geotechnics

MDPI

Article

Numerical Analysis of Jacked and Impact-Driven Pile Installation Procedures in Offshore Wind Turbine Foundations

Ka Lok Chan [1], Susana Lopez-Querol [1] and Pedro Martin-Moreta [2,*]

[1] Department of Civil, Environmental and Geomatic Engineering, University College London (UCL), London WC1E 6BT, UK; k.chan.23@alumni.ucl.ac.uk (K.L.C.); s.lopez-querol@ucl.ac.uk (S.L.-Q.)
[2] Department of Civil and Environmental Engineering, Brunel University London, Uxbridge UB8 3PH, UK
* Correspondence: pedro.martin-moreta@brunel.ac.uk; Tel.: +44-(0)-1895-265805

Abstract: The increasing global demand for renewable energy has resulted in a high interest in wind power, with offshore wind farms offering better performance than onshore installations. Coastal nations are thus, actively developing offshore wind turbines, where monopiles are the predominant foundation type. Despite their widespread use, the effects of monopile installation methods on the overall foundation behaviour are not sufficiently yet understood. This study investigates how different pile installation procedures—jacked and impact-driven—affect the lateral capacity of monopile foundations under both monotonic and dynamic lateral loads, by comparing them with wished-in-place monopiles, the usual assumption in design, for which no soil disturbance due to installation is considered. Three finite element 3D models were employed to simulate these cases, i.e., wished-in-place monopile, jacked, and impact-driven pile, incorporating soil zoning in the latter cases to replicate the effects of the installation methods. Comparisons between all these models, when subject to lateral monotonic and cyclic loads, are presented and discussed in terms of displacements in the soil and horizontal normal stresses. Results reveal that these installation methods significantly influence soil reactions, impacting the lateral performance of monopiles under both monotonic and dynamic conditions. The impact-driven pile demonstrated the most significant influence on the monopile behaviour. These findings highlight the need for engineers to account for installation effects in the design of monopile foundations to enhance performance and reliability, as well as the optimisation of their design.

Keywords: offshore wind turbine foundations; monopiles; pile installation; soil-structure interaction

check for updates

Academic Editors: Grigorios Tsinidis and Anna Karatzetzou

Received: 29 December 2024
Revised: 25 January 2025
Accepted: 27 January 2025
Published: 6 February 2025

Citation: Chan, K.L.; Lopez-Querol, S.; Martin-Moreta, P. Numerical Analysis of Jacked and Impact-Driven Pile Installation Procedures in Offshore Wind Turbine Foundations. *Geotechnics* **2025**, *5*, 11. https://doi.org/10.3390/geotechnics5010011

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The global effort to minimise the effects of climate change has led to a significant shift in energy policies worldwide. International agreements such as the Kyoto Protocol and the Paris Agreement have established ambitious goals to reduce CO_2 emissions and other greenhouse gases [1]. Climate change has become a critical priority for governments, driving the urgent need to transition from fossil fuels to cleaner, renewable energy sources. The importance of this shift is underscored by available data which indicate that electricity and heat production account for approximately 34% of global greenhouse gas emissions [2]. With the International Energy Agency [3] forecasting a continued increase in global electricity demand during the upcoming years, the development of renewable and clean energy systems is essential to meet energy needs while reducing their environmental impact.

Among the various renewable energy technologies, wind energy has gained widespread attention. Offshore wind energy, in particular, offers distinct advantages over onshore installations. Wind energy is especially popular in coastal nations like the United Kingdom, Germany, and China, where offshore wind farms have played a pivotal role in reducing national carbon footprints [4]. Offshore wind energy contributed to the reduction of over 10 million tons of CO_2 emissions annually in the UK by 2018 [1]. Offshore wind farms also avoid land use conflicts, as they are situated at sea, and they benefit from more stable and higher wind speeds compared to onshore sites [5].

The successful deployment of offshore wind turbines relies on the performance of their foundations, with monopiles being the most widely used type. A monopile is a large, hollow steel cylinder vertically driven into the seabed, with its dimensions—diameter, thickness, and embedment depth—dictated by site-specific conditions [6]. Recent developments have led to the construction of larger monopiles, with diameters reaching up to 10 m and embedment depths exceeding 30 m [7]. The growing size and complexity of monopiles have highlighted the need for more robust design and analysis methods, particularly regarding the effects of installation procedures on the soil-structure interaction.

Current research on monopile foundations has focused primarily on their performance under lateral loads, with limited attention to the effects of the installation methods on soil characteristics and behaviour. Monopiles are typically installed using jacked or impact-driven procedures, both of which can alter the properties of the surrounding soil. Many reported studies fail to account for these installation effects, potentially leading to inaccurate predictions of monopile capacity and long-term performance [8]. Given the dynamic loading conditions faced by offshore wind turbines—due to waves, wind, and operational loads—it is critical to understand how the installation methods influence the original soil conditions, and consequently, the performance and serviceability of the soil-monopile system.

This study aims to address this research gap by using numerical modelling to evaluate the effects of jacked and impact-driven pile installation procedures on the lateral monotonic and dynamic capacity of monopile foundations. The research objectives include (1) investigating some installation methods and their general impact on soil, (2) reviewing past research on soil-pile interaction, (3) establishing a validated numerical model, (4) conducting a set of numerical simulations, and (5) evaluating the results to determine the influence of installation on the performance of the monopile. By providing new insights into the effects of pile installation, this study aims to support the design of more efficient and resilient offshore wind turbine monopile foundations.

2. Literature Review

2.1. Installation of Monopiles

Monopile installation typically follows a multi-stage process, which includes the transportation of the monopile, its vertical positioning on the vessel, followed by the initiation of the main installation, which consists of the penetration of the monopile in the soil [9] (in [10] construction stages are sketched and explained). Monopile installation methods have evolved to meet the challenges of deeper waters and more demanding operational environments. The primary techniques for monopile installation are based on driving the monopiles into the soil, usually by applying a set of impacts on top of the pile until the penetration reaches the target depth [6]. The shock wave produced by the impact travels down the pile, resulting in soil displacement and the subsequent penetration of the monopile. Nowadays, impact-driving still remains the most widely used method for monopile installation. Modern hydraulic hammers applying impact on top of the pile operate on the same principle as older systems but now offer greater efficiency due to higher impact energies and advanced control systems [10]. A specific type of impact-driving procedure is the so-called Jack-up Vessel Installation, which is a traditional methodology that relies on a jack-up vessel to position the pile and hammer. The vessel's crane lifts the monopile into a guide frame known as a "piling gate", allowing precise alignment before the hammer is placed at top of the pile [6]. This approach requires stable seabed conditions and calm weather to ensure operational safety. An alternative to this driving method is the Submerged Support Structure for Installing a Pile (SSIP) that offers a more versatile approach by using a reusable subsea support structure. As detailed by [11], this process involves pre-positioning the SSIP at the installation site. The pile, fitted with end caps, is towed to the location, where the top cap is removed, and water is pumped into the pile, causing it to sink under its own weight. Once the pile reaches the seabed, the SSIP stabilises it, and hammering begins. The SSIP then floats to the surface for reuse, offering cost and time savings over traditional jack-up vessel methods.

