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► **To cite this version:**

Christelle Nadine Abadie, Byron Byrne, Guy Houlsby, Harvey Burd, Ross Mcadam, et al.. Modelling of offshore wind monopile lifetime performance. 4th International Symposium on Frontiers in Offshore Geotechnics (ISFOG), Aug 2022, Austin (Texas, USA), United States. 10.17863/CAM.83193. hal-04397349

HAL Id: hal-04397349

<https://hal.science/hal-04397349v1>

Submitted on 18 Jan 2024

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MODELLING OF OFFSHORE WIND MONOPILE LIFETIME PERFORMANCE

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ABSTRACT

Robust design of offshore wind turbine foundations requires that the ultimate capacity is acceptable. In addition the accumulated deformations over 25 years of operational life, typically 10^8 cycles, must also be limited. This paper outlines a numerical method for modelling the response of monopiles to monotonic and cyclic lateral loading to very large cycle numbers, by combining the PISA design model (e.g. Byrne *et al.*, 2019a) and the HARM framework (e.g. Abadie *et al.*, 2017b; Houlsby *et al.*, 2017). The approach is used to determine the in-service performance for a typical offshore monopile, embedded in a layered soil, and subjected to a load signal representing a 25 years of service loading, followed by a severe storm. The model captures the pile response to 3×10^8 cycles in 30 minutes computational time on a standard lap-top computer. The results identify the effect of ratcheting on the foundation response.

Keywords: monopile foundation, cyclic loading, constitutive modelling, lifetime prediction

INTRODUCTION

Offshore wind turbines are commonly founded on short rigid monopiles, of typical length to diameter ratio, L/D , of 3 to 6 (Fig. 1). The foundation is subjected to large lateral loads, comprising a combined moment and a horizontal load, arising from the action of the wind, waves and currents on the support and super-structure, as well as the operation of the turbine. Due to the repetitive nature of these loads, the design load scenarios include cyclic load

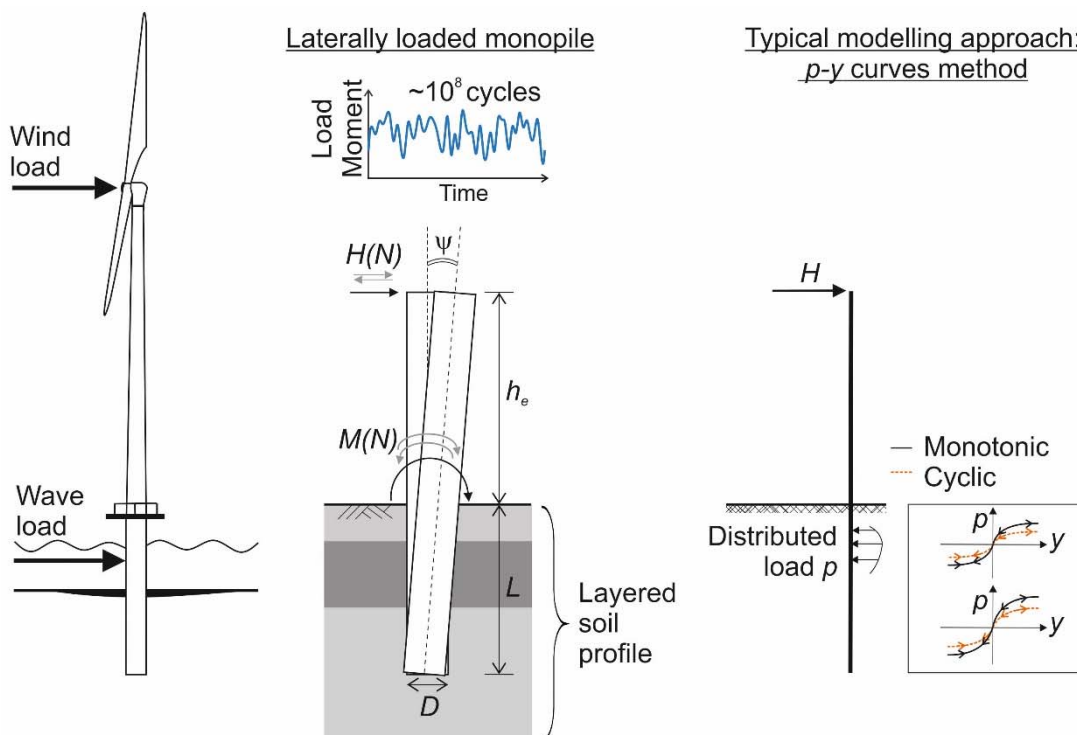


Fig. 1. Current modelling method for laterally loaded monopile

packets of variable amplitudes and magnitudes, with very large cycle numbers. Robust design of the foundation requires ensuring that the capacity is sufficient as well as limiting the deformation over 25 years of service life, typically 10^8 cycles, to acceptable levels. However, both the monotonic and cyclic responses are highly non-linear, and assessing the pile deformation over a large number of cycles accurately can be computationally prohibitive.

