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Impact of cyclic soil degradation on the design of offshore wind turbine foundations

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ABSTRACT: Offshore wind energy plays a critical role in meeting global renewable energy demands. The appropriate design of foundations for offshore wind turbines is a crucial aspect of successful offshore wind farm development, typically accounting for 20% to 30% of the overall capital costs. While many researchers have studied and proposed different approaches to determine soil springs for soil-structure interaction employed for foundation design, there is a general lack of consistency in adopting the soil spring methods across different parts of the world, and no clear guidelines in design codes and standards regarding the applicability of soil springs for different sites and environmental loading conditions. This is particularly the case when it comes to using soil springs to model foundation response under cyclic and seismic loadings. This paper investigates the influence of cyclic soil degradation on the lateral response of large-diameter monopile foundations, using simplified degradation models applied to PISA-based soil springs. A representative case study from East Asia is analysed, adopting various degradation approaches from literature and practice. Sensitivity analyses are conducted to assess impact of degradation on key design metrics, including natural frequency, pile deflection, and internal forces. The study provides practical insights into the selection of appropriate cyclic degradation approach in early design stages of offshore wind foundations.

KEYWORDS: offshore wind turbines, monopile foundations, p-y springs, PISA approach, cyclic degradation

1 INTRODUCTION

The foundations supporting offshore wind turbines are subjected to cyclic loadings primarily induced by wind, waves, and earthquake events throughout their life. Cyclic loadings can cause the accumulation of strain and excess porewater pressure in the soil layers supporting the foundation, often resulting in the degradation of the soil shear strength and stiffness. Understanding the cyclic behaviour of Offshore Wind Turbine (OWT) foundations is a critical aspect of design to ensure structural stability and meeting the performance requirements.

Soil behaviour under cyclic loading is a complex phenomenon, and there is currently no widely accepted methodology in the industry for use in the design of OWT foundations. A reliable assessment of the foundation cyclic response normally requires:

- High-quality in-situ and cyclic laboratory testing (e.g., cyclic simple shear, cyclic triaxial, or cyclic hollow cylinder tests). Anderson (2015) outlined the key cyclic soil parameters for offshore foundation design. It is important to note that soil shear strength and deformation parameters are stress path dependent and the laboratory testing should aim to replicate the anticipated loading conditions.
- Numerical modelling techniques employing advanced cyclic constitutive soil models, such as SANISAND or similar, simulating the porewater pressure development and cyclic degradation in soils. This approach has been successfully adopted by the authors in the design of monopiles for offshore wind turbines. Refer to Gallese et al. (2023); Go et al. (2025) for details.

However, cyclic laboratory testing results are typically unavailable or limited at the early stages of a project. Furthermore, advanced numerical models are computationally intensive, require specific input soil parameters, and demand expertise in model development, load application, and results interpretation. Therefore, more simplified methods are usually preferred at the early design stages of the offshore wind projects.

The simplified methods often include applying a degradation factor to the static p–y soil springs to account for the effects of cyclic loading. In the authors' experience from working on several offshore windfarm projects in East Asia, different cyclic degradation factors have been adopted by designers. This paper compares some of the commonly used approaches and evaluates their impact on the selected case study of a 15 MW turbine supported by an extra-large monopile with ~ 9m diameter embedded into granular soil layers in the East Asia region.

2 METHODOLOGY

2.1 *Static p-y springs*

Lateral soil springs (known as p-y springs) are commonly used to simulate soil-structure interaction and the lateral behaviour of piles under the imposed environmental and operational loadings in the early stages of the design. Among the most widely adopted methodologies in the offshore wind sector are API and PISA approaches.

The API p–y springs were initially developed from field tests on long, slender piles, and the shortcomings of their application to large-diameter monopiles (e.g., piles with diameters exceeding 2.5 m) have been well recognized. To overcome these limitations, modified API springs can be used, mainly by adjusting the initial stiffness (i.e., modifying the initial portion of the API p–y curves) to obtain a more accurate estimation of monopile response (Yin et al., 2023).

