Calibration of cyclic loading models for monopile foundations

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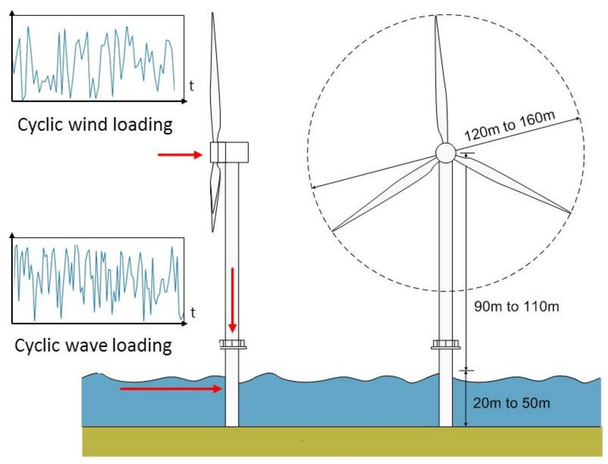
INTRODUCTION

- Monopiles are the most popular foundation for offshore wind turbines
- They are subjected to cyclic lateral loading from wind and waves which causes permanent deformation and changes to pile stiffness
- Most current design methods do not accurately predict this response

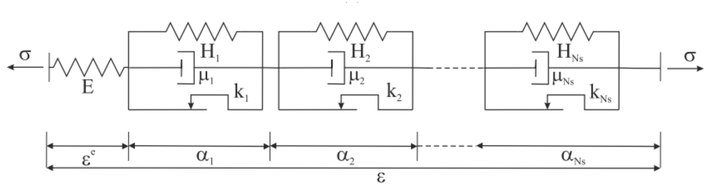


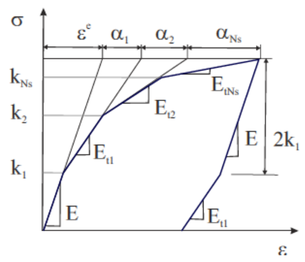
- A new constitutive model, Hyperplastic Accelerated Ratcheting model (HARM), captures response on a cycle by cycle basis
- Currently calibrated with experimental data at macro-scale (full pile rotation)
- For design, calibration for site-specific conditions using laboratory element tests is likely to be required

Research Objective:

- To make the connection between element tests and prediction of long-term cyclic behaviour of a monopile

KINEMATIC HARDENING MODEL





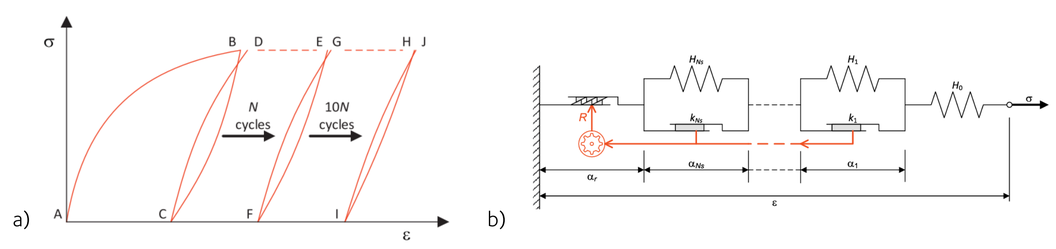
Kinematic hardening model (rate dependent series form) conceptual model
Right: multisurface response Ns=3 (Abadie, 2015)

- Multisurface plasticity consisting of N units each formed of:
  - Sliders of strength k_n
  - Springs of stiffness H_n
  - Dampers of viscosity μ_n - incorporates rate effects
- H_n & k_n fitted to monotonic response which follows equation:

$$\varepsilon = \frac{\sigma}{E_0} + \varepsilon_{pU}\left(\frac{\sigma}{k_{U0}}\right)^{m_h}$$

- Where m_h is exponent defining shape of backbone curve
- K_{u0} & $\boldsymbol{\varepsilon}_{pU}$ are ultimate stress and strain respectively

HARM – RATCHETING



a) features of one-way loading response of a pile b) HARM model (Houlsby et al, 2017)

- Experimental work (Abadie, 2015, etc.) shows:

a) Accumulation of deformation (ratcheting) when subject to one-way non-zero mean loading