In addition to the traditional impact-driving techniques, pile-jacking has also been discussed as an emerging method, though its application in offshore monopile installation is still limited [12]. Pile-jacking, also known as press-in piling, offers a quieter and less disruptive alternative to impact-driving. Unlike the impact or vibratory methods, pile-jacking uses a hydraulic ram to apply a static force to push the pile into the seabed [13]. This process significantly reduces noise pollution and ground vibrations, making it an attractive option in noise-sensitive environments. However, despite these environmental advantages, the adoption of pile-jacking in offshore applications is still limited and further investigation is yet required to establish its operational feasibility and long-term performance.

Driving and jacking are not the only installation methods for monopiles. Vibratory Driving is a process that involves vertical vibrations applied to the pile, causing the surrounding soil to experience cyclic loading. As soil strength temporarily decreases due to these vibrations, the pile can be driven into position. These vibratory devices typically operate at frequencies of 20 to 40 Hz [14]. Vibratory driving is often preferred for its reduced noise impact, making it a more environmentally friendly option compared to conventional hammer-driven methods [15].

The lateral forces exerted on a monopile during its service life are varied and substantial. The interaction between the monopile and the surrounding soil plays a critical role in the structural integrity of the foundation [16]. Given this critical aspect, it is essential to explore how installation methods impact the soil behaviour and monopile performance after installation.

2.2. Effects of Installation on Sands

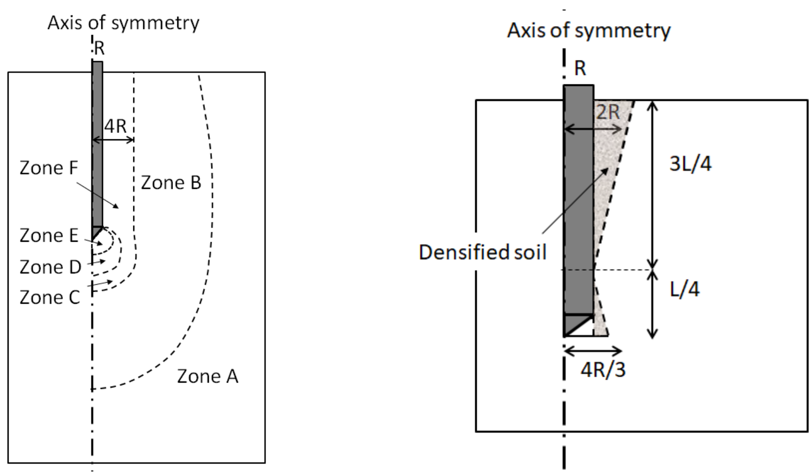
The soil response to monopile installation varies depending on the method used and the soil properties. The most critical changes are observed in the void ratio, horizontal stress, soil plugging, and soil settlement. Fan, Bienen, and Randolph (2021) [12] conducted numerical simulations to study the impact of driving and jacking on silica sand of different relative densities (Dr = 38%, 60%, 88%). Their findings indicate that the void ratio, horizontal stress, and soil plugging differ significantly between the two methods. During pile-jacking, dense sand tends to dilate, whereas medium-dense sand densifies. This pattern of dilation and densification affects the void ratio, with denser sands experiencing larger dilation. In contrast, impact-driving causes densification in the surrounding sand, leading to lower void ratios outside the pile. The relationship between the pile installation method and sand relative density is crucial for understanding how soil deformations evolve.

Both impact-driving and pile-jacking cause an increase in horizontal stress around the pile. However, jacking produces significantly higher radial stresses, especially inside the pile, due to the direct application of static force. This increased stress, combined with the reduction in void ratio, leads to an overall increase in soil strength [12].

Soil plugging occurs when soil is retained inside the pile during penetration. Pile-jacking results in higher soil plugging due to its reliance on continuous static force, while impact-driven piles experience less plugging. This distinction is important for pile capacity and load-bearing behaviour.

Impact-driven piles cause settlement of the soil outside the pile. For medium-dense sands, settlement occurs inside the pile as well, but for dense sands, soil heave is observed inside the pile. Pile-jacking produces heave both inside and outside the pile due to the volumetric expansion of displaced soil [12].

The impact of pile installation extends to distinct zones within the soil. The identification and classification of these zones enable better prediction of soil response and load transfer. Fan, Bienen, and Randolph (2021) [12] used finite element modeling for jacked installation of a monopile in soils with different relative densities, showing distinct soil response zones. Based on numerical analyses and experimental results, Yang et al., (2020) [17] proposed different zones around a solid pile, with different properties as the result of the installation. Cuéllar (2011) [18] proposed a simplified zonation model for defining the geometry of densified soil as two truncated cones with a common base at the rotation centre. This model has limitations, as it fails to account for the complex soil behaviour evident in numerical simulation [12], but can be adopted as a first approximation, obtaining average properties for the soil in each of the simplified zones. Both zonation approaches can be seen in Figure 1.



(**a**) (**b**)

Figure 1. Zonation in the installation of piles (jacking) in sand, (**a**) after Yang et al. (2020) [17]; (**b**) after Cuéllar (2011) [18]. Zones A–E: incrementally varying from zero to a high plastic shear strain rate and very low to mean stress (<0.2 MPa to >3 MPa) Zone F: low incremental plastic shear strain rate and low mean stress (P < 0.5 MPa).

Soil disturbance during installation can also play a critical role in the long-term performance of monopile foundations. Impact-driven monopiles typically experience greater initial soil disturbance compared to jacked or vibratory methods [15,17]. Over time, however, reconsolidation of the disturbed soil can partially restore lateral capacity, especially in cohesive soils [12]. Jacked installations, which minimise soil disturbance, tend to provide more stable lateral capacity from the outset. In cyclic loading, disturbed soils are more prone to degradation, leading to increased displacement and rotation of monopoles compared to monotonic loads. Higher-frequency loading, such as that induced by wave or wind excitation, may lead to increased dynamic amplification and reduced lateral resistance due to higher strain rates and accelerated degradation of soil properties [8,13]. Other factors such as soil stratigraphy, groundwater conditions, and pile material properties can also significantly influence monopile behaviour [7,8,12].

Numerical models, such as the finite element method (FEM), are used to simulate the complex interactions between monopiles and the surrounding sand soil in offshore foundations. These numerical models allow for detailed analysis of factors such as soil nonlinearity, pile-soil interaction, scour [19], long-term settlement [20,21], and particularly, the effects of cyclic loading [22–24], making them a powerful tool for optimising monopile designs. Ho et al. (2024) [24] utilised FEM (SANISAND-MS model) to investigate the importance of considering installation effects, which significantly influenced the initial stiffness and load-displacement behaviour of monopiles. The study also emphasised the limitations of the "wished-in-place" approach, which neglects the effects of pile installation. Kainya et al. (2022) [22] used experimental data and case studies to validate a numerical simulation model, VibPile, for the simulation of the nonlinear dynamic response of large monopiles under harmonic loading and installation by vibration or impact-driving. The study highlighted the importance of considering dynamic soil-structure interaction and soil-specific characteristics to optimise the process.