As a result, methods often used for pile design (e.g. the p - y method, DNV, 2014), typically employ simplified approaches adopting the Winkler modelling assumptions (Winkler, 1867). The pile is modelled as a 1D beam with the pile-soil interaction response represented by non-linear independent springs down the pile length. These springs relate the local soil resistance p to the pile displacement y at each depth (Fig. 1). Soil layers can be considered, but the model typically does not capture any interaction between the strata. Cyclic loading is typically addressed by applying degradation factors to the monotonic p - y curves, to represent degradation of the soil-pile springs with cyclic loading and to capture accumulation of permanent deformation for a representative number of cycles. Figure 2 illustrates how pile cyclic response may be modelled using such degradation factors for the Mustang Island pile (Reese *et al.*, 1974). As the global pile response is derived from the combined effect of these degraded curves, the global ground-level pile response would also display similar behaviour. This approach is computationally fast, and has been adopted in the offshore wind industry as a satisfactory compromise between conservative design and computation time. Industry practice sometimes adopts cyclic p - y springs to capture the degraded secant stiffness only, applied to both quasi-static and dynamic loads for structural design purposes. Pile accumulated rotation is assessed by applying the maximum FLS load to the static monotonic curve, and unloading with the initial stiffness using an isotropic hardening model (Fig. 2(b)).

With the increasing growth of the offshore wind industry, combined with strong governmental and industrial incentive for design optimization and cost reduction, there is a strong motivation to develop pile design methods further, particularly for cyclic loading. Monitoring of full-scale turbines (e.g. Kallehave *et al.*, 2012) demonstrates that the natural frequency of wind turbines is higher than that predicted using the normal p - y methods. In addition, the degradation factors currently employed to capture the design for cyclic loads are independent of the number of cycles applied (e.g. Fig. 2), and of the amplitude of those cycles. In response to these concerns, recent research has led to improved design approaches guidelines for ULS conditions (e.g. the PISA method - Byrne *et al.*, 2019a; Jeanjean *et al.*, 2017; the SOLCYP project - Puech, 2017) that should enable better optimisation of future monopile foundations.

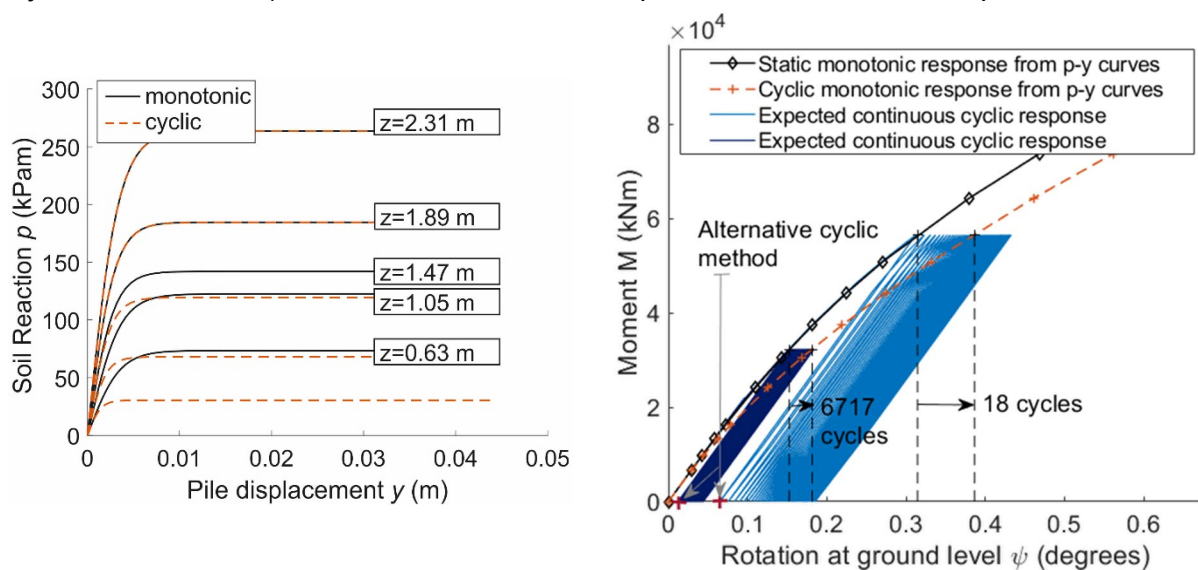


Fig. 2. Schematic representation of (a) the use of degradation factor for p - y curves to (b) compute the FLS pile response for Mustang Island pile (Reese *et al.*, 1974)