PISA project was initiated aiming to address the limitations of the conventional methods for large diameter monopiles in offshore wind industry. PISA approach (e.g., Burd et al., 2020) introduces a more comprehensive framework for modelling soil-pile interaction by incorporating four components of soil reaction acting on the monopile (see Figure 1), including:

- Distributed lateral load (p)
- Distributed moment (m)
- Base horizontal force (H_B)
- Base moment (M_B)

These components enable more realistic simulation of monopile behaviour under the applied loading conditions. The PISA methodology has been successfully applied to offshore wind projects in Europe and Asia, offering improved accuracy and design efficiency for large diameter monopiles. However, PISA approach was derived from field tests conducted under static loading conditions, which limits its direct applicability under cyclic loadings without further validation.

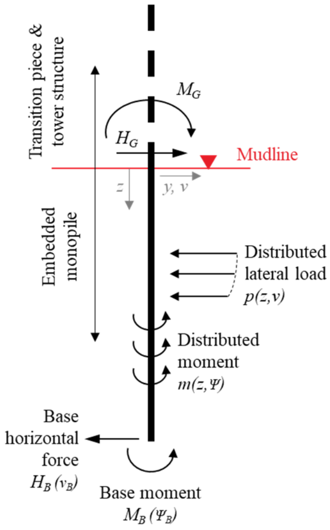


Figure 1. PISA Approach (After Burd et al. (2020))

2.2 *Cyclic degradation*

2.2.1 *API approach*

The main international standards and recommended practices for offshore windfarm foundation design, such as API RP 2GEO (2021), DNV-RP-C212 (2021), ISO 19901-4 (2025), refer to the conventional p-y curves initially developed by O'Neill and Murchinson (1983) for granular soils. To consider the cyclic loading effect on laterally loaded piles in granular soils, API approach applies a reduction factor to degrade the soil resistance in static p-y curves, see Equation (1):

$$p = A \times p_u \tanh\left[\frac{k \times z}{A \times p_u}\, y\right] \qquad (1)$$

where,

$$A = \left(3.0 - \frac{0.8z}{D}\right) > 0.9\ for\ static\ actions, and$$

$$A = \ 0.9\ for\ cyclic\ actions$$

The definitions of the remaining parameters in Equation (1) can be found in API RP 2GEO (2021). Equation (1) indicates a 70% reduction at the mudline for cyclic actions, with a linear increase down to a depth of 2.625D, where D is the pile diameter. Below this depth, no distinction is made between the static and cyclic p–y curves (see Figure 2).

2.2.2 *Alternative approaches*

In the authors' experience and based on the literature review, the following approaches, among others, have been adopted as an alternative to API approach:

- Ignazio et al. (2025) recommends an approach based on cyclic contour diagrams. For instance, this approach results in a degradation factor of 0.6 at the mudline, increasing to 1.0 at a depth of 1.8 pile diameters (D), remaining constant until 2.67D, and then gradually decreasing with depth in dense granular material.
- Baek & Kim (2022) suggest that for dense soil (i.e. D_r ~90%), the degradation factor starts at 0.75 at the mudline and increases to 1.0 at a depth of 13D. For looser soil (i.e. D_r ~40%), begins above 1.0 (reaching 1.15 at the mudline due to loose soil densification under cyclic loadings) and decreases linearly to 1.0 at 19D.
- Gazioglu & O'Neil (1984) is a more conventional approach adopted in practice which proposes a constant value of 0.8 to represent cyclic reduction effects.

These approaches for dense granular soils are illustrated in Figure 2, which plots degradation factors against normalized depth (z/D). Refer to the cited references for further details.

