

EVALUATION OF LATERAL RESPONSE IN OFFSHORE WIND MONOPILES: A COMPARISON OF ANALYTICAL AND NUMERICAL APPROACHES

Fatma Dulger Canogullari¹, Ozgur L. Ertugrul²

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Abstract

This paper investigates results of analytical and numerical approaches for analyzing static response of monopile foundations in a comparative way. In this study, static behaviour of NREL 5 MW wind turbine foundation under lateral loads was analyzed using the Winkler Approach with linear and nonlinear springs individually and numerical modelling using finite element method. The linear Winkler method, while straightforward to use, considerably underestimates both the initial stiffness and the ultimate resistance whereas utilizing the nonlinear Winkler springs, reflect the expected bilinear behaviour characterized by a rigid initial reaction and a limit in ultimate capacity. It was observed that three-dimensional numerical modelling provides a conservative assessment of soil resistance, owing to comprehensive stress-strain soil modelling and realistic boundary effects, which show a more gradual mobilization of resistance.

Key words: p-y curve, finite element method, monopile, offshore wind turbine

Introduction. In these days, when energy crisis is on the agenda for most countries, research towards clean and renewable energy sources has become a critical issue to reduce society's dependence on fossil fuels and to achieve a more sustainable future. The primary benefits of renewable energy sources encompass their global availability, environmental sustainability, perpetual usability, and long-term economic feasibility. Wind is among the most popular forms of renewable energy sources, especially in the offshore environment.

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According to renewable energy literature, monopile foundations are considered the most commonly used foundation type in offshore environments. Monopiles, typically having large-diameters due to supporting high-capacity wind turbines are open-ended steel pipes embedded in the seabed, where their design is made depending on the stiffness and strength of the surrounding soil to withstand substantial environmental stresses from wind, waves and turbine blades. Monopile diameters typically vary from 4 to 6 m; however, due to the increase in turbine dimensions and relevant water depths, jumbo monopiles with diameters of up to 10 m are also under consideration [1].

Monopile foundations are required to be able to endure horizontal stresses and overturning moments that are induced by external sources such as wind, waves, and currents throughout the operational lifespan of offshore wind turbines. For this reason, it is crucial to conduct a detailed examination of how monopiles react to horizontal loading in order to ensure the stabilized operation of the turbine as well as its safe operation. MATLOCK [2] conducted field experiments on flexible piles with a diameter of 0.324 m in Sabine River as part of the first investigation of laterally loaded piles. He also suggested a p - y curve model that was optimized for soft clay soils. This approach was later accepted by the American Petroleum Institute [3] and Det Norske Veritas [4] and has been extensively utilized in the industry. The offshore design standards released by the API and DNV accept the p - y curve method as the standard approach for determining the capacity of horizontally loaded monopiles. This approach, according to the Winkler foundation, delineates the nonlinear correlation between the soil response (p) at a specific depth and the horizontal displacement (y) of the pile. The p - y curve models endorsed by API and DNV have been formulated mostly from field testing on flexible and thin piles with diameters under 0.65 m and length-to-diameter ratios above 30 [2, 5]. Nevertheless, the diameters of monopile foundations utilized in practice typically exceed 4 m, and they will definitely increase in the future due to ever increasing turbine sizes. Consequently, the methodologies described in the API and DNV standards are not entirely applicable to the monopile foundations utilized in today's practice. With this motivation, researchers have been conducting numerous studies in recent years to enhance the current p - y curves. BHATTACHARYA et al. [6] examined the Winkler approach for modelling soil-structure interaction in various foundations of offshore wind turbine support systems. ZHU et al. [7] investigated the interaction between piles and soil and suggested an analytical p - y curve model that takes into account the stress-strain behaviour of soils at minimal strain levels. LIU et al. [8] aim to create an integrated computational framework for various failure scenarios based on previous investigations in their study. The analysis of the pile-soil interaction was carried out by utilizing the finite element method (FEM), taking into account a number of distinct failure modes. The analysis focused on the correlation between soil resistance and displacement for a variety of pile diameters, as well as the depth-dependent variations in bearing capacity.

In the design of monopile foundations, it is necessary to calculate the bending moment, shear force, and deformation values along the entire length of the pile. For example, in piles used as energy-dissipating elements in marine structures, the bending moment curve and the changes in force and deformation are of great importance.

