^{acc}\}_1 + \{\delta\varepsilon^{acc}\}_2}{2}$ is used in the conventional elasto-plastic integration. If the underlying yield surface is inactive, the first stage suffices.

3 MODEL CALIBRATION FOR DUNKIRK SAND

3.1 Low-cycle (conventional) model

The low-cycle calibration used the laboratory and field data reported during the PISA project (Taborda et al., 2020) and followed the method outlined by Taborda et al. (2022). Material parameters used here are those reported by Pirrone and Taborda (2023).

3.2 High-cycle strain accumulation

Dunkirk sand laboratory test data for $\varepsilon_{ampl}(N)$ and $\varepsilon_{acc}(N)$ for eleven drained cyclic triaxial tests (DcycTX) is available in Liu (2018). Two parameter sets were calibrated for Dunkirk Sand:

(i): Using granulometry correlations (Wichtmann, 2016) for all $C_{\_}$ parameters and $\phi_{HCA} = \phi'_{cs}$, and

(ii): C_{ampl}, C_e, C_p, C_Y, C_{N1}, C_{N2}, C_{N3}, ϕ_{HCA} fitted to all 11 DcycTX tests.

For brevity, the simple brute-force strategy in Wichtmann et al. (2015) was used to fit (ii). 100,000 parameter combinations were picked out using a latin hypercube sampler. The value of $\|\varepsilon^{acc}\|$ was calculated using an integration driver for equation (5). A non-weighted average root mean squared error was calculated for each laboratory test at 21 cycle numbers evenly (log-) spaced between $N = 1$ and $N = 10000$. A simple mean of this error across all eleven tests is then calculated to determine the best (smallest error) set of parameters.

As expected, calibration procedure (ii) produced a better fit against strain accumulation measured in element laboratory tests. However, the granulometry correlations also gave a reasonable fit against element tests and a first estimate of HCA parameters.

Table 1. Summary of calibrated HCA parameters.

	(i)	**(ii)**
$\boldsymbol{C_{ampl}}$	1.7	1.8
$\boldsymbol{C_e}$	0.51	0.0050
$\boldsymbol{C_p}$	0.46	0.28
$\boldsymbol{C_Y}$	2.2	2.9
$\boldsymbol{C_{N1}}$	7.0E-4	1.2E-4
$\boldsymbol{C_{N2}}$	0.22	0.57
$\boldsymbol{C_{N3}}$	4.7E-5	1.5E-5
$\boldsymbol{\phi_{HCA}}(°)$	32	29
$\boldsymbol{e_{max}}$	0.91 (Liu, 2018)	
$\boldsymbol{K_{HCA}^{ref}}$ *	120,900 kPa	
$\boldsymbol{\nu_{HCA}^{ref}}$ *	0.32	

*Values from Wichtmann (2016:p.211) for fine sand

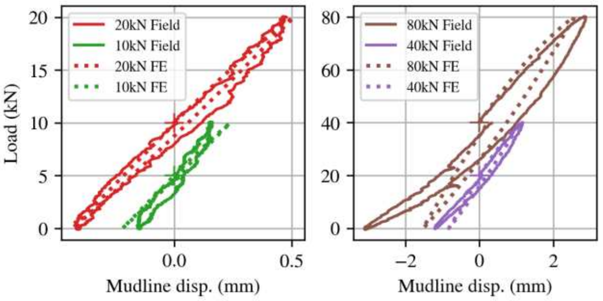

Figure 1. Low-cycle FE versus one-way field response.

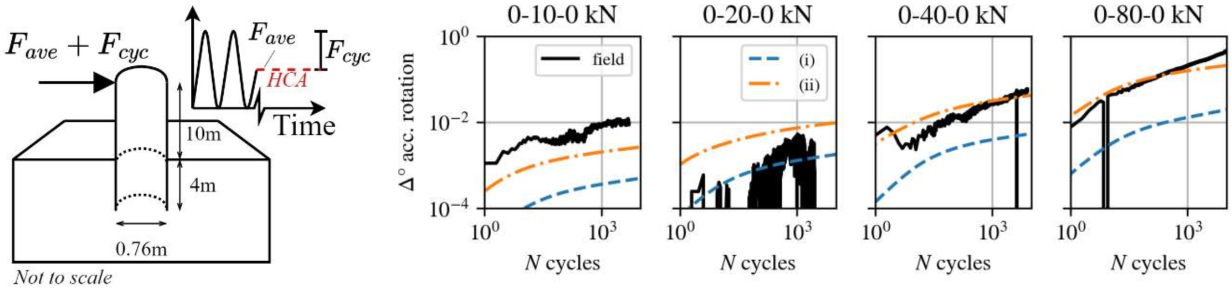

Figure 2. FE schematic and HCA simulation results compared against measured field response at mudline level.

4 FE MONOPILE PREDICTION

The initial HCA recording stage showed a reasonable match between the low-cycle model prediction and the field response (Figure 1) for the medium-sized (D=0.76m) one-way cyclic lateral pile test at Dunkirk (Byrne et al., 2020) loaded to 10 kN (N=5100), 20 kN (N=3300), 40 kN (N=8100) and 80 kN (N=11110). All analyses assumed a drained response in the sand.

In contrast to the single element response, the two calibration procedures differed by an order of magnitude in the prediction of accumulated pile head rotation (Figure 2). This is likely associated with the highly sensitive C_e parameter. The single element sensitivity reported in Wichtmann et al. (2015) seems further magnified for field-scale predictions.

5 CONCLUSION AND FURTHER WORK

A brief evaluation of the use of the HCA framework to design monopiles subjected to regular lateral loading is presented. Comparison between FE results and the field response suggests that a detailed programme of site specific drained cyclic triaxial tests is required to calibrate HCA parameters for engineering use.

Further sensitivity studies are essential to guide practitioners in the use of the HCA framework for long-term cyclic predictions, especially if calibrating using a combination of correlations and laboratory tests. An assessment of drainage effects, strain amplitude update, incorporation of sophisticated low-cycle models, and associated problems with state variable update are all keenly needed. A next step for design is to assess HCA's capability to predict soil state (e.g. void ratio distribution) and global stiffness evolution to inform dynamic and fatigue limit state design.

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