However, optimization of pile geometry for ULS design might lead to excessive deformations caused by long-term small-magnitude cyclic loads. Hence the development of more accurate and rigorous approaches for SLS and FLS design is needed.

Recently a new method for fast computation of long-term cyclic loading response of monopiles is emerging through the HARM framework (Abadie, 2015; Abadie *et al.*, 2017b, 2019; Houlsby *et al.*, 2017). This paper outlines a numerical modelling approach, combining the PISA design model and the HARM framework, to enable prediction of the pile ULS, SLS and FLS performance. An example application to a full-scale monopile, installed in a layered soil profile and subjected to a 25 year lifetime load signal, followed by a storm is used to illustrate the method.

MODELLING FRAMEWORK

The method employed in this paper consists of using the 1D PISA design model to derive the monotonic response accurately, followed by application of the HARM macro-element (0D) model to compute the cyclic response. The monotonic response is used as the input backbone curve. This analysis scheme is illustrated in Fig. 3. This approach has computational time advantages over a fully-integrated 1D model (discussed further in Beuckelaers (2017)).

1D PISA Design Model for Monotonic Loading

The 1D PISA modelling approach is described in Byrne *et al.* (2019a, 2019b) and Burd *et al.* (2020b), with further details about the modelling in layered soils provided in Burd *et al.* (2020a). In the method the monopile is represented by a line mesh of two-noded Timoshenko beam finite elements. The soil lateral response acting at the nodes is captured through four components: distributed lateral load p , distributed moment m , base horizontal force H_B and base moment M_B , as shown in Fig. 3, top left. These encapsulate the combined action of the lateral soil resistance and shear along the pile shaft and base.

Calibrated parametric “soil reaction curves” are derived to capture the soil reaction with local pile displacement v and rotation ψ . A conic function is used for each of the soil reaction curves, and normalised (Byrne *et al.*, 2019b). During the first phase of the PISA project, a method for calibration of the conic function for homogeneous soils was derived and validated for site-specific homogeneous soil profiles. The calibration process is derived from 3D finite element analyses, with the procedure outlined in Byrne *et al.* (2019b) for stiff glacial clay till and Burd *et al.* (2020b) for marine sand with varying relative densities ($D_R = 45\%$ to $D_R = 90\%$).

Modifications for layered soils

Extension for layered soil profiles is achieved through the hypothesis that *the soil reaction curves calibrated using homogeneous soil profiles can be employed directly to conduct 1D analyses of monopiles embedded in a layered soil* (Byrne *et al.*, 2019a). In other words, the interaction between layers is ignored in the 1D model. Within each layer, the normalised soil reaction curves are computed using the appropriate sand or clay framework derived from the homogeneous soil calibration, and the local values of small strain shear modulus G_0 , undrained shear strength s_u and initial vertical effective stress σ_v' (e.g. Fig. 4). Nodes are generated at the soil layer boundary to facilitate the layer change. Validation of this hypothesis is demonstrated by Burd *et al.* (2020a), showing that the 1D PISA design model provides sufficiently accurate predictions for most practical design cases.

The PISA method gives the monotonic pile response at ground level, to enable assessment of pile capacity and initial stiffness. This response also forms the *backbone curve* in the HARM approach. One of the more realistic soil profiles and pile geometry – case F1 in Byrne *et al.*