Materials and methods. This research examines monopile foundations utilized in the design of offshore wind turbines. The monopile foundation characteristics used in this study align with the specifications of the 5 MW NREL test turbine [9]. The monopile, designed according to the specified characteristics, was assessed using the Winkler approach with both linear and non-linear springs, utilizing a numerical model based on the three-dimensional finite element method. The shear force, bending moment and p-y curves (lateral soil resistance p vs. lateral displacement y) of the monopile foundation of the wind turbine were obtained for different load levels, and the results derived from the Winkler approach with linear springs, nonlinear soil reaction case and the finite element method were compared for a better understanding of the pile-soil interaction.

Analytical modelling with linear and nonlinear soil springs. The p-y curve method, commonly used for laterally loaded piles, was first introduced by McCLELLAND and FOCHT [10]. This approach depicts the soil with distributed nonlinear horizontal springs along the pile, so describing the nonlinear interaction that occurs between the pile and the soil. Laterally loaded piles are defined as a vertical Winkler elastic foundation beam in this method. In order to explore the association between the local lateral soil response (or p) and the corresponding lateral deflection of the pile (or y), the method makes use of nonlinear p-y springs. It is important to recognize that the relevance of conventional analytical methods utilizing standard p-y curves may be constrained, particularly for large-diameter monopiles within the 5–8 m diameter range and possessing an aspect ratio of around 5 [11]. Traditional p-y formulations, originally developed from tests on thin and flexible piles, may result in an excessively flexible pile response when directly applied to modern offshore wind turbine monopiles. In fact, large-diameter monopiles demonstrate increased rigidity under combined lateral loads and overturning moments, with rotational deformation mechanisms prevailing. Thus, the deformation model and soil-structure interaction attributes of modern offshore monopiles diverge from the conditions that informed the creation of the original p-y curve [12,13]. This constraint must be acknowledged when analyzing the comparative outcomes of analytical and numerical methods.

The Winkler method involves solving a differential equation to understand pile behaviour. Therefore, it is necessary to solve the equation

$$(1) \quad E_p I_p \frac{d^4 x}{dz^4} + k_h x = 0,$$

where x is the horizontal deformation of the pile, k_h is the horizontal ground

reaction coefficient of the soil, z is the pile depth, E_p and I_p are the modulus of elasticity and the moment of inertia of the pile, respectively. The horizontal ground reaction coefficient of the soil can be obtained from the horizontal reaction of the soil and the horizontal deformation of the pile as follows

$$(2) \quad k_h = \frac{p}{x},$$

where p is the soil reaction acting on the unit length of the pile. In this study, the coefficients A_x , B_x , A_m , B_m , A_p , B_p , A_v , and B_v , are utilized in the calculations of shear force, bending moment, pile deflection, and horizontal soil deformation within the Winkler approach, based on MATLOCK and REESE's [14] research. Like any methodology, the Winkler approach has its own limitations. The Winkler approach ignores shear transmission and the interaction of soil springs, treating the soil as possessing uniform stiffness, which may not accurately reflect the actual heterogeneity of the soil.

The literature lacks a universally acknowledged methodology for formulating p-y curves for soils exhibiting both cohesive and frictional characteristics. In foundation design with p-y analysis, the soil is defined simply by either its cohesion (c) or friction (ϕ) value, but not by both simultaneously. The primary studies that generated p-y curves were performed on soils characterized exclusively by cohesion (c) or friction (ϕ). In the LPILE software [15], the ultimate soil resistance (p_{ul}) is determined by evaluating the passive soil resistance on the front surface of the pile in the direction of horizontal displacement, the sliding (shear) resistance on the lateral surfaces of the pile, and the active soil pressure force on the rear surface of the pile for soils that have both cohesive and frictional characteristics. EVANS [16] introduced an approximation equation to determine the peak resistance for c - ϕ soils:

$$(3) \quad p = \sigma_p \cdot b = C_p \sigma_h b,$$

where σ_p is the passive lateral pressure (incorporating the three-dimensional passive wedge effect), b is the width of the pile and γ' is the effective unit weight of the soil. The Rankine passive pressure for a wall of infinite length is articulated as follows:

$$(4) \quad \sigma_h = \gamma' z \tan^2 (45^\circ + \phi/2) + 2c \tan (45^\circ + \phi/2),$$

where σ_h denotes horizontal passive earth pressure, z is the depth (the vertical distance from the ground level to the pile), c denotes cohesion, ϕ is the internal friction angle of the soil and C_p is the dimensionless correction factor that denotes the three-dimensional passive wedge impact on the surface. The ultimate lateral displacement of the soil, y_u , is:

$$(5) \quad y_u = 3b/80.$$

The methodology suggested by REESE et al. [5] was formulated for sandy soils; nevertheless, due to the stress-strain characteristics of $c-\phi$ soils approximating those of cohesionless soils, this approach is preferred.

The LPile program directly provides graphs showing deflection, shear force, and bending moment in the pile resulting from the modelled pile-soil interactions, and it also produces p-y curves based on multiple methodologies. The soil and monopile characteristics used for the analysis have been entered into the LPile software, and graphs have been obtained for comparing results with those of the finite element approach.

Numerical modelling. Within this study, the response of laterally loaded monopiles is investigated using Plaxis 3D software [17], which is suitable for intricate modelling of structures through the use of embedded beam and plate elements, while supporting complex boundary conditions and load conditions. The software is capable of analyzing soil-structure interaction problems under static, dynamic, and coupled hydro-mechanical situations. For the numerical model given in Fig. 1, a hollow cylindrical pile is considered extending 25 m below and 20 m above the seabed level. The horizontal forces, under the specified static conditions, were applied on the top of the pile. The Mohr-Coulomb soil model was used, and a water layer was defined at a height of 20 m above the soil surface.

In the Plaxis 3D software, defining a monopile as a hollow cylindrical plate element, excludes the computation of shear force and bending moment graphs for the pile. Therefore, p-y curves cannot be directly generated as an output in Plaxis 3D software. In order to obtain the data required for the construction of the p-y curves, an interface element was created surrounding the monopile, described as a plate element, and an Excel macro was programmed to extract the p (soil stress) values using this interface element. Subsequently, the y values were extracted and p-y curves were generated in Excel. To generate the shear force, bending moment and deflection diagrams, the pile with identical characteristics was simulated as

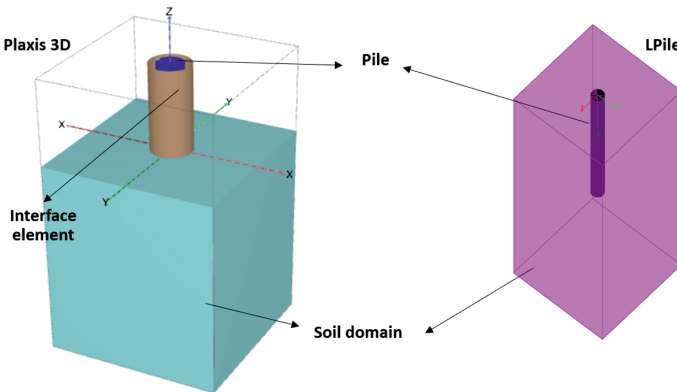


Fig. 1. The geometric model analyzed in the LPile software and Plaxis 3D software

a beam element and diagrams were generated for comparison with the analytical solution.

In this study, sandy silt characteristics were used to simulate the seabed soil characteristics. Cohesion and internal friction angle have been established for the seabed soil, and the parameters of the NREL 5 MW wind turbine have been used for the monopile foundation. The static load variations applied to the pile top are selected as 2050 kN and 700 kN considering the characteristics of the wind turbine and the reported values by NREL [9]. The soil has an elastic modulus of 15 MPa, an internal friction angle of 20° , and a cohesion value of 10 kPa. The hollow steel pile has an elastic modulus of 210 000 MPa and a unit weight of 85 kN/m^3 .

Discussion of the results. The shear force, bending moment, and pile deflection graphs for monopile foundations for the reference 5 MW NREL offshore wind turbine for a static load of 2050 kN were calculated using the analytical and numerical approaches, as seen in Fig. 2.

It was observed that the shear force and bending moment profiles for the upper 40% of the pile height, analytical and numerical approaches are quite similar. As the depth increases, the agreement of the results diminishes. In terms of displacements, analyses with linear and bi-linear behaving soil springs and numerical modelling results are in good agreement, however, numerical analyses results are generally higher compared to the values obtained by Winkler approach. Figure 3 depicts similar responses for the 700 kN loading cases.

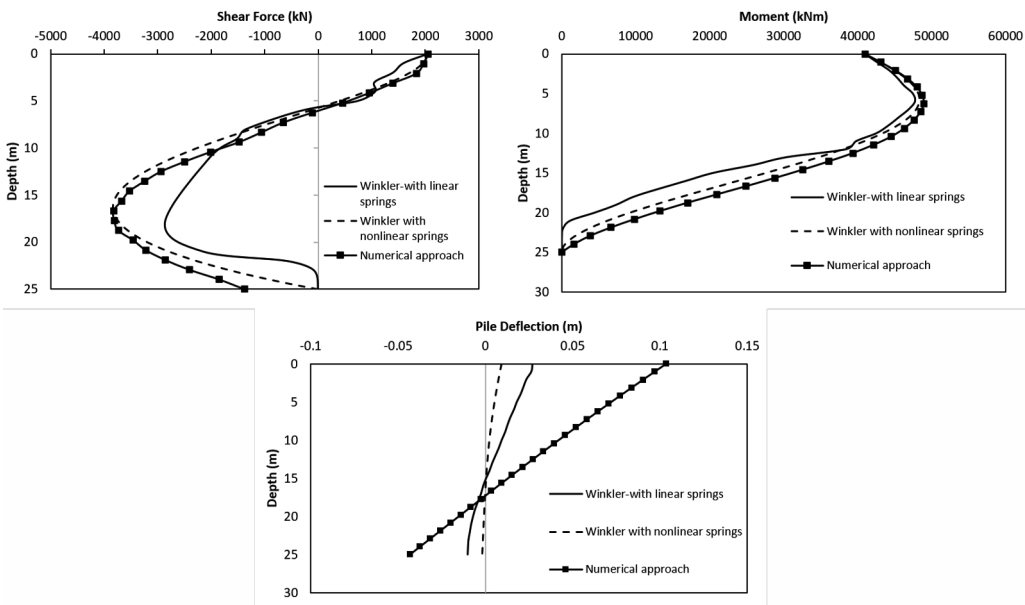


Fig. 2. The shear force, bending moment and pile deflection graphs for monopile foundations for the reference 5 MW NREL offshore wind turbine for a static load of 2050 kN

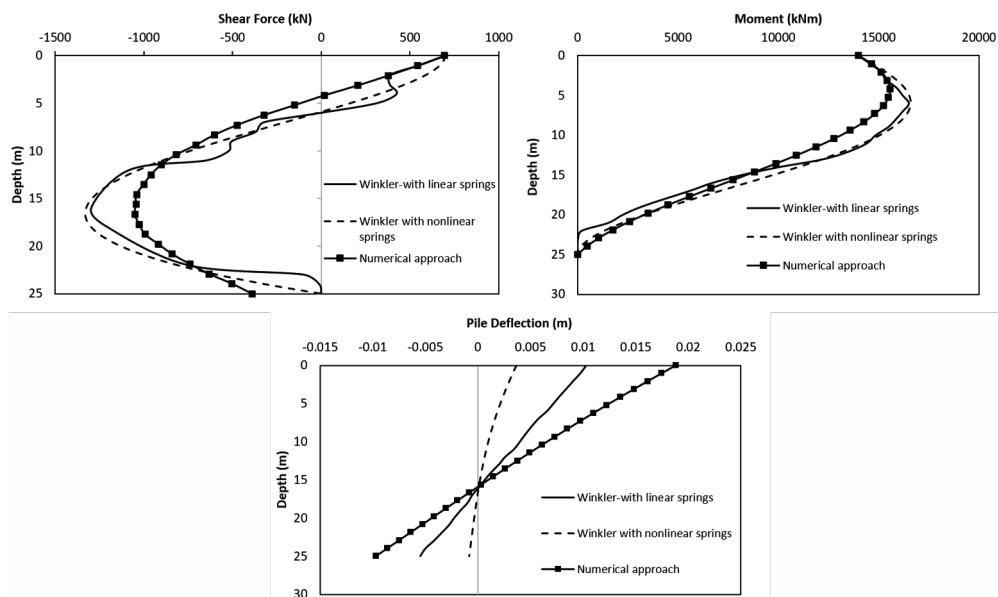


Fig. 3. The shear force, bending moment and pile deflection graphs for monopile foundations for the reference 5 MW NREL offshore wind turbine for a static load of 700 kN

