Effect of Uncertainty in CPT End Resistance on Predicted Monopile Head Load-Displacement Responses for Offshore Wind Turbines

Luke J. Prendergast
Assistant Professor, Dept. of Civil Engineering, University of Nottingham, Nottingham, UK

Jacques Tott-Buswell
PhD Researcher, Dept. of Civil Engineering, University of Nottingham, Nottingham, UK

Cormac Reale
Lecturer, Dept. of Civil Engineering, University of Bath, Bath, UK

ABSTRACT: The increasing demand for renewable energy has led to the rapid growth of the offshore wind sector, leading to larger Offshore Wind Turbines (OWT) being developed in deeper water locations further offshore. The geotechnical design procedures therefore become increasingly uncertain as ground investigations become more challenging, and the use of traditional design methodologies are applied to configurations outside of the datasets from which they were originally derived. This paper evaluates the influence of certain elements of geotechnical uncertainty on the monotonic load-displacement behaviour of laterally loaded monopiles. A traditional Beam on Nonlinear Winkler Foundation (BNWF) model is used to characterise the lateral pile-soil interaction, and the *p-y* springs are informed using Cone Penetration Test (CPT)-based functions. Geotechnical uncertainty is evaluated through the spatial variability of the CPT end resistance profile. Results suggest that spatial variability in end resistance profiles has limited effect on the pile head displacement predictions, highlighting a potential issue whereby local variations in soil properties may not be captured in *p-y* only models. This implies other spring-type components associated with diameter-dependency are necessary in the BNWF model to capture rigid pile behavior.

1. INTRODUCTION

Transitioning away from fossil fuels towards clean renewables is now a major central agenda of governments in Europe to combat climate-change effects. Of the variety of renewable energy sources, renewable electricity from offshore wind turbines is among the most technologically-mature. In the UK, 12 GW of installed capacity already exists across more than 38 sites, which already supplies 12% of the UK's energy needs (UK Department for International Trade 2023). A recent British Energy Security Strategy aims to have 50 GW installed capacity by 2030, sufficient to power every home in Britain. This requires significant expansion of the sector.

The rate of development of technology in the offshore wind sector has accelerated since the early 2000s, with larger turbine sizes leading to higher energy yields and increased efficiency. Since 2002, wind turbines have increased in height from an average of 93 m to more than 235 m in 2022 (UK Government 2019). The rapid technological developments enabling this advancement have come at the cost of certainty in the design and behavior of supporting foundations. To date, 81% of installed offshore wind turbines in Europe are supported on single, large-diameter piles known as monopiles (WindEurope 2021). The pace of development in turbine technology has led to the increase in the size of monopiles being used as support structures. Monopile diameters have increased from an average of 4-6 m in the 2010s (Peder Hyldal Sørensen and Bo Ibsen 2013; Prendergast et al. 2015) to over 10 m and beyond in development today. In that time, embedded lengths have remained relatively stable at between 20 m and 40 m. This means the slenderness ratio, length (*L*), normalized by diameter (*D*), has reduced substantially. This implies that the systems in use today are significantly more rigid than those used to support other offshore structures such as oil and gas platforms, which typically had high flexibility (large *L*/*D* ratios).

The design of offshore monopiles against lateral loading from wind and waves traditionally involves treating the pile as a beam on a Winkler foundation (Dutta and Roy 2002; Prendergast and Gavin 2016) and modelling the soil-structure interaction using a series of uncoupled springs along the pile beam. Known as the *p*-*y* method, this approach is favoured among designers due to the ease of specifying the spring properties. The *p*-*y* method involves characterizing soil spring behavior as a nonlinear function of lateral soil pressure (*p*) against lateral displacement (*y*), and is prescribed in offshore design codes such as the American Petroleum Institute (API) (API 2007) and Det Norske Veritas (DNV) (Det Norske Veritas 2011). In the past, methods that were originally intended for long, flexible piles such as the API method in sand, which prescribes a hyperbolic tangent model for the *p*-*y* curves, has been extensively used. As monopiles have become more rigid, newer approaches have been proposed. The main drawback with the API approach for piles in sand lies with the specification of geotechnical parameters. It relies on a depth-independent coefficient of subgrade reaction, the angle of friction, and relative density only to characterize the soil response. This has been found to be increasingly problematic when applied to monopile design (Burd et al. 2020; Byrne et al. 2019; Chortis et al. 2020; Reale et al. 2021; Xue et al. 2016).