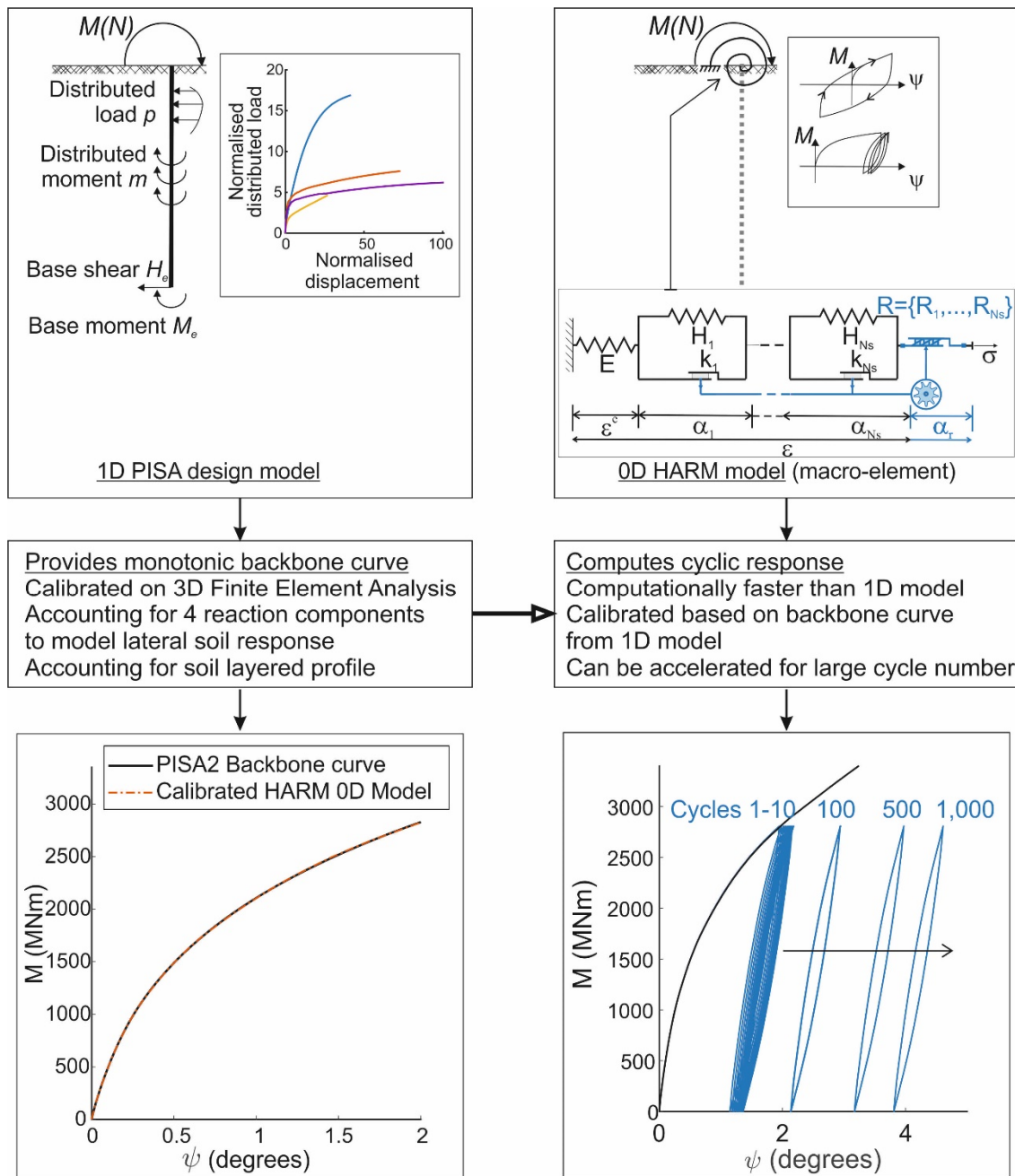


Fig. 3. Design Method (illustrated based on Case F1 response, see Fig. 4)

(2019a) – is used for the example calculation presented in this paper. Details of the soil profile for F1 are shown in Fig. 4, together with the pile response, as well as the G_0 , s_u and σ_v' profiles. The pile geometry is given in Table 1. Comparison with the computed 3D FE response shows that, in this case, the 1D model demonstrates excellent accuracy.

OD HARM Macro-Element for Cyclic Loading

The HARM approach is a development of constitutive modelling, derived through the hyperplasticity framework (Houlsby and Puzrin, 2006), specifically intended to capture ratcheting. The full details of the model are presented in Houlsby *et al.* (2017), with a calibration method and applications to rigid pile design to lateral cyclic loading shown in Abadie *et al.* (2019).