Figure 4 shows the p - y curves (lateral soil resistance p vs. lateral displacement y) derived from three different modelling methodologies: Winkler approach with the linear and the non-linear springs as well as the numerical model utilizing the three-dimensional finite element method. These curves show the soil-pile

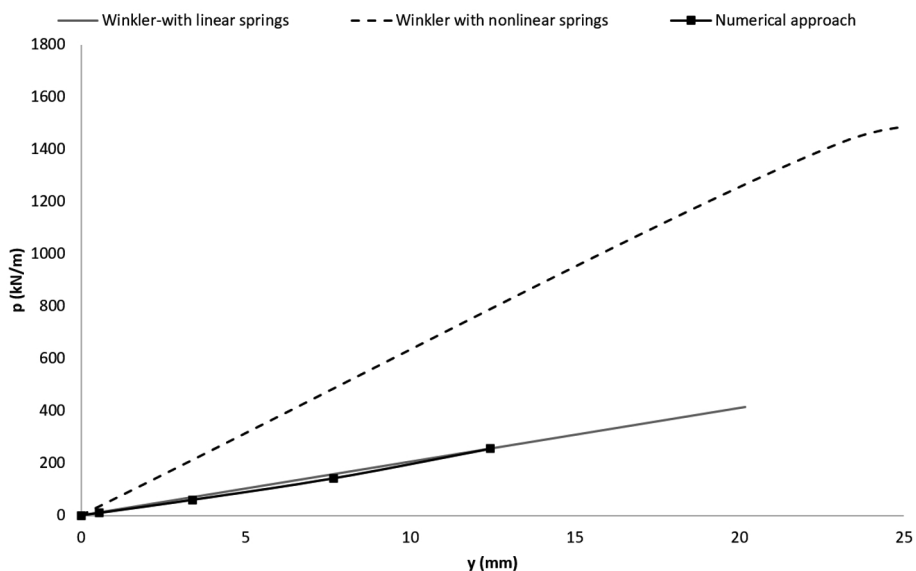


Fig. 4. p - y curves obtained at a depth of 3 meters from a soil surface

interaction at depth of three meters. The initial stiffness derived with the analytical approach is calculated as around 62 kN/m/mm, however, in the numerical analyses it was estimated as 21 kN/m/mm. Since the surrounding soil exhibits significantly reduced rigidity in the three-dimensional numerical model, higher lateral displacements were observed at the pile tip, with more pronounced rigid rotation as well as smaller contribution of the pile flexibility effects.

The results of this study indicate that analytical methods frequently referenced in the literature, initially formulated from experimental studies on small-diameter piles, should be employed carefully when evaluating current offshore wind turbine monopiles with progressively larger diameters. Although analytical methods may be appropriate for initial design and screening assessments, their direct application could result in too flexible response predictions for large-diameter monopiles. For intricate design phases, especially when precise assessment of stiffness, rotation, and soil-structure interaction is essential, the application of three-dimensional numerical modelling is suggested. These methodologies provide a more accurate depiction of wave and wind loading conditions, along with sophisticated constitutive modelling of soil behaviour, thereby offering a more reliable foundation for the design of offshore monopile structures [13].

Conclusion. In this study, analyses were performed using three approaches: the Winkler method with linear and non-linear springs, and 3D finite element modelling, to assess monopile behaviour under lateral loads. Higher lateral displacements were observed in FEM due to soil yielding. Shear force and moment distributions matched the analytical approaches in the upper 40% of the pile, with increasing depth causing slight discrepancies. Non-linear springs aligned better with FEM results. The linear Winkler method yielded a constant-slope p-y line, underestimating both stiffness and capacity. Bi-linear springs improved p-y response representation, while FEM captured realistic soil behaviour with 3D and stress-strain effects.

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¹*Department of Civil Engineering, Toros University, P.O. Box 33210, Mersin, TURKEY
e-mail: fatma.dulger@toros.edu.tr (<https://orcid.org/0000-0002-0927-7132>)*

²*Department of Civil Engineering, Mersin University, P.O. Box 33343, Mersin, TURKEY
e-mail: ertugrul@mersin.edu.tr (<https://orcid.org/0000-0002-1270-3649>)*