Newer approaches make use of in-situ geotechnical data such as Cone Penetration Tests (CPT) to characterize the soil-structure interaction response. CPT data, which provides an indication of the soil strength with depth, has been used to develop axial capacity design approaches such as the IC-05 (Jardine et al. 2005) and UWA-05 (Lehane et al. 2005) approaches due to the analogy between installing a CPT cone and installing a pile (Byrne et al. 2018). A variety of approaches have been proposed to derive *p*-*y* curves using CPT data. One such method by Suryasentana and Lehane (2014) proposes an exponential function for *p*-*y* curves in sand derived as a function of CPT cone resistance.

The rate of development in offshore wind from the perspective of evolving structural geometries, increased turbine heights, move to deeper water offshore locations, uncertainty in geotechnical testing, CPT-based *p*-*y* formulations, added mass of soil (Prendergast et al. 2019; Wu et al. 2018), and model uncertainty, means the responses of offshore monopiles to wind and wave loads is not well-understood. In this paper, the influence of geotechnical uncertainty in CPT data on the resulting monopile head deflections is investigated by means of probabilistic analysis of CPT data and development of a beam supported by *p*-*y* springs.

2. UNCERTAINTY IN GEOTECHNICAL DATA

Soil is a natural and variable material, and its characterization is subject to significant uncertainty. Aleatory uncertainty (or natural variability) refers to spatial and temporal variations (Reale et al. 2017) in soil and is a fundamental soil property. Epistemic uncertainty is caused by a lack of understanding. Geotechnics is full of various forms of uncertainty including model uncertainty, measurement issues, parameter transformation, and layering (stratification). In the present paper, uncertainty related to the spatial variability of soil (CPT) data is analyzed in terms of how it influences the predicted load-displacement behavior of a monopile. Stochastic CPT data is created using a random field approach (Fenton and Vanmarcke 1990; Griffiths et al. 2009; Lloret-Cabot et al. 2014; Reale et al. 2021), which can describe the spatial variation in soil strength. These CPT data are developed using estimations of the mean, standard deviation, and the scale of fluctuation (θ), where θ represents the average distance over which significant correlation exists in soil properties. Information on how to develop spatially-varied CPT data are available in Refs. (Prendergast et al. 2018; Reale et al. 2021). An example of the generated CPT data is presented in Figure 1. Figure 1(a) shows data for a uniform strength profile (akin to an over-consolidated deposit), and Figure 1(b) shows a linearly increasing strength profile (akin to normally-consolidated). The data shown is for CPT data with a scale of fluctuation of θ = 1 m and with a Coefficient of Variation (CoV) = 0.3.

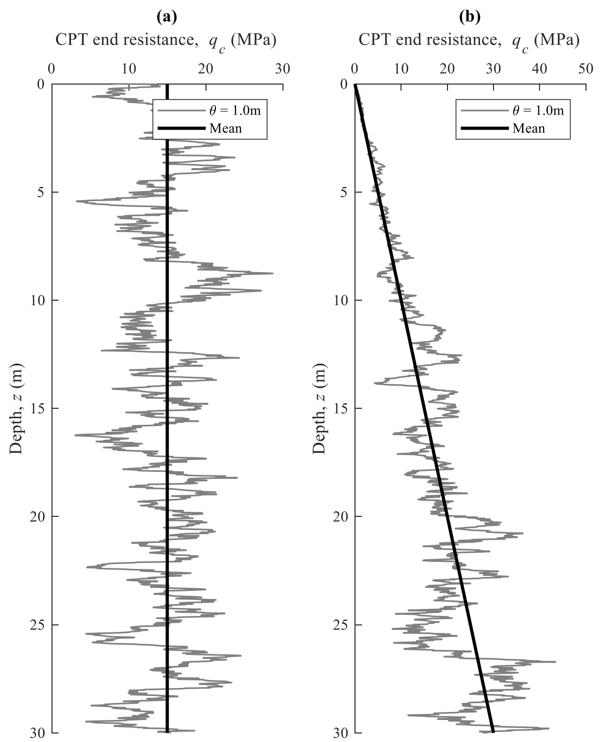

Figure 1: Example CPT data with scale of fluctuation of 1 m, (a) uniform profile, (b) linearly increasing profile