Table 1. Monopile dimensions used for modelling

Pile	D (m)	h (m)	h/D	L (m)	L/D	t (mm)	D/t
D2t	8.75	87.5	10	35	4	150	59

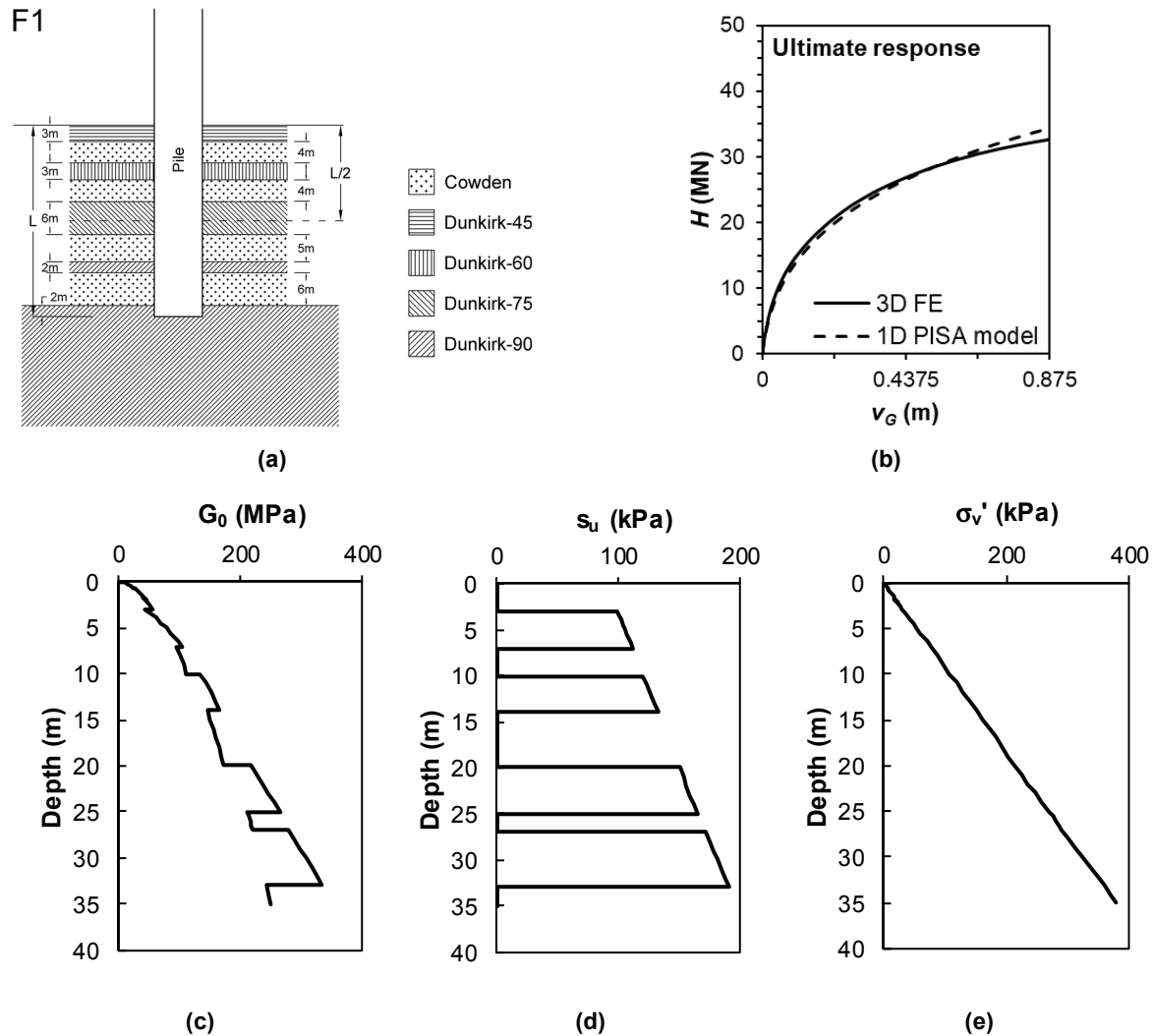


Fig. 4. Layered case F1 (Byrne *et al.*, 2019a)

HARM combines a ratcheting element with a kinematic hardening plasticity model (Fig. 3, top right), which provides both the accumulation of deformation with cycling, and the Masing behaviour commonly observed in pile tests (see for example Fig. 3). The amount of ratcheting strain accumulated during any un-load re-load loop is controlled through the family of parameters R_n , while the shape of the loop is defined by the backbone curve, itself described by the set of parameters E , H_n and k_n (see further detail in Abadie *et al.*, 2019).