- Rate of ratcheting decreases with number of cycles (m_r)
- Rate of ratcheting increases with magnitude of stress (m_k)
- Modelled as additional ratcheting strain (α_r) related to ratcheting parameter:

$$R_n = R_0\left(\frac{k_n}{k_{U0}}\right)\left(\frac{\beta}{\beta_0}\right)^{-m_r}\left(\frac{|\sigma|}{\sigma_0}\right)^{m_s} \qquad \text{Where } \beta = |\alpha_n|$$

b) Hysteresis loop changes shape with cycle number (stiffness & damping), incorporated by changing the strength at which each surface acts (m_k):

$$k_n = k_{0n}\left(\frac{\beta}{\beta_0}\right)^{m_k}$$

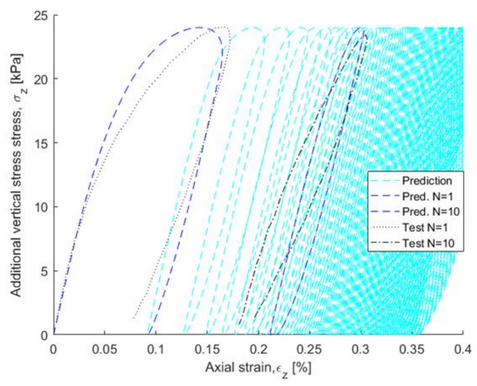
- Equations for stress, σ and total strain, ε (elastic (ε^e), plastic (α_n) & ratchet (α_r) can then be derived from 'hyperplasticity' framework (Houlsby et al, 2017)
- Model can be defined for any conditions by calibrating: $\boldsymbol{m_h, m_k, m_r, m_s, R_0}$

INITIAL STUDIES

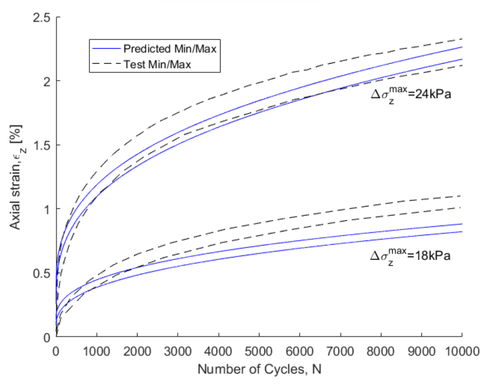
CTXL – Cyclic Triaxial Compression Tests

- One-way cyclic triaxial tests in Wenzhou soft clay (Cai et al, 2017)
- 10000 cycles. Varying axial loading amplitude ($\Delta\sigma_z$ = 0.6-24kPa), constant confining pressure (σ_r = 41kPa).

Calibrate → Predict



Calibration of HARM parameters using $\Delta\sigma_z$=24kPa test results at cycle no. (N) 1 & 10



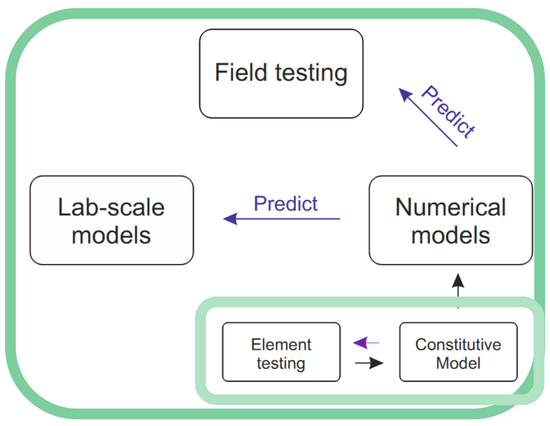
Permanent strain with cycle number, HARM prediction and test results

- Calibrated model shows good fit when predicting tests
- Cycle-by-cycle stress-strain relationship for 10000 cycles calculated in <40s
- Parameters of similar magnitude at large, model and element scale, independent of soil type - potential for link to be made

Table of HARM parameters from previous publications and initial studies

Reference	Test type	Soil type	mh	mk	mr	ms	R0
(Abadie, 2015)	Lab-scale model piles	Leighton Buzzard SAND	3.2	0.0	4.5	5.0	4000
(Guo, et al., 2017)	CTXL tests	Wenzhou Soft CLAY	3.4	-0.1	2.0	4.0	15000

FUTURE WORK



Proposed calibration and prediction using HARM

Phase 1: (Element => Element)
Predict element tests from similar & distinct element test *(ongoing)*

Phase 2: (Element => Full Pile)
Predict pile response from element test. Pile at macro/Winkler/FEA (0D/1D/3D)

Phase 3: Design
Framework for testing -Systematic choice of test type, number and location

SUMMARY

- Calibrating HARM from element tests
- Promising prediction and similar values of parameters (so far …)
- Moving towards a systematic framework for element testing to apply to full scale pile response

References:

Abadie, C. N. (2015). *Cyclic lateral loading of monopile foundations in cohesionless soils.* University of Oxford.
Guo, L., Cai, Y., Jardine, R. J., Yang, Z., & Wang, J. (2017). Undrained behaviour of intact soft clay under cyclic paths that match vehicle loading conditions. *Canadian Geotechnical Journal*, 1–41
Houlsby, G. T., Abadie, C. N., Beuckelaers, W. J. A., P., & Byrne, B. W. (2017). A model for nonlinear hysteretic and ratcheting behaviour. International Journal of Solids and Structures, 1–14

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