3. MONOPILE *P-Y* MODEL

The static nonlinear response of a monopile can be calculated using beam on nonlinear Winkler foundation (BNWF) models. These comprise Euler-Bernoulli or Timoshenko beams (Clough and Penzien 1993; Kwon and Bang 2000) coupled with discrete nonlinear springs (Winkler 1867). The soil reaction (p) - lateral displacement (y) properties of these springs can be characterized using a variety of approaches, detailed in the API (API 2007) and DNV (Det Norske Veritas 2011) offshore design codes. These typically require the input of parameters such as angle of friction or relative density and require that soil layers be discretized with average layer properties. More recently, methods have been developed to characterize these *p-y* curves using CPT data (Suryasentana and Lehane 2014), which provides an improved estimate of the inherent soil properties and its variability. A schematic of a monopile modelled using discretized BNWF elements is shown in Figure 2, whereby the super-structural loads can be reduced to a set of pile head loads and moments.

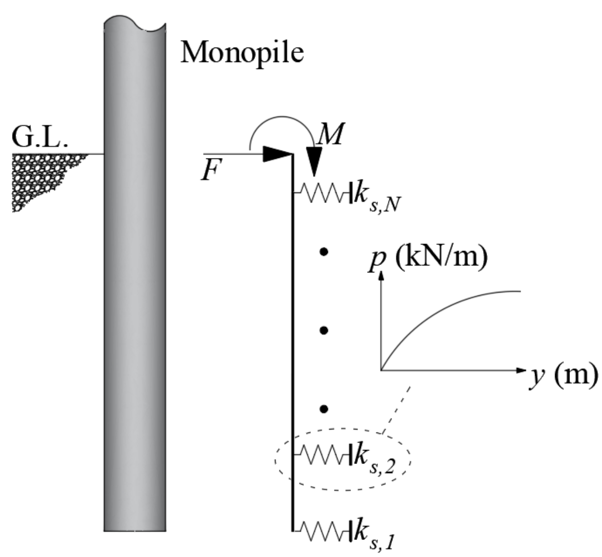

Figure 2: Monopile model as BNWF with inset p-y curve (G.L.= ground line, M = moment, F = force)

The CPT-based *p-y* model used in this paper is shown in Equation (1).

$$\frac{p}{\gamma z D} = 2.4\left(\frac{q_{c,avg}}{\gamma z}\right)^{0.67}\left(\frac{z}{D}\right)^{0.75} \times \left\{1 - \exp\left(-6.2\left(\frac{z}{D}\right)^{-1.2}\left(\frac{y}{D}\right)^{0.89}\right)\right\} \quad (1)$$

where p is the soil reaction at a given spring depth (kN/m), γ is the bulk unit weight of the soil (kN/m^3), z is the depth to each spring (m), D is pile diameter (m), y is lateral spring deflection (m), and $q_{c,avg}$ is the CPT end resistance value averaged over the discretised spring length (kPa). Equation (1) is an exponential function of p and y. The initial slope of the exponential function is infinite, so the expression in Equation (2) has been proposed to specify the initial stiffness, which is used as the starting stiffness in nonlinear analysis (Prendergast and Igoe 2022) or as the small-strain stiffness in dynamic analysis.

$$E_{s0} = \left(\frac{dp}{dy}\right)_{y=0} \approx 4G_0(1+v_0) \approx 4.5G_0 \qquad (2)$$

where G_0 is the initial shear modulus of the soil and v_0 is the Poisson ratio. The initial shear modulus can be correlated to CPT end resistance using the rigidity index (Lunne et al. 1997), as demonstrated in Prendergast et al. (2013) for a dense sand site, whereby $G_0 = nq_c$, n = 5 to 8 for dense sand.