One of the strengths of this model is that any amount of ratcheting strain accumulated within a group of cycles of the same magnitude and amplitude can be accelerated by simply multiplying the ratcheting rate R_n by the number of cycles to be skipped, enabling very fast computation for a large cycle number. The model naturally tracks each load increment, regardless of the load history. This means that, in the case of multi-amplitude load packets, the model captures the response to complex load scenarios, without the need to introduce additional assumptions such as Miner's rule (*e.g.* LeBlanc *et al.*, 2010; Miner, 1945). On changing load magnitude and/or amplitude, the acceleration factor must be disabled.

Table 2. Parameters for calibration of the HARM 0D model

	Definition	Value
β_0	Initial ratcheting strain	1×10^{-4}
m_r	Exponent defining the decrease of ratcheting rate with cyclic history	2.2
m_s	Exponent defining the increase of ratcheting rate with load intensity	8.9
R_0	Initial ratcheting rate	1.7

The HARM framework can be applied as the constitutive relationship for the stress/strain response at any level (macro-response of the pile or local soil response). Hence, HARM could be integrated within any of the monopile modelling approaches adopted to characterize cyclic behaviour at element level for 3D FE modelling, local response for 1D modelling or macro-response (0D model). However, the simplest and fastest approach is the 0D model, where the foundation reaction is captured using a macro moment-rotation spring (Fig. 3) only. Even as simplified to moment-rotation the current 0D model implementation provides a highly efficient link to structural analysis, and provides a very fast tool for investigation and modelling of wind turbine performance. For accuracy, it is recognised that future development could include the " $H - v_G$ " component and the induced cross-coupling terms between " M " and " H ", but it is unlikely that these developments would incur any great computational cost.

Calibration

The model relies on accurate prediction of the backbone curve, here produced using the 1D PISA design model. This backbone curve is used as an input for calibration of parameters E , H_n and k_n , and corrected to account for ratcheting, as described by Abadie *et al.* (2019). This provides the monotonic response shown in Fig. 3, which matches that obtained from the 1D PISA design model in Fig. 4(b).

Calibration of the ratcheting behaviour is achieved through the choice of the ratcheting rate R_n , according to:

$$R_n = R_o \left(\frac{k_n}{k_U} \right) \left(\frac{\beta}{\beta_o} \right)^{-m_r} \left(\frac{|\sigma|}{\sigma_0} \right)^{m_s} \quad \text{Equation 1}$$

Where β is the accumulated ratcheting strain, which acts as a memory of the cyclic history. β_0 is an arbitrarily small value used for normalisation purposes, σ_0 is the ultimate stress level, R_0 is the initial ratcheting rate and m_r and m_s are empirical exponents that control the evolution of the ratcheting rate with load history and stress/load level respectively. Accordingly, the ratcheting rate decreases with the accumulation of load cycles and increases with load magnitude.

The calibration method follows that outlined in Abadie *et al.* (2019) for laboratory piles in sand, with the same methodology and set of ratcheting parameters applied successfully for the modelling of large-scale field tests in clay by Abadie *et al.* (2017a). A consistent set of ratcheting parameters are hence adopted in this paper, as provided in Table 2. Given that the cyclic behaviour for clay and sand is very similar, it is likely that the framework applies similarly for layered soil profiles comprising of the same materials.

The modelling framework as presented here is used (i) to illustrate the design method, (ii) to

Table 3. Load regime characteristics

	Lifetime	Short Storm
Maximum moment [MNm]	1,270	2,250
M_{max}/M_{ult}	0.42	1/1.35=0.74
M_{min}/M_{max}	-0.97	-0.37
No. of cycles	2.6503 x10 ⁸	150
No. of load events	65,534	150
Modelling	Accelerated	Incremental
Computed number of cycles	187,459	150
Calculation time (0D, 500 increments) (Intel® core i7-8565U, 16GB RAM)	1,960 s.	0.38 s.

identify the potential of the method, and (iii) to display the type of behaviour expected from lifetime response. Of course more detailed analysis might require a 1D layered model, adapted to the HARM formulation; however, that is beyond the scope of this paper. It would also come at a higher computational cost.

MODELLING OF LIFETIME PERFORMANCE IN LAYERED SOIL

Loading History

The above framework was applied to the pile specified in Table 1, for the layered soil profile of Fig. 4, to explore performance under the loading given in Fig. 5. The monotonic response computed with the 1D PISA design model predicts an ultimate capacity of $M_{ult} = 3045\text{kNm}$, obtained for a maximum ground level displacement of $v_{G,ult} = 0.875\text{ m} = 10\% D$, and rotation of $\psi_{ult} = 2.43$ degrees. The loading represents a lifetime load signal, immediately followed by an extreme storm, and has been computed for a full scale offshore wind turbine. The loads have been scaled to be appropriate for foundation F1. Table 3 provides the characteristics of both the short storm and lifetime signals, with M_{ult} the ultimate moment capacity, M_{max} and M_{min} the maximum and minimum moment values.