3. Methodology

A set to 3D Finite Element models developed in Ansys 2024 R1 have been developed. In these models, to account for the effects of both impact-driving and jacking installation effects, different zones in the soil domain have been established, based on previous numerical simulations of these installation procedures in sands reported in the literature. For each model configuration, lateral loads (monotonic and cyclic) have been applied. The lateral responses are compared with the wished-in-place pile (i.e., ignoring the installation), and conclusions on the effects of both installation procedures are derived.

The geometric model of the monopile was designed to reflect current industry practice. Offshore monopiles typically have diameters that range from 8 to 10 metres and embedment depths from 30 to 50 m [7]. Accordingly, the monopile used in this model had a diameter of 8 m, a total length of 60 m (of which 30 m was embedded), and a wall thickness of 90 mm, consistent with previous studies [5]. The surrounding soil model had a depth of 50 m and a total diameter of 90 m, with the monopile centrally positioned. This arrangement allows for an adequate representation of the soil-pile interaction. The installation of these piles was modelled by FEM before cycling loading is applied [12,18]. Figure 2 shows the geometry of the conducted models. It can be seen that, both geometry and loads being symmetric, only half of the model has been simulated, to reduce computational effort.

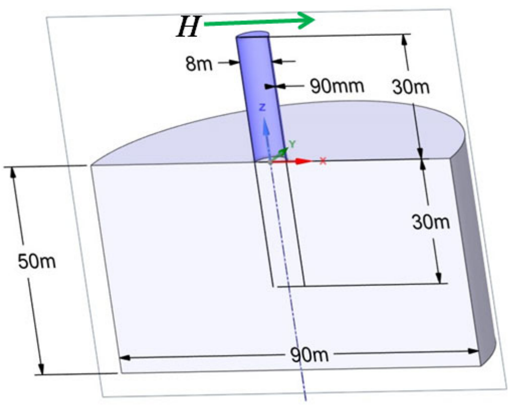


Figure 2. Dimensions of the soil-monopile system in the FE simulations. Horizontal load (H).

The monopile material was modelled as S355 steel, with properties taken from [25]: density of 7850 kg·m^{-3}, Young Modulus of 21 GPa, and Poisson's ratio of 0.3. The material properties of the soil were modelled as dry sand, using an elasto-plastic Mohr–Coulomb model, as this approach offers a balance between computational efficiency and simulation accuracy for soils. Lopez-Querol et al. (2020) [5] demonstrated that under 100 load cycles, results from a homogeneous soil model and a heterogeneous soil model are comparable, justifying the simplification in this study. The use of dry sand in this modelling is justified by the numerical results presented in [12,26] who validated numerical models of soil installation through several centrifuge tests conducted on dry sand. As the paper compares different soil-pile configurations (wished-in-place, jacked, and impact-driven), the influence of density is low which is significant in determining which method induces the greatest soil disturbance, and which has the most pronounced effects.

The soil's mechanical properties are adopted from Lopez-Querol et al. (2020) [5] and are presented in Table 1. The wished-in-place model, with homogeneous soil conditions, is validated under both monotonic and cyclic lateral loads, with the results presented in [5], obtaining identical results, as the model is exactly the same.

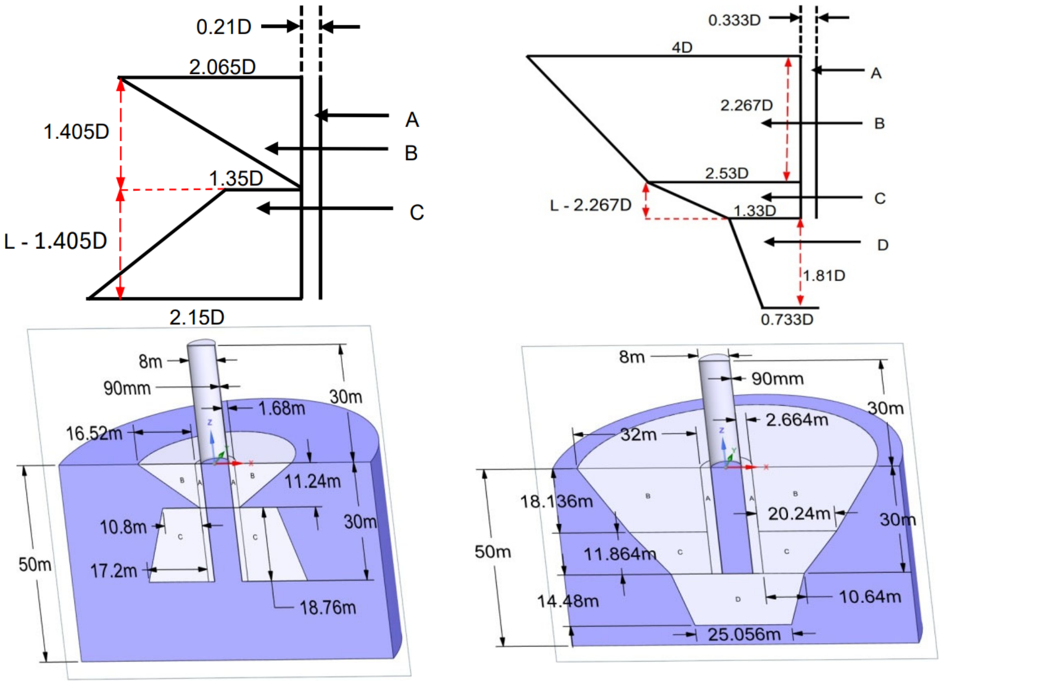
Table 1. Soil properties in the numerical models.

Density (ρ), kg/m^3	Young Modulus (E_0), MPa	Poisson's Ratio (v)	Friction Angle (φ), °	Dilatancy (δ), °	Cohesion (c), kPa
2000	40	0.25	35	5	1

After the successful validation of the model was achieved, both installation procedures (impact-driving and jacking) were represented. Given the computational effort required of directly simulating pile installation, a simplified zoning approach was adopted to capture the effects of installation on different locations in the surrounding soil. Similar models to the one proposed in [18] have been adopted for both driving and jacking installation methods. The zones are adopted based on the results reported by Spyridis and Lopez-Querol (2024) [26], where the affected areas surrounding the monopile are defined for both driving and jacking. The axisymmetric geometries of the adopted zonation in both cases are represented on top of Figure 3a,b. In both sketches, the right vertical line represents the external contact between pile and soil. For jacked piles, the soil is divided into three zones, while for impact-driven piles, four zones were used. The shapes and sizes of all zones are referred to the pile diameter for further extrapolation in different pile geometries. For impact-driven piles, the higher affected area reflects the greater variation in soil disturbance caused by this installation method [26]. The bottom graphs in the figure represent the geometries adopted in the models. It is worth highlighting that the wished-in-place case does not have any zoning as the soil is considered homogeneous (as in Figure 2). The distinction between the zones in the numerical models for installed monopiles was guided by the horizontal stress distributions observed in the previously mentioned studies. Horizontal stress-based modifications to Young's modulus were applied to reflect the installation effects for each soil zone. The updated Young's modulus values were computed using the empirical relationship proposed in [27,28]:

$$E = E_0 \left(\frac{\sigma_h}{\sigma_{h0}} \right)^n \tag{1}$$

where E and E_0 are the current and the original Young Modulus, respectively, n is an empirically obtained exponent with usual values for sands ranging between 0.3 and 0.5 (in this case, n = 0.5) and σ_h and σ_{h0}, respectively, denote current (after installation) and initial horizontal normal stresses (as in wished-in-place) at the centre of each zone, which are representative locations for each one of them. The updated Young's moduli applied in each zone, obtained with Equation (1) and employed, are shown in Table 2.



(a) (b)

Figure 3. Simplified axisymmetric section and full model geometries for the different zones adopted in the numerical simulations. (**a**) Jacking; (**b**) Impact-driving. Densification and dilation zones A, B, C, D are based on zoning obtained by [12,26].

Table 2. Updated stiffness in all zones of the models for the numerical analyses.

Zone (See Figure 3)	Original Young Modulus (E_0), MPa	Updated Young Modulus Jacking (E), MPa	Updated Young Modulus Impact-Driving (E), MPa
A	40	111.63	30.21
B	40	38.27	25.49
C	40	103.97	38.38
D	40	-	30.98

Boundary conditions are standard ones, i.e., fixed in the bottom boundary, and vertical movement allowed but restricted horizontal displacements are considered in the lateral sides of the model. In the symmetry plane, no displacement perpendicular to it is allowed (usual symmetry condition). The size of the model has been tested to make sure that the lateral boundaries are sufficiently far away from the pile [5]. The contact between the pile and the soil is simulated as frictional, with a friction coefficient of 0.4 [29].

Sensitivity analysis was performed to determine the optimal mesh size for each type of pile installation. The analysis assessed horizontal displacement at the top of the structure (i.e., 30 m above the mudline). The analysis identified suitable mesh densities for each model, leading to final node counts of:

- Jacked: 98,939 nodes
- Impact-driven: 124,720 nodes
- Wished-in-place: 50,850 nodes

Note that the impact-driven case requires a higher number of nodes, as a consequence of the higher complexity of geometry in this case. These mesh sizes ensured convergence for all static and cyclic simulations. Mesh refinement was applied near the monopile and the soil zones directly affected by installation to enhance the accuracy of the results. Coarser meshes were applied further from the pile, where stress gradients were smaller. The final mesh configurations are illustrated in Figure 4.

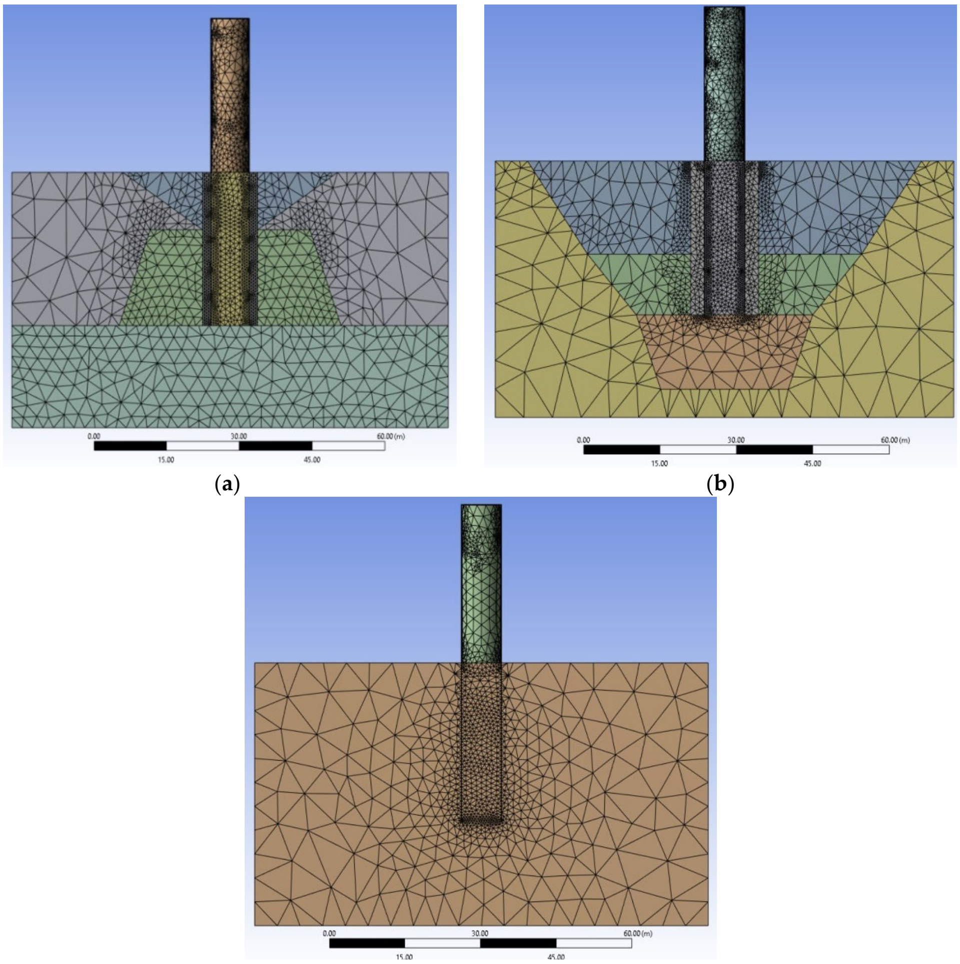


Figure 4. Meshes in the symmetry planes in the conducted numerical models. (**a**) Jaking; (**b**) Impact-driving; (**c**) Wished-in-place.

The loading conditions considered included both static and cyclic loads to evaluate the impact of pile installation on lateral and vertical load responses. In both cases, the lateral load is applied on top of the simplified structure (in this case, 30 m over the mudline—Figure 2) to represent not only load but also moments at the mudline. Gravity loading was first applied to account for the self-weight of the pile, including the application of a vertical load of 3 MN on top of the structure to represent the weight of the turbine and the part of the tower that has not been included in the models. These vertical loads are followed by either monotonic horizontal loading (to find the different lateral reactions in the pile) or cyclic loading (to simulate the operational forces from wind and wave-induced lateral loads).

The dynamic input loads on a monopile arise from a combination of wind and sea waves, each characterised by distinct amplitudes and frequencies. Standard 5 MW offshore wind turbines can be represented by a peak force of 4 MN, a value that has been widely adopted in numerical models throughout the literature [5,29]. Sea waves typically have frequencies in the range of 0.1 Hz, while wind frequencies are around 0.01 Hz. The entire structure tends to vibrate at frequencies near 1 Hz. This paper explores the effects of two different input load frequencies, both corresponding to realistic load conditions, aiming to capture the influence of natural vibrations and sea waves. Given that wind is slower, it can be represented by monotonic loads. All these factors are considered in this work.

The cyclic horizontal loads were defined using the following sinusoidal function, as suggested in [5]:

$$h(t) = H\, sin(2\pi f t) \tag{2}$$

where H is the amplitude of the input horizontal load (4 MN), f is the load frequency (1.0 or 0.1 Hz), and t denotes time (in s). To simulate the load of the remaining tower (over the point of application of the horizontal load) and the turbine, a vertical load of 3 MN is applied in all models at the same time as the initial gravity load. This study limited cyclic loading to 40 cycles to maintain computational efficiency while capturing sufficient trends of the behaviour for analysis. Longer simulations would, however, be beneficial for understanding the long-term behaviour. Table 3 presents the full range of loading cases, with key distinctions made for jacked piles (J), impact-driven piles (I), and wished-in-place (W) piles. In the denomination of the cases, M or C, respectively, refer to monotonic or cyclic loads. Simulations for wished-in-place models are also included to provide a baseline comparison.

Table 3. Conducted numerical analyses.

Case	Installation Type	Loading Type	Frequency (Hz)
JM1	Jacked	Monotonic	N/A
JC1	Jacked	Cyclic	0.1
JC2	Jacked	Cyclic	1.0
IM1	Impact-driven	Monotonic	N/A
IC1	Impact-driven	Cyclic	0.1
IC2	Impact-driven	Cyclic	1.0
WM1	-	Monotonic	N/A
WC1	-	Cyclic	0.1

4. Results and Discussion

4.1. Comparison of the Response of the Three Monopiles Under Monotonic Lateral Load

Figure 5 shows two vertical profiles of the horizontal displacements in the soil domain at horizontal distances of 0.15 D and 0.5 D from the pile (see Figure 6 for the location of these profiles) for the jacked, impact-driven, and wished-in-place cases, under monotonic horizontal load (JM1, IM1, and WM1 cases in Table 3). As can be seen in the figure, both soil profiles tend to rotate quasi rigidly in all cases (i.e., the displacements are proportional to the depth, indicating rotation of the geometry surrounding the monopile). Looking at the closest location to the pile (0.15 D), we can conclude that, under the same horizontal, monotonic load, the displacements for the impact-driven case are the highest one (both positive value—on top of the pile—and negative—at the bottom), followed by the jacked pile and the wished-in-place case. This result illustrates the higher effect of the impact-driving in the soil condition as well as the soil-pile interaction, compared to the jacked monopile, and in both cases, the displacements are higher than those found in the wished-in-place pile. As we move away from the pile, at a distance of 0.5 D, this effect is not as clearly observed as all the results are very close, only showing slight differences.

Figure 6 represents the horizontal displacements for the same cases in the symmetry plane of the models. Taking the wished-in-place case as a reference (Figure 6c), two main conclusions could be obtained: firstly, and as concluded above, the higher effects of the impact-driven procedure are again evidenced by the greater displacement values seen in the soil domain for this case close to the pile (Figure 6b), although the differences between the three cases are very local and minimised as we move away from the pile. The second aspect that can be observed from these graphs is that the rotation point (i.e., location of zero displacement in the axis of the pile) is at a lower position in the wished-in-place case, followed by the jacked and finally by the driven pile, which displays the highest elevation of this rotation point. Both effects combined mean that the rotation of the pile, under the same monotonic load, is expected to be higher in the case of the impact-driven pile than in the jacked or wished-in-place cases, confirming the discussion of results from Figure 5.

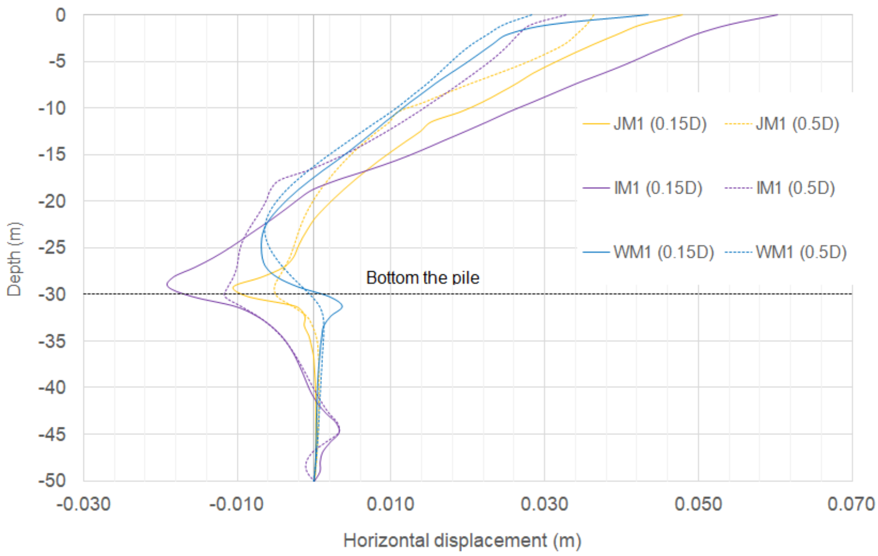


Figure 5. Vertical profiles of horizontal displacements at distances 0.15 D and 0.5 D from the pile for cases JM1, IM1, and WM1 (see location of the soil profiles in Figure 6). The top of the figure represents the mudline (soil surface) and the discontinuous horizontal line represents the bottom of the pile.

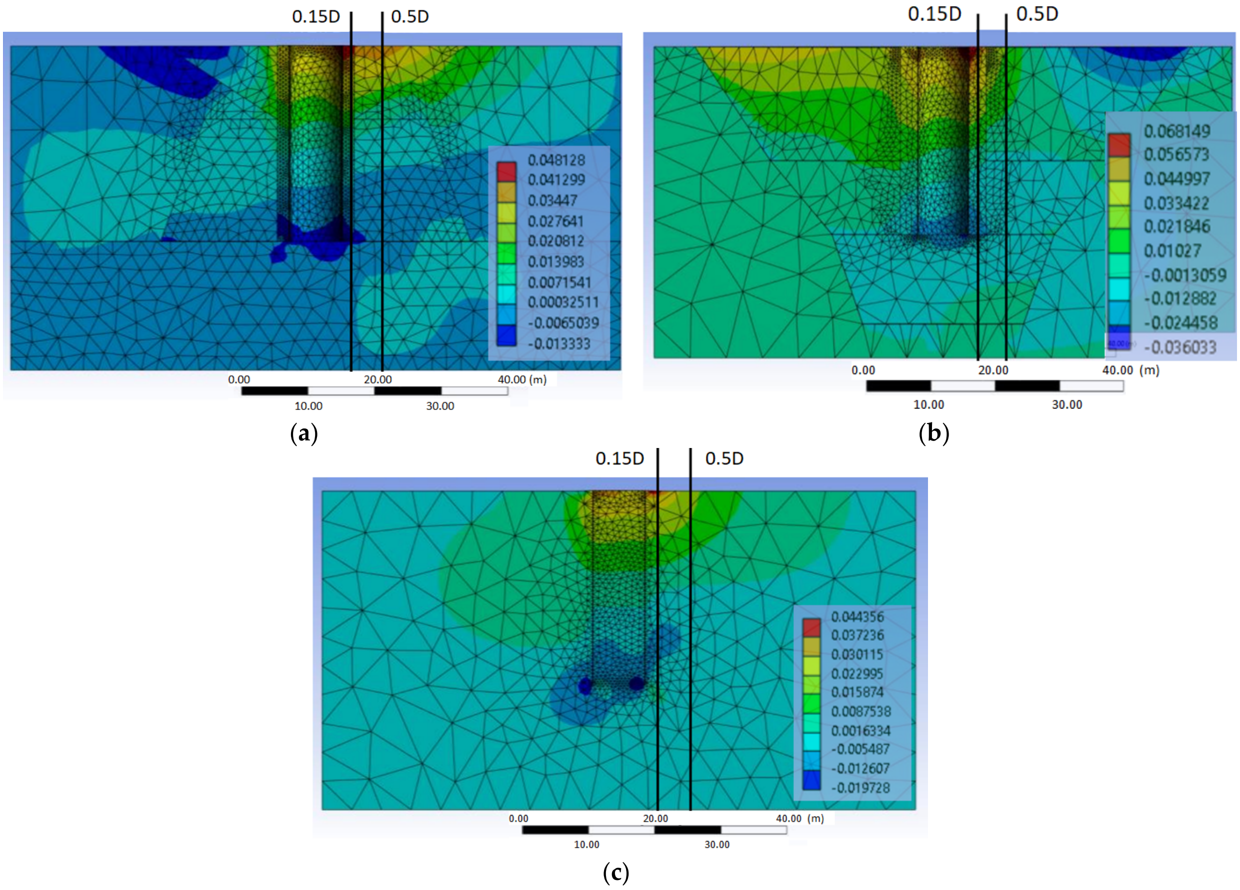


Figure 6. Horizontal displacements (m) in the symmetry plane of the soil domain: (**a**) jacking (JM1); (**b**) impact-driving (IM1); (**c**) wished-in-place (WM1).

Interestingly, from Figure 6, we can see that the pattern of displacements are not very dissimilar in the proximity of the pile in all the analysed cases. However, negative displacements on the soil surface can be observed for both jacked and driven piles, but at different sides of the pile. This is an effect of the sharp change in the Young's moduli between the different zones of both models, but should not represent the real behaviour in real cases where that transition is expected to be more progressive. In any case, and despite this limitation of the simplified zoning approach, the conditions in the monopile and immediately surrounding soil are properly captured by the models.

Figure 7 presents the solution of the horizontal normal stresses in the symmetry planes of the three models (it is worth noting here that the negative sign represents compressive stress). From this figure, we can conclude that the horizontal normal reactions around the monopile follow a very similar pattern for both installation methods (jacked and impact-driven, in Figure 7a,b, respectively), but the peak values, found in the left bottom corner of the monopile, are higher in the case of the impact-driven pile, although very localised. For the impact-driven pile, however, unlike in the jacked case, a thin area on the right soil-pile contact is observed with low stresses, which means a lower lateral reaction in the pile in this location, which justifies the higher horizontal displacements obtained in this case. In any case, in both the jacked and impact-driven pile, stresses on the right and left of the pile are very different, unlike in the case of the wished-in-place pile, that shows very similar stresses at both sides, with the exception of the top-right side of the pile, with a localisation of low stresses in the mudline.

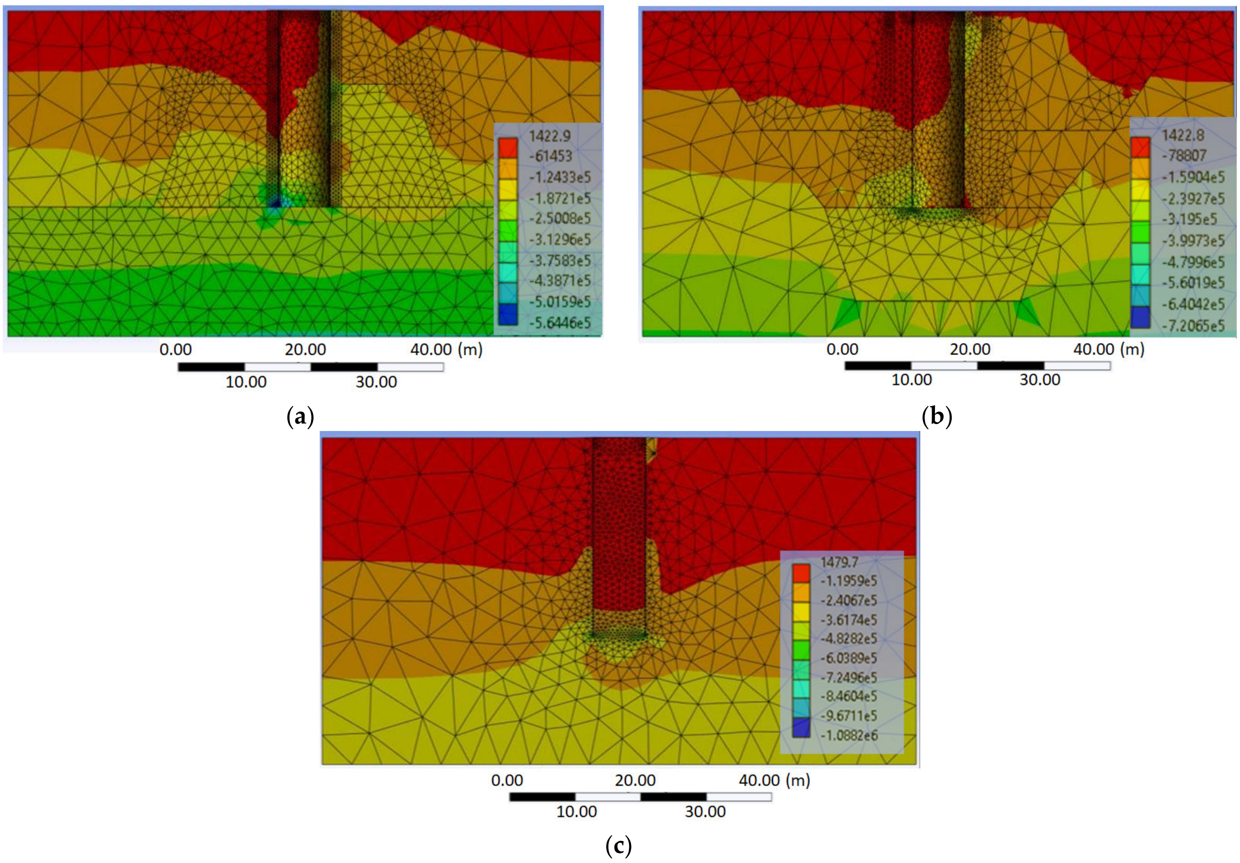


Figure 7. Horizontal normal stresses (Pa) in the symmetry plane of the soil domain: (**a**) jacking (JM1); (**b**) impact-driving (IM1); (**c**) wished-in-place (WM1).

4.2. Comparison of the Response of the Three Monopiles Under Cyclic Lateral Load

When subjected to horizontal loads, whether monotonic or cyclic, monopiles tend to exhibit rigid rotational behaviour. This rotation is characterised by the angle formed relative to their original vertical position. Greater rotations of the pile pose an increased risk to structural integrity. Typically, rotations of 0.5 degrees or more necessitate the decommissioning of the structure.

The analysis of the monopiles under cyclic load is based on the analyses and comparison of the time histories of rotation in the monopile. As mentioned in the Methodology, the constitutive model used (Mohr–Coulomb) is not capable of capturing some of the phenomena that happen in soils under vibration (such as dynamic degradation or ratchetting). However, it is considered to be sufficiently representative of the dynamic response of the monopile. Hence, Figure 8 shows the evolution in time of the rotation of the monopile during the cyclic load for both frequencies (C1: 0.1 Hz and C2: 1.0 Hz). For the wished-in-place monopile, only the slowest frequency was simulated (C1, Figure 8a), and for it, the amplitude of rotation is similar (although a bit smaller) than the one for the jacked pile, and them both, much smaller than the one for the impact-driven pile. In the case of the fastest frequency (C2, in Figure 8b), again the impact-driven pile shows a higher amplitude than the one of the jacked pile, and both of them are much higher than those found for 0.1 Hz. Interestingly, the case IC2 failed after a few seconds, due to a high distortion of the elements as a result of excessive deformation, with rotations in the range of 1 degree, which are not acceptable to guarantee a good performance and integrity of monopiles. This shows the instability of the monopile in this case, demonstrating that this installation procedure compromises the pile integrity under serviceability conditions. Even with the number of cycles modeled, restricted to 40, the model yields steady responses with constant amplitudes and frequencies, which are adequate for comparing the results across the different methodologies.

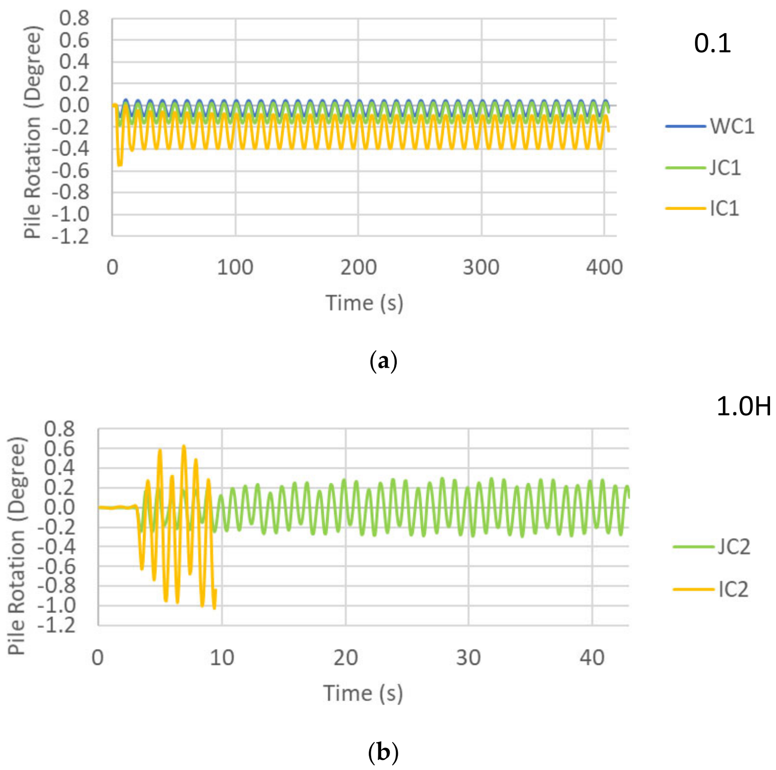


Figure 8. Time history of the rotation of the monopile for all cases. Input load: (**a**) 0.1 Hz; (**b**) 1.0 Hz.

5. Conclusions

This study has provided valuable insights into the impact of installation procedures on the lateral capacity of monopile foundations for offshore wind turbines. By employing 3D finite element (FE) simulations in Ansys, it was possible to model the effects of both jacked and impact-driven installation methods, alongside a wished-in-place model serving as a baseline. The division of soil into three zones for the jacked model and four for the impact-driven model enabled a detailed assessment of the soil-structure interaction, capturing the distinct influence of each installation procedure. The transient dynamic response is captured through the time integration implemented in the simulations for two different input load frequencies. While the constitutive soil model employed (Mohr–Coulomb) does not allow for the investigation of soil relaxation, equalisation, or degradation, it is suitable for providing insights into the effects of jacked and impact-driven installation, and presenting a methodology that practitioners can readily implement in commercial FEM packages to account for these factors.

The findings highlight that the installation process significantly affects the monopile's lateral capacity. Of the methods studied, the impact-driven installation exhibited the most pronounced effects, with larger displacements in the soil, compared to the wished-in-place and jacked models. This pronounced effect is attributed to the nature of the impact-driven process, which introduces significant energy into the soil, causing greater deformation and stress redistribution. It is worth highlighting here that these effects, found numerically in the present research, have already been reported in the literature from experimental research.

Additionally, the cyclic loading analysis revealed that cyclic frequency plays a critical role in response of the monopiles. Higher cyclic frequencies resulted in more substantial deformations, with the impact-driven model displaying the most notable effects. These results underscore the importance of considering cyclic loading conditions in the design and assessment of monopile foundations, as repeated loading can exacerbate the impact of the installation process.

In conclusion, this study has demonstrated that the monopile installation process plays a critical role in determining its lateral capacity. The impact-driven method, in particular, was shown to have the most pronounced influence on soil displacement, strain, and stress, raising important considerations for the design and construction of offshore wind turbine foundations. Engineers can integrate installation effects into foundation designs by making adjustments for reduced initial stiffness due to soil disturbance and modeling post-installation recovery processes like reconsolidation. Moreover, updated design guidelines should reflect the influence of installation effects to improve reliability. This study's findings can guide real-world offshore wind farm projects by encouraging site-specific optimisation of installation methods to reduce soil disturbance and enhance long-term stability. For instance, vibratory installation may be preferable in soft soils with high plasticity to minimise disturbance, while impact-driving may be suited to dense sands where lateral capacity is less sensitive to initial soil disturbance.

The findings suggest that further research should be undertaken to explore additional factors influencing the installation effect, such as different soil types, installation sequences, and long-term cyclic loading. Such research would support the development of more accurate predictive models and contribute to the optimisation of monopile design and installation strategies for offshore wind turbines.

Author Contributions: Conceptualization, K.L.C., S.L.-Q. and P.M.-M.; methodology, K.L.C. and S.L.-Q.; validation, K.L.C.; formal analysis, K.L.C.; investigation, K.L.C. and S.L.-Q.; writing—review and editing, S.L.-Q., P.M.-M. and K.L.C.; supervision, S.L.-Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data obtained in this research are available upon request.