The nonlinear displacement response of the monopile is derived as follows. An initial stiffness is applied to each spring in the assembled multi-degree-of-freedom (MDOF) model (see Figure 2) using Equation (2). The load and moment are applied and the displacement along the pile is derived by inverting the stiffness matrix and multiplying by the applied forcing vector. The new spring displacements are substituted into Equation (1) to derive new soil reactions, and a new estimate of the stiffness of each spring is calculated as p_i/y_i for the *ith* spring. This process repeats until a tolerance is met whereby the displacements for iteration n are within a fixed acceptable distance of those of iteration *n-1*.

4. ANALYSIS AND RESULTS

In this section, the results of applying lateral loads and moments to an example monopile to ascertain the influence of spatially varied CPT data on the response features are presented. The properties of the monopile used are presented in Table 1.

Table 1: Parameter values.

Parameter	*Value*	*Units*
Diameter	6	m
Thickness	0.08	m
Elastic modulus (Steel)	200	GPa
Length	30	m

The loads applied are design loads and moments, which are derived for a typical offshore wind turbine, and are 1155 kN and 93225 kNm, respectively. These are derived assuming a simplified load basis for environmental (wind and wave) loads, more detail of which is presented in Prendergast et al. (2018).

The influence of varying the spatial variability (scale of fluctuation) of the CPT profiles on the resulting pile head lateral deflections and rotations is investigated. Both the linearly increasing and uniform CPT mean profiles from Figure 1 are used in the analysis. The results are presented in Figure 3 for the uniform CPT mean profile for varying scales of fluctuation, and for the linearly increasing CPT mean profile in Figure 4 for varying scales of fluctuation. Part (a) of both plots shows the pile head displacements, and part (b) shows the pile head rotations.

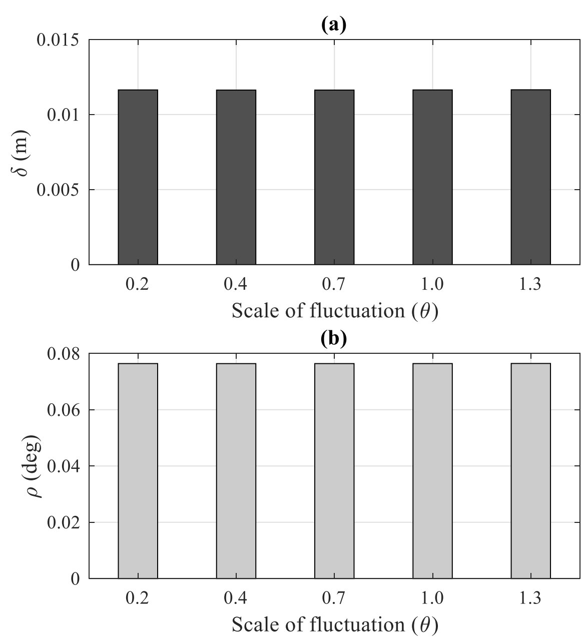

Figure 3: Pile head (a) deflection and (b) rotation with varying scales of fluctuation for uniform CPT profile

The data in Figures 3 and 4 show that increasing the scale of fluctuation has a negligible effect on the resulting pile head displacement and rotation, for a given mean CPT profile. This suggests that in the process to obtain discrete spring stiffness moduli for the Winkler springs, the variability averages out. The displacements and rotations are quite consistent for increasing values of the scale of fluctuation.

The pile head displacements are larger for the linearly increasing mean CPT profile than for the uniform profile. This is not unexpected since the uniform profile comprises relatively larger CPT values closer to the soil surface, which affect the resulting displacements more significantly than the relatively larger CPT values at depth in the linearly increasing profile.