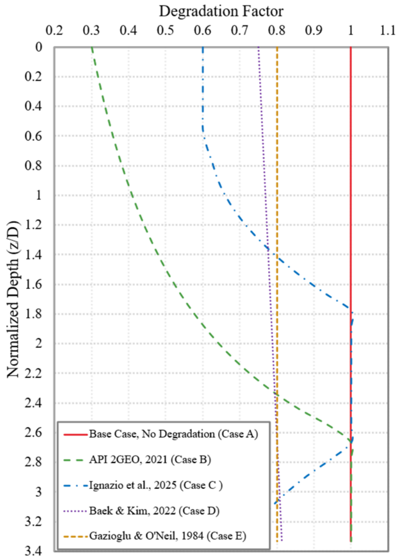
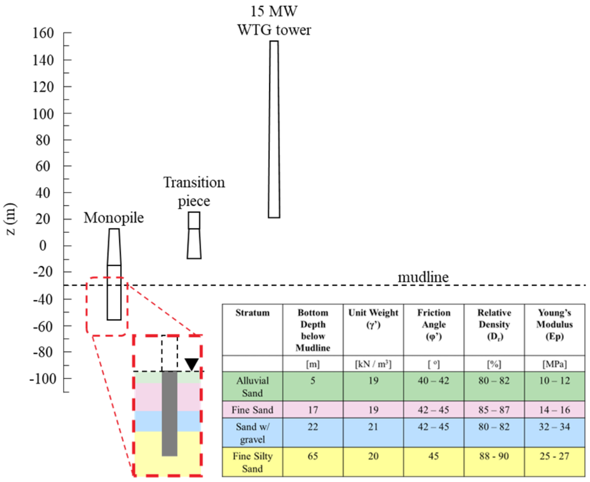


Figure 2. Cyclic degradation factors along pile depth in dense granular soil.

3 CASE STUDY

3.1 *Selected case study*

This case study examines an idealised offshore site modelled after real-world conditions encountered during the design of an offshore wind farm in East Asia. The site features shallow water with a depth of approximately 28 meters. The soil stratigraphy consists of generally dense sandy layers overlaying fine-grained sedimentary rock (siltstone). Figure 3 presents the geological profile of the project case, highlighting key geotechnical parameters that were derived from site investigation. The engineering bedrock is located 65 meters below the seabed.



Stratum	Bottom Depth below Mudline	Unit Weight (γ')	Friction Angle (φ')	Relative Density (D_r)	Young's Modulus (Ep)
	[m]	[kN / m³]	[°]	[%]	[MPa]
Alluvial Sand	5	19	40 – 42	80 – 82	10 – 12
Fine Sand	17	19	42 – 45	85 – 87	14 – 16
Sand w/ gravel	22	21	42 – 45	80 – 82	32 – 34
Fine Silty Sand	65	20	45	88 - 90	25 - 27

Figure 3. Schematic geometry of the offshore wind turbine structure along with representative design profile and key soil parameters

The optimised structural configuration is also illustrated in Figure 3, showing monopile (MP), transition piece (TP), tower, and rotor nacelle assembly (RNA). The MP has a top diameter of 7.3 meters, which gradually increases to 9 meters and remains constant down to the bottom. It features an embedment length of 28 meters, with can thicknesses ranging from 85 to 100 mm. The TP has a diameter of 8 meters at the interface and includes a tapered section that widens to approximately 9 meters at the bottom for connection with the MP. The can thickness of the TP ranges from 70 to 80 mm. The MP and TP are connected by a grouted connection.

3.2 *Design of substructure*

The substructure is designed to satisfy the requirements for Serviceability Limit State (SLS), Ultimate Limit State (ULS), Fatigue Limit State (FLS), and Accidental/Earthquake Limit Stage (ALS). This includes, but is not limited to, geotechnical checks, structural checks for MP and TP, system natural frequency checks, fatigue analysis and deformation/rotation checks.

In offshore foundation design, the loadings broadly can be categorized in permanent, environmental and functional loads in accordance with DNV-ST-0437 (2024). In the preliminary design stage, the information for deriving functional loads is generally not available. Therefore, permanent and environmental loads including gravity, wind, hydrodynamic and seismic loads are commonly relied for preliminary foundation sizing. Refer to Yin et al. (2023) for more details on the adopted design approach.

To perform the analyses against all the above-mentioned checks, generic input data for a 15 MW offshore wind turbine was adopted, including tower geometry, interface loads, and the mass of secondary steel and appurtenances. This standardized configuration ensures consistent comparison across different degradation models.

The ground profiles, geometric data, and design loads were input into Optif, Arup's in-house automated offshore wind foundation design tool. Optif utilizes Oasys GSA as its finite element solver, providing results consistent with those from DNV GeniE, ensuring reliability and comparability in evaluating foundation response under the applied loads.

3.3 *Sensitivity analyses*

To evaluate the influence of cyclic degradation on monopile performance, four different cyclic degradation approaches were applied to modify PISA-derived soil springs:

- API RP 2GEO (2021) – Case B
- Ignazio et al. (2025) – Case C
- Baek & Kim (2022) – Case D
- Gazioglu & O'Neil (1984) – Case E

The degradation factors applied along the pile depth for each method are illustrated in Figure 2. For a more comprehensive comparison, a base case with no degradation was also included in the sensitivity analysis, referred to as Case A from hereafter.

The sensitivity analysis was conducted using monopile configurations embedded in the geological profiles, as shown in Figure 3.

3.4 *Analysis results*

The monopile responses in terms of bending moments, shear forces, and lateral deflections for different sensitivity cases are shown in Figure 4 and Figure 5, respectively. The analysis results show that smaller degradation factors lead to increased structural demands, as expected. For instance, the peak values of the bending moments and shear forces are increased up to 5% and 29% as compared to the base case (Case A).

Using different degradation approaches not only impacts the peak values, but also the bending moment and shear force profiles along the monopile embedded depth, which can be more critical for the design perspective. For instance, the monopile section at the elevation of ~-48m experiences up to 42% extra bending moments in Case B as compared to Case A. This value for Cases C, D, and E is limited to 12%.

Referring to the shear force profile in Figure 4, while the shear forces at the lower portion of the embedded monopile reduce by adopting the degradation factors, this is not the case for the upper portion of the embedded depth (say above ~45 m). For instance, the shear force in Case B at the elevation of ~36 m is close to zero (which corresponds to the location of maximum bending moment), but the same value in the other cases is up to ~30 MN. This means that applying a lower degradation factor may not necessarily result in a safe design.

Table 1 summarises the 1st natural frequency and monopile rotation at the mudline for different sensitivity cases. The natural frequency of the entire system (tower and foundation) is a key design requirement specified by the wind turbine supplier to ensure it remains within the permissible range relative to the expected rotor and blade excitation frequencies. According to Table 1, the impact of different degradation factors on the natural frequency of the system appears to be minor and limited to less than ~3%.

Furthermore, and referring to Table 1, while the monopile rotation at the mudline remains well within the acceptable design limit of 0.25 degrees throughout the structure's lifetime, the impact of adopting different degradation approaches is apparent. For instance, Case 2 results in ~30% extra rotation at the mudline level in the selected case study.

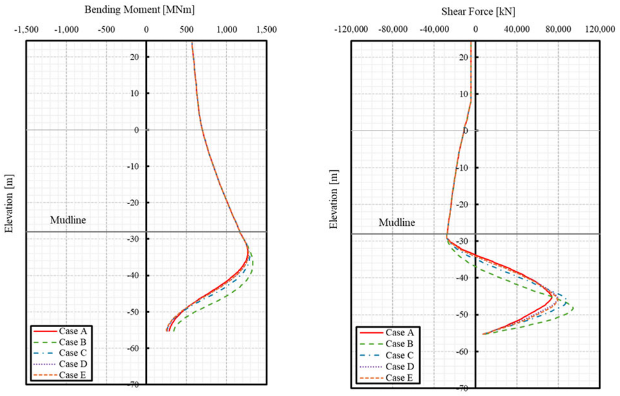


Figure 4. Profile of bending moment (left) and shear force (right)