The signal (Fig. 5(a)) includes $\approx 3 \times 10^8$ cycles, consisting of 65,534 individual load packets (referred to as “No. of load events” in Table 3), occurring in a random order. This was modelled using an acceleration programme that computed the first cycle of each load packet incrementally, with the remainder of each load series accelerated by a factor equal to the number of cycles of the series minus 2, with the last cycle of each load packet being computed incrementally. The first cycle must be computed incrementally to preserve the Masing behaviour and not distort the backbone curve; the remainder of the series can be accelerated without loss of accuracy. Computing the last cycle incrementally allows the cyclic response at the end of each load packet to be obtained independently. However, this is unnecessary if the intermediate response is not needed, with a small saving in computational time. In total, the acceleration procedures mean that 131,068 cycles were modelled for the lifetime load, with 500 load increments per computed cycle. The computation took approximately 30 minutes on a standard laptop (Table 3). Further reduction in computational time can be achieved by reducing the number of increments.

The lifetime signal is immediately followed by an extreme storm event (Fig. 5(b)), consisting of 150 cycles of random amplitude, all modelled incrementally. The maximum load of this signal is equal to $M_{max} = M_{ULS}/1.35 = 0.74 \times M_{ULS}$.

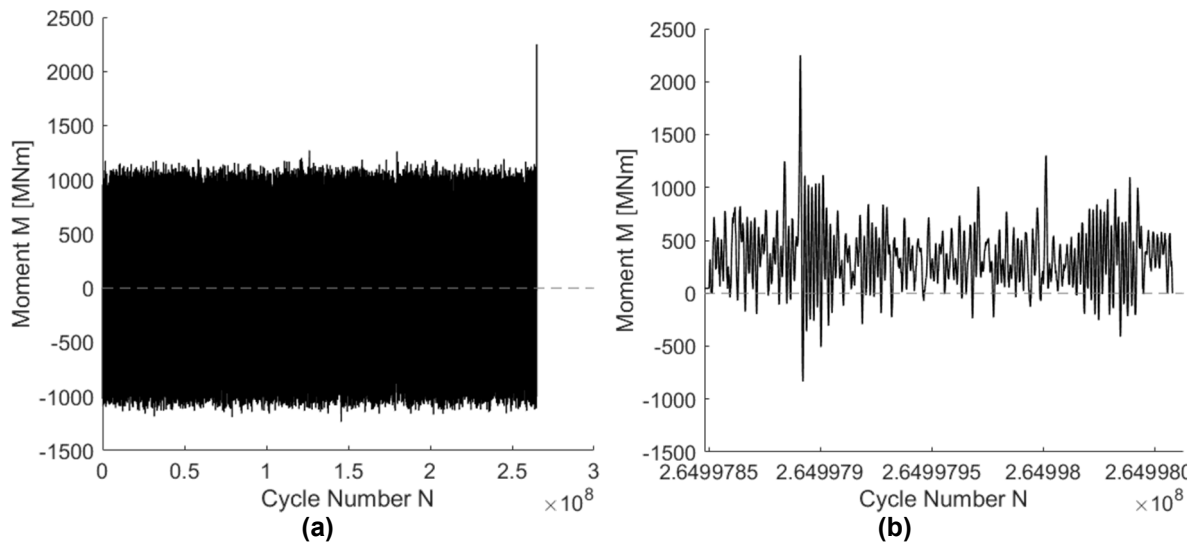


Fig. 5. (a) Modelled load signal; (b) final extreme storm event

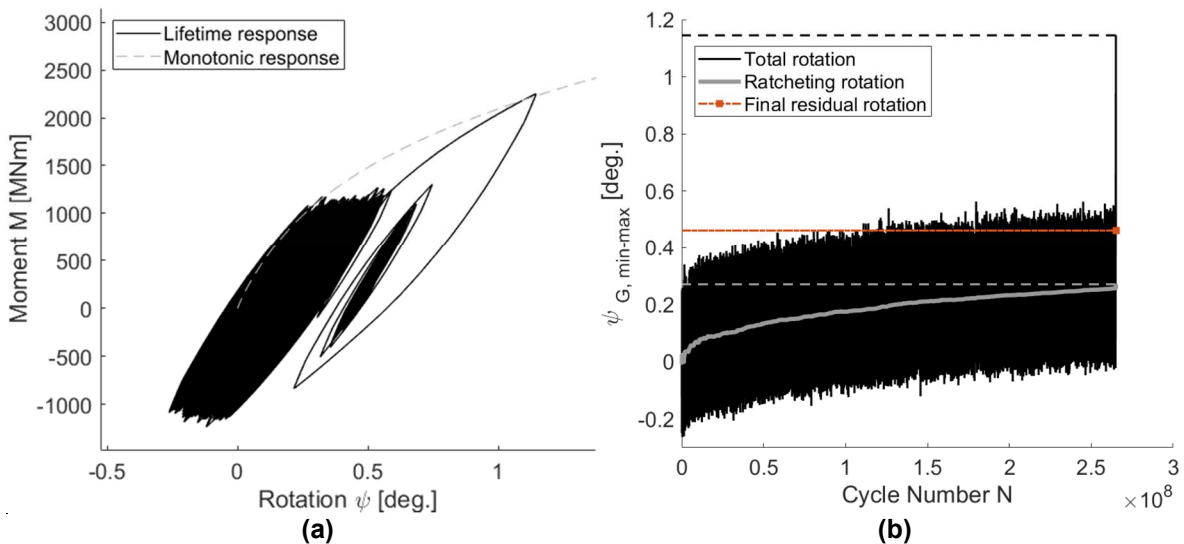


Fig. 6. Predicted pile response: (a) moment-rotation curve; (b) Evolution of the rotation with cycle number

Pile response

The resulting pile response is provided in Fig. 6, showing the evolution of the rotation with both moment loading and cycle number. Figure 6(b) highlights the evolution of the ratcheting strain, *i.e.* the proportion of permanent deformation caused by cyclic loading within the ratcheting element in HARM. The remainder of the deformation is caused by kinematic hardening plastic strain. Figure 6(b) also displays the final residual rotation, *i.e.* the rotation after complete unloading to zero. Typically for design, the residual rotation has to be limited to 0.5 degrees overall, with a maximum of 0.25 degrees caused by cyclic loading (*e.g.* Achmus *et al.*, 2009; DNV, 2014; Section 10.3.2.6, p. 173).