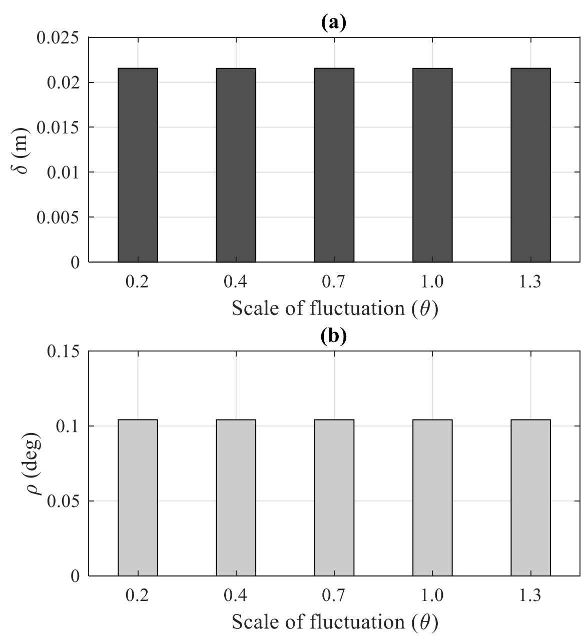

Figure 4: Pile head (a) deflection and (b) rotation with varying scales of fluctuation for linear CPT profile

The difference in predicted pile head displacement for a pile embedded in a soil profile characterized by the uniform and linearly increasing CPT profiles for a given scale of fluctuation are shown in Figure 5. The scale of fluctuation used for the analysis in this figure is θ = 0.2. This plot further highlights that surface soils exhibit significant influence on the resulting displacements of the pile, even when, on average, the CPT data over a depth has the same mean value. From Figure 1, both CPT profiles have a mean CPT q_c of 15 MPa over a depth of 30 m (the pile embedment). The significant variation in the response of the monopile for both profiles suggests that surface stiffness values are very important in determining the resulting deflections under applied load and moments.

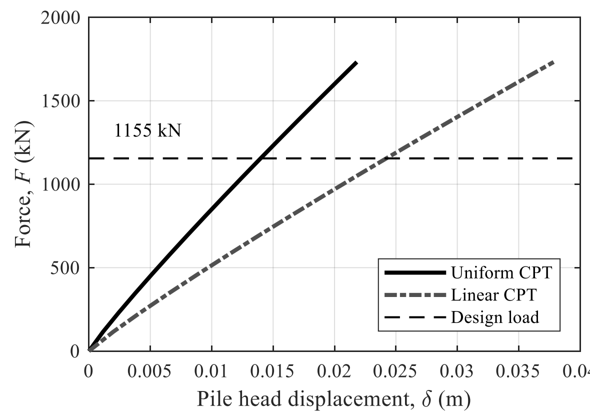

Figure 5: Pile load-displacement data for uniform and linearly increasing CPT profiles for a scale of fluctuation of 0.2

5. CONCLUSIONS

Monopiles dominate the offshore wind foundation market and are experiencing rapid technological developments at present. In general, as wind turbines become larger to harness more energy, monopile diameters have been increasing, resulting in more rigid foundation systems. Monopiles have strict serviceability requirements while in service, often specified as an allowable pile mudline rotation or displacement. Designers generally use *p-y* models to estimate the load-displacement behavior of monopiles under expected environmental loading to facilitate varying the geometry for the purpose of design. Recent developments in *p-y* models have begun to use CPT data to inform the response features, which raises questions about the issue of geotechnical uncertainty. In this paper, different CPT profiles are generated which have varying scales of fluctuation in order to ascertain how this parameter influences the predicted pile head displacement and rotation of a typical monopile. A uniform CPT profile and a linearly increasing

CPT profile are created with varying scales of fluctuation. Results suggest that in the process to develop discrete *p-y* curves, the statistical variation in CPT data averages out over a given spring layer, and the predicted displacements are very close to one another, for a given CPT profile. This suggests that *p-y* only models may not capture local variations in CPT data very well. Furthermore, the linearly increasing CPT profile exhibits larger pile head deflections than the uniform profile, suggesting that near surface soil stiffness governs the response (the uniform profile has relatively higher near surface stiffness values). This suggests that near surface soil stiffness values should be specified with a high degree of confidence as they essentially govern the response prediction.

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