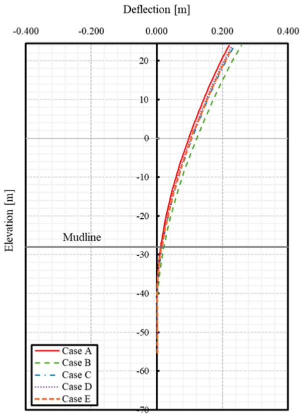


Figure 5. Profile of deflection

Table 1. Summary of natural frequency and pile rotation at mudline

Case	1st natural frequency [Hz]	Rotation at Mudline [deg]
A	0.171	0.136
B	0.166	0.178
C	0.169	0.155
D	0.169	0.147
E	0.170	0.144

4 COMPARISON BETWEEN PISA AND API SPRINGS

As mentioned in Section 2.1, the modified API p-y springs, beside PISA approach, have been commonly used in the industry for offshore wind turbines foundation design. Unlike PISA approach, which consists of four components as discussed in Section 2.1, API approach only relies on a single set of p-y springs to represent the soil reaction.

To assess the impact of soil spring methodologies on the design, a comparative analysis was conducted using soil springs derived from both API and PISA methods. The analysis employed identical turbine structure configurations, geological profiles, and geotechnical parameters as presented in Figure 3.

The same modelling framework and sensitivity analysis approach used for cyclic degradation assessment were applied to this comparison. Specifically, the influence of API and PISA soil springs, incorporating a cyclic degradation factor of 0.8 (i.e., Case E applied to PISA springs), on foundation performance was evaluated.

This approach enables a direct comparison of the dynamic and structural responses resulting from different soil spring formulations, offering insights into the impact of the selected approach on the design of large diameter monopiles under realistic offshore conditions.

4.1 *Analysis Results*

The derived API and PISA lateral load springs are shown in Figure 6 at selected depths. It can be seen that at the given geology the Modified API springs tends to have higher initial stiffness (corresponding to the soil layer stiffness at small strain) as compared to PISA springs. However, the overall monopile response appears to be generally comparable with different in mudline rotation of less than 4% and estimated maximum bending moment and shear forces within ~3% and 15%, respectively.

Note that this comparison highly depends on the ground conditions, foundation geometry, and the applied loads. Three-dimensional numerical pushover analysis (e.g. using LS-DYNA or similar) are recommended to verify the selected soil springs for the design.

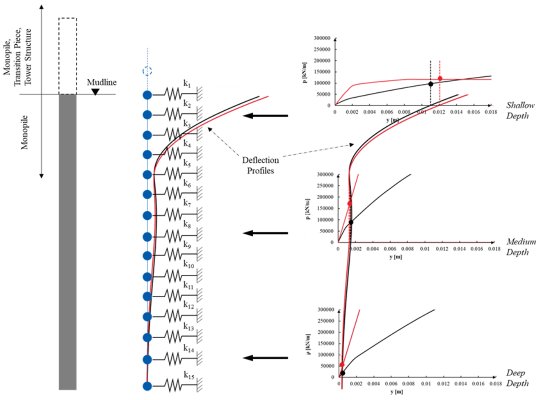


Figure 6. Comparison between PISA and API p-y springs. The black deflection profile and soil reaction curves correspond to PISA, while the red profile and curves correspond to API.

5 CONCLUSIONS

The main conclusions and recommendations are as follows:

- Despite several efforts in recent years coinciding with the rapid development of offshore wind energy, there is currently no widely accepted methodology to account for cyclic behaviour of the granular soil in practical design.
- API approach, originally developed for slender long piles, has certain limitations and does not capture the key parameters impacting the cyclic behaviour of granular soils, such as relative density, fine contents, load characteristics, etc.
- While API approach appears to suggest smaller degradation factors as compared to the alternative approaches in this study, it may not necessarily result in a conservative design, as shown in the presented results.
- The alternative approaches (Case C, Case D, and Case E) appear to predict comparable behaviour in the selected case study for the early design stage.
- High-quality soil in-situ and cyclic laboratory testing results together with advanced numerical simulations are recommended for verification purposes at the detailed design stage.

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