Figure 6(b) shows that the effect of ratcheting on the response is significant during long-term cyclic loading at moderated load magnitude, as shown by the final residual ratcheting deformation highlighted by the dashed grey line. During the final short storm event, the effect of ratcheting on the overall response is limited, and the response is dominated by the deformations induced by the largest load event.

When comparing with the behaviour obtained from conventional cyclic p - y approach (e.g. Fig. 2), the key differences are:

- (i) The integrated PISA-HARM approach captures unloading, and hence, residual deformation following a specific load series,
- (ii) The model accounts for cycle number,
- (iii) The model captures the response to load packets of varying magnitude and can capture the change in behaviour between long-term cyclic loading of medium intensity, followed by a storm,
- (iv) The model tracks the evolution of the pile response over time/cycle number, and could enable to assess lifetime extension for already installed monopiles if the past load history were known.

CONCLUSIONS

This paper outlines a method for computation of the response of large diameter monopiles to long-term cyclic loading, representative of the service life for an offshore wind turbine. The model combines the 1D PISA design model and the HARM framework, enabling the computation of pile response to very large cycle number, of varying load magnitudes and amplitudes.

The method is demonstrated through modelling of a pile in a layered soil profile subjected to a realistic load signal representing lifetime loading, followed by a large storm. The results illustrate the accumulation of permanent deformation throughout the 3×10^8 cycles, predicting both pile deformation caused by cyclic loading and residual deformation after unloading. The model shows progressive accumulation of permanent deformation over the lifetime of the turbine, with the response to the final storm dominated by the monotonic response to the largest load.

This modelling framework is a useful tool that enables further understanding of pile response to cyclic loading, and could, for example, be used to investigate the effect of load history on pile response. The HARM model adopted for the example accounts only for kinematic hardening and ratcheting, but other phenomena, such as rate dependency and gapping, could also be incorporated in the future.

ACKNOWLEDGMENTS

The authors acknowledge the financial and in-kind support of Ørsted. Byrne is supported by the Royal Academy of Engineering under the Research Chairs and Senior Research Fellowships scheme.

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