Review

Failure-Mechanism and Design Techniques of Offshore Wind Turbine Pile Foundation: Review and Research Directions

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Abstract: Wind energy is one of the most sustainable and renewable resources for power generation. Offshore wind turbines (OWTs) derive significant wind energy compared to onshore installations. One of the greatest challenges encountered by installing the OWTs is the adequate design of their foundation in relatively soft and compressible marine soil. In most cases, the OWTs are supported by a single pile, termed as ‘monopile foundation’. Apart from the usual loads from the superstructure, these piles are subjected to complex loading conditions under static and cyclic modes in the axial, lateral, and torsional directions due to the primary actions of the wave, wind, and current. To incorporate an appropriate design methodology, understanding the failure mechanisms of such piles is of the utmost necessity. This review paper aims to focus on the progressive development in the analysis of failure mechanisms and design practice relevant to the monopile foundations for OWTs by theoretical and experimental studies conducted globally. An extensive literature survey has been carried out to study the gradual progress on offshore pile-soil interaction, failure mechanisms, and design techniques of OWT supporting monopile foundations. Based on the studies, a brief overview of the various aspects of analysis and design has been carried out, and the relevant conclusions are drawn therefrom.

Keywords: failure mechanisms; offshore pile foundations; offshore wind turbine; wind energy

1. Introduction

Wind power in coastal zones has attracted much attention in the last couple of decades as an alternative energy source due to several advantages, including a stable energy source, high wind speed, and significant power efficiency, among others [1]. Offshore wind turbines (OWTs) are widely installed in coastal zones in many parts of the world. Apart from the analysis and design of electrical, mechanical, and structural components of these turbines, an undeniable challenge is the design and installation of a suitable foundation supporting the heavy turbine structure. Among various types of foundations adopted for OWTs (including multipod, suction caisson, etc.), the monopile foundation seems to be the most effective [2]. Apart from significant dead weights, the dynamic loads from rotating components of the turbine and cyclic loads due to combined actions of wave, wind, and current require critical analysis and design of these monopiles [3–5].

Providing an adequate factor of safety against ultimate failure against multidirectional static and cyclic loading associated with acceptable displacement components of foundations and supporting structures is the primary concern of the analysis and design of offshore monopiles. The imposed multimodal loading (static and cyclic) in axial, lateral, and torsional directions adversely affects the safety and serviceability of the foundations.
Although several analytical and numerical solutions for piles subjected to static and cyclic axial, lateral and torsional loads are available [9–27], still a complete solution for OWT monopile foundation behavior is yet to be available.

Alternative models for large diameter OWT monopiles with different base conditions (including fixed, flexible, and distributed spring bases) subjected to extreme loading conditions were simulated under stochastic analysis by Bush and Manuel [28], and it was observed that flexible bases are more reliable for long-term safety and serviceability. The installation effects for large-diameter monopiles influence their long-term lateral and axial static and cyclic performances, which essentially demand appropriate theoretical and field-based investigations [29,30]. The influence of erosion and scour under current is likely to influence the performance of monopile foundations as well [31].

To increase the cost effectiveness of OWT foundations, monopiles are sometimes used with circular precast concrete plates at the top, thereby reducing the pile size; such a system is termed a hybrid foundation [32]. However, a comparative study suggested that tripod or multiple foundations sometimes increase the overall stability of the OWTs, although they are not cost-effective [33]. In seismically active areas, an eccentric jacket substructure, together with a monopile foundation, would improve the stability of the OWT [34]. The importance of an optimized design procedure for OWT foundations in different soil types has been studied by Ravichandran et al. [35] using a generic algorithm coupled with Monte Carlo simulation.

This paper sequentially presents an in-depth review and analysis relevant to the failure mechanism and design techniques for the OWT monopile foundation. Based on the entire study, relevant research directions have been included, and relevant conclusions have been drawn.

2. Methodology

The methodological approach for this study was based on the analysis of various problem areas pertaining to the OWT monopile foundation. Through extensive literature surveys in the leading universities, institutions, state and local libraries, and also through collecting massive online materials utilizing Google Scholar, DOAJ, Scopus databases, etc., the search was mainly focused on journal articles, peer-reviewed conference proceedings, and other study materials, including books and academic theses, mainly published in the last two decades. The research materials produced under the topic were found to represent several issues, solutions, tools, and methods. Based on the analysis of the literature collected, the study materials have been categorized as: offshore pile-soil interaction, failure mechanisms, and design techniques. The number of study materials reviewed here is shown in Figure 1.