Acknowledgments: The first author gratefully acknowledges the financial support provided by his parents, Sek Tim Chan and Lee Hung Wong, which enabled him to undertake his postgraduate studies at University College London (UCL). Their generous support also made it possible to conduct the research presented in this paper. The author extends his deepest gratitude for their unwavering encouragement and belief in his academic pursuits.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Díaz, H.; Soares, C.G. Review of the current status, technology and future trends of offshore wind farms. *Ocean Eng.* **2020**, *209*, 107381. [CrossRef]
2. USEPA. Global Greenhouse Gas Overview. Available online: https://www.epa.gov/ghgemissions/global-greenhouse-gas-overview (accessed on 2 June 2024).
3. IEA. Electricity Mid-Year Update: July 2024—Analysis. Available online: https://www.iea.org/reports/electricity-mid-year-update-july-2024 (accessed on 2 June 2024).
4. Broom, D. These 3 Countries Are Global Offshore Wind Powerhouses. Available online: https://www.weforum.org/agenda/2019/04/these-3-countries-are-global-offshore-wind-powerhouses/ (accessed on 2 June 2024).
5. Lopez-Querol, S.; Spyridis, M.; Moreta, P.J.M.; Arias-Trujillo, J. Simplified Numerical Models to Simulate Hollow Monopile Wind Turbine Foundations. *J. Mar. Sci. Eng.* **2020**, *8*, 837. [CrossRef]
6. Baldock, N.; Sevilla, F.; Redfern, R.; Storey, A.; Kempenaar, A.; Elkinton, C. *Optimisation of Installation, Operation and Maintenance at Offshore Wind Projects in the U.S.: Review and Modeling of Existing and Emerging Approaches*; OSTI OAI (U.S. Department of Energy Office of Scientific and Technical Information): Washington, DC, USA, 2014. [CrossRef]
7. Byrne, B.W.; McAdam, R.A.; Burd, H.J.; Beuckelaers, W.J.A.P.; Gavin, K.G.; Houlsby, G.T.; Igoe, D.J.P.; Jardine, R.J.; Martin, C.M.; Muir Wood, A.; et al. Monotonic laterally loaded pile testing in a stiff glacial clay till at Cowden. *Géotechnique* **2020**, *70*, 970–985. [CrossRef]
8. Markou, A.A.; Kaynia, A.M. Non-linear soil-pile interaction for offshore wind turbines. *Wind Energy* **2018**, *21*, 558–574. [CrossRef]
9. Wittingen, M. Offshore Wind Turbine Monopile Foundation Installation with a Dynamic Positioned Vessel: A Feasibility Study by Modeling. Level of Thesis, Semantic Scholar. Available online: https://www.semanticscholar.org/paper/Offshore-Wind-Turbine-Monopile-Foundation-with-a-A-Wittingen/3c131261bb83f0028d4c49f392ba39c7fe090bf1 (accessed on 1 June 2024).
10. Jiang, Z. Installation of offshore wind turbines: A technical review. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110576. [CrossRef]
11. Sarkar, A.; Gudmestad, O.T. Study on a New Methodology Proposed to Install a Monopile. In Proceedings of the International Society of Offshore and Polar Engineers (ISOPE) Conference, Rhodes, Greece, 17–22 June 2012. Available online: https://onepetro.org/ISOPEIOPEC/proceedings-abstract/ISOPE12/All-ISOPE12/12532 (accessed on 31 December 2024).
12. Fan, S.; Bienen, B.; Randolph, M.F. Effects of Monopile Installation on Subsequent Lateral Response in Sand. I: Pile Installation. *J. Geotech. Geoenviron. Eng.* **2021**, *147*, 04021021. [CrossRef]
13. Fan, S. Effect of the Installation Process on the Subsequent Response of Monopiles Under Lateral Loading in Sand. Ph.D. Thesis, The University of Western Australia, Crawley, Australia, 2020. [CrossRef]
14. Tara, D.; Middendorp, P.; Verbeek, G. Modeling and Observations of Pile Installation Using Vibro Hammers in Fraser River Delta Soils. Semantic Scholar. Available online: https://www.semanticscholar.org/paper/Modeling-and-Observations-of-Pile-Installation-in-Tara-Middendorp/77b81623d4cc5e74982e10d3ea904904cb28ed8f (accessed on 5 June 2024).
15. Remspecher, F.; Le, V.H.; Rackwitz, F.; Herwig, V.; Matlock, B. Vibratory Driven Installation of Monopiles—An Experimental Investigation of the Soil-Pile Interaction. In Lecture Notes in Civil Engineering. In Proceedings of the 1st Vietnam Symposium on Advances in Offshore Engineering, Hanoi, Vietnam, 1–3 November 2018; Springer: Singapore, 2019; Volume 22, pp. 171–176. [CrossRef]
16. Byrne, B.W.; Burd, H.J.; Zdravkovic, L.; Abadie, C.N.; Houlsby, G.T.; Jardine, R.J.; Martin, C.M.; McAdam, R.A.; Pacheco Andrade, M.; Pedro, A.M.G.; et al. PISA Design Methods for Offshore Wind Turbine Monopiles. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 6–9 May 2019. [CrossRef]
17. Yang, Z.; Gao, Y.; Jardine, R.J.; Guo, W.; Wang, D. Large Deformation Finite-Element Simulation of Displacement-Pile Installation Experiments in Sand. *J. Geotech. Geoenviron. Eng.* **2020**, *146*, 0402271. [CrossRef]
18. Cuéllar, P. Pile Foundations for Offshore Wind Turbines: Numerical and Experimental Investigations on the Behaviour Under Short-Term and Long-Term Cyclic Loading. Ph.D. Thesis, University of Berlin, Berlin, Germany, 2011.

19. Zhang, Q.; Zhu, W.; Gao, B.; Ye, G.; Jeng, D.-S.; Wang, T. Numerical investigation on horizontal deformation of large diameter monopile under cyclic wave loading with local scour holes. *Ocean Eng.* **2022**, *266*, 113059. [CrossRef]
20. Sarımurat, S. Investigation of the effects of cyclic lateral load characteristics on monopiles in saturated sandy soils using hypoplastic material model. *Wind Energy* **2023**, *26*, 1165–1187. [CrossRef]
21. Nguyen, T.T.; Le, V.D.; Huynh, T.Q.; Nguyen, N.H.T. Influence of Settlement on Base Resistance of Long Piles in Soft Soil—Field and Machine Learning Assessments. *Geotechnics* **2024**, *4*, 447–469. [CrossRef]
22. Kaynia, A.M.; Hebig, J.; Pein, T.; Shin, Y. Numerical model for dynamic installation of large diameter monopoles. *Soil Dyn. Earthq. Eng.* **2022**, *161*, 107393. [CrossRef]
23. Liu, H.; Kementzetzidis, E.; Abell, J.A.; Pisanò, F. From cyclic sand ratcheting to tilt accumulation of offshore monopiles: 3D FE modelling using SANISAND-MS. *Geotechnique* **2022**, *72*, 753–768. [CrossRef]
24. Ho, H.M.; Del Brocco, I.; Li, Z.; Pisanò, F. FE Modelling of Monopiles in Sand Under Monotonic and Cyclic Lateral Loads. In Proceedings of the International Conference on Geotechnics for Sustainable Infrastructure Development, Hanoi, Vietnam, 14–15 December 2023; Springer Nature: Singapore, 2023; pp. 2643–2657.
25. *BS EN 10025-2:2019*; Tracked Changes. Hot Rolled Products of Structural Steels. Technical Delivery Conditions for Non-Alloy Structural Steels. British Standard Institution: London, UK, 2019. Available online: https://bsol.bsigroup.com/Bibliographic/BibliographicInfoData/000000000030405717 (accessed on 12 July 2024).
26. Spyridis, M.; Lopez-Querol, S. Installation of open-ended piles: A numerical investigation into the effects on the state of silica sand. *Soils Found.* **2024**, *64*, 101458. [CrossRef]
27. Hardin, B.O.; Black, W.C. Vibration Modulus of Normally Consolidated Clay. *J. Soil Mech. Found. Div.* **1968**, *94*, 353–369. [CrossRef]
28. Seed, H.B.; Idriss, I.M. Soil Moduli and Damping Factors for Dynamic Response Analyses. Available online: https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/PB197869.xhtml (accessed on 31 December 2024).
29. Achmus, M.; Kuo, Y.S.; Abdel-Rahman, K. Behavior of monopile foundations under cyclic lateral load. *Comput. Geotech.* **2009**, *36*, 725–735. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.