![Bar Chart](image-url)
3. Pile-Soil Interaction in Offshore Environment

Apart from the usual static loads from the superstructure, the offshore environment initiates cyclic loading on piles in axial, lateral, and torsional modes. Such loading initiates reversals in normal and shear stresses on the surrounding subsoil, which alters the strength and stiffness of the soil. Such alteration is produced by the generation of excess pore water pressure produced during stress reversal, rearrangement, and realignment of soil particles and the development of irrecoverable plastic deformation in soil [11]. In the case of soft marine clay, deterioration in its strength and stiffness occurs, while for sand, a stiffening effect is produced [16,22]. Opposing such phenomena, the influence of strain rate based on the frequency of cyclic loading has been observed to increase the soil strength and stiffness in marine clay [7,10]. Based on these studies, a nondimensional degradation factor (Ds) was introduced, defined as the ratio of postcyclic to precyclic values of soil strength and stiffness, and quantified by [17,22].

\[
D_s = \left[1 + F_L \frac{\lambda}{\lambda_r} \right] (N^{-f_d})
\]  \(1\)

where \(F_L\) is a loading rate coefficient, \(\lambda\) and \(\lambda_r\) are the actual and reference strain rates, respectively, \(N\) is the number of load cycles, and \(f_d\) is a degradation parameter, which is a hyperbolic function of induced strain amplitude for clay, and depends upon cyclic load ratio, pile installation, and soil density in case of sand.

Randolph [36] proposed a hysteresis-based analysis of pile-soil interaction under axial cyclic loading. The model proposed appropriate yield criteria, cyclic residual shaft friction, creep effects, hyperbolic pile base response, and group effects. Computations were performed employing explicit time integration, incorporating the residual stresses and external soil movement. During cyclic loading, two alternative yield criteria were chosen, the relevant correlations of which are as shown:

\[
\tau_y = \tau_{min} + \frac{1}{2} (1 + \varepsilon) (\tau_{peak} - \tau_{min})
\]  \(2\)

\[
\tau_y = \tau_{min} + \varepsilon (\tau_{peak} - \tau_{min})
\]  \(3\)

where, \(\tau_y\) is the yield shear stress with the minimum and peak values of \(\tau_{min}\) and \(\tau_{peak}\) respectively, and \(\varepsilon\) is the point of nonlinearity.
One of the most widely accepted models for cyclic pile-soil interaction has been the p-y curve method, where the soil surrounding the pile surface is replaced by a series of nonlinear springs in axial, lateral, and lateral modes [14,37–39]. The soil pressure (p) and the resulting displacement (y) were correlated with nonlinear equations, which progressively degraded with ascending load cycles. The primary correlations for static and cyclic p-y curves were suggested by Equations (3) and (4), respectively, given as follows:

\[ p = \left(\frac{N_p c_u D}{2}\right)\left(\frac{y}{y_c}\right)^{1/3} \quad \text{(for } y < 8y_c) \]

\[ p = \left(\frac{N_p c_u D}{2}\right)\left(\frac{y}{y_c}\right)^{1/3} \quad \text{(for } y < 3y_c) \]

\[ p = \left(\frac{N_p c_u D}{2}\right)[0.72 + (6/125)(z/z_r - 1)(y/y_c)] \quad \text{(for } 3y_c \leq y < 18y_c) \]

\[ p = 0.72(z/z_r)\left(\frac{N_p c_u D}{2}\right) \quad \text{(for } y \geq 18y_c) \]

where, \( N_p \) is a bearing capacity coefficient, \( c_u \) is the undrained cohesion of clay, \( D \) is the pile diameter, \( y_c \) is the reference displacement, and \( z \) is the depth with a critical value of \( z_r \).

The loading imposed by the rotating electrical components of OWT necessitates the monopiles to be analyzed and designed based on dynamic pile-soil interaction [40–42]. In earthquake-prone areas, seismic pile-soil interaction is essential [43–45]. Quite often, the OWT monopiles are found at greater water depths where proper analysis is necessary [46].

A coupled finite element and computational fluid dynamic analysis to incorporate wave and wind time dependency was carried out by Seo et al. [47]. The study revealed that a disparity in wind speed had a greater impact on pile-soil interaction, initiating higher pile displacements compared to the variation in wave height. Multimodal loading was also observed to impart fatigue soil yield. A schematic diagram showing a typical OWT monopile foundation subjected to a multi-wind-wave simulation is depicted in Figure 2.
Boominathan et al. [48] carried out small-scale laboratory model tests to study the bending behavior of single aluminum pipe piles embedded in soft clay under lateral, static, and cyclic loading. The maximum bending moment (BM) was observed to take place at the fundamental frequency of the pile-soil system, while the maximum cyclic BM was 1.5 times the corresponding static value, occurring at a depth of 1.5 times the static depth.

Carswell et al. [49] carried out a reliability study on offshore pile-soil interaction via a probabilistic approach under a serviceability limit state. The influence of variation in
soil parameters, pile geometry, and loading conditions on pile reliability was presented. The relevant correlations used are as follows:

\[ P_{\text{failure}} = F(-\beta) \]  

(6)

Where \( P_{\text{failure}} \) is the failure probability of monopile, \( F \) is the standard normal cumulative distribution function, and \( \beta \) is the reliability index.

An integrated 3D numerical analysis of pile foundation response to oscillatory wave loading was performed by Asumadu et al. [50]. The analysis involved the Navier-Stokes equation with Biot’s poroelastic theory. The study revealed that the wave impact on gravity-based foundations was greater than on monopiles.

Shirzadeh et al. [51] conducted laboratory model tests and computational studies to estimate the damping on cyclic pile-soil interaction for an OWT monopile. Design uncertainties owing to complex pile-soil interactive response under critical loading conditions have been introduced as a practical challenge, although in the last few decades, the installation of OWT has significantly increased [52], as can be seen in Figure 3.

![Figure 3](image)

Figure 3. Annual offshore wind power generation in Europe during 1993–2020. (Data source: [52, 53]).

4. Failure Mechanism

The failure of the monopile foundation is usually accompanied by ultimate failure (i.e., an inadequate factor of safety) or excessive displacement (i.e., serviceability criteria). In the former case, failure occurs due to the yielding of soil adjacent to the interface. In the latter case, failure is induced due to insufficient relative pile-soil stiffness, leading to excessive displacements under ocean wave currents and storm and seismic loads, jeopardizing the serviceability of the offshore structure [54, 55]. A typical monopile subjected to a multidirectional loading pattern in vertical, lateral, and torsional modes under static and cyclic modes induces axial and shear stress reversals in the supporting adjacent subsoil [56]. Complex stress conditions in soil with reversals in axial and shear stress components in 3D space in the vicinity of the pile-soil interface are shown in Figure 4. Reversal of the stresses due to the cyclic nature of imposed loading induces progressive deterioration in the strength and stiffness of the surrounding soil, producing gradual degradation of the capacity of the monopile foundation associated with amplified displacement components [57, 58].
Tang et al. [59] analyzed the bias errors and reliability of axially and laterally loaded piles, which reduced the uncertainties of pile capacity in clay, thereby increasing its performance. The major sources of uncertainties in the axial and lateral performances of piles in clay and sand were identified and analyzed through a simplified probabilistic model for the evaluation of the reliability of pile systems. A field-based study on the bias factors of piles supporting offshore platforms was investigated, in particular by Aggarwal and Littor [60]. Analysis and calibration of the failure of offshore piles through observed behaviors of jacket platforms and caissons were conducted, whereby lateral shear failure and overturning were identified as the two main bias factors.

Bhattacharya et al. [43] predicted an alternative mechanism for seismic pile failure in liquefiable soil through Euler’s buckling analysis, introducing the parameter ‘pile slenderness ratio’. The predicted model was validated through several reported case histories and centrifuge test results. It was observed that the elimination of soil effective stress due to seismic excitation would likely initiate the failure of piles by buckling. The authors suggested appropriate modifications to codes of practice based on the observations.

Fan and Meng [61] conducted a numerical study on the failure mechanisms of pipe piles under combined vertical, horizontal, and torsional loads via 3D finite element modeling using ABAQUS. The failure envelopes were studied with soil deformation mechanisms, based on which the stability of the pile foundation was evaluated with the yield design theory.

The quasi-static granular convective flow and micromechanical densification of sand around offshore pile foundations under cyclic lateral loading impart land subsidence and stiffening effects on the embedded pile, as analyzed by Cuellar et al. [62] through a series of physical model tests. It was pointed out that in extreme conditions, such a convective flow would lead to direct shear failure of the soil surrounding the piles.

The wind turbines are sometimes affected by adverse typhoons, leading to both structural and foundation failures [63]. A failure analysis of wind turbines by typhoon damage was conducted by Zhang et al. [64] with finite element modeling. The numerical data were used for a case study of wind turbines at Dongtai Farm in China. As far as the supporting piles were considered, the piles and the windward and leeward sides were found to be most vulnerable due to the occurrence of critical axial forces and bending.
moments. The relevant aerodynamic forces at the rotor hub and the tower were expressed mathematically by Equations (7) and (8), respectively, given by:

\[ F_y(t) = C_D \rho A v_x(t) \]  
\[ F_T(t) = \mu_s A_e p_w(t) \]

where, \( F_y(t) \) and \( F_T(t) \) are the aerodynamic forces at the rotor hub and the tower, the \( C_D \) is the aerodynamic drag coefficient, \( A \) is the swept area, \( A_e \) is an element area, \( \mu_s \) is a shape coefficient, and \( v_x(t) \) and \( p_w(t) \) are the wind velocity and pressure, respectively.

Banerjee et al. [65] conducted a stochastic dynamic analysis of OWTs considering frequency-dependent soil-structure interactive performance. Finite element modeling was carried out using ANSYS 14 software. The rotational and lateral stiffness of the monopile foundations were considered in the soil-structure interaction. The influence of wind and wave loading was taken into account in the frequency domain. The study revealed that, under soft soil conditions, the displacement responses of monopiles and their peak values were significantly amplified due to wind loading compared to the low-frequency wave loading.

The computation of the fatigue life of monopiles supporting OWTs was performed by Beuckelaers [66] using the kinematic hardening soil model. The amplitude-dependent material damping in the pile-soil interactive response was taken into account. The soil failure was characterized by cyclic \( p-y \) curves associated with kinematic hardening rules [67]. The resulting \( p-y \) response correlates with:

\[ p = p_0 + 2 A p_u \left[ \frac{k z}{A p_u} \left( \frac{y - y_0}{2} \right) \right] \]

where \( p_0 \) and \( y_0 \) are the initial values of \( p \) and \( y \), \( k \) is the modulus of the soil reaction, \( z \) is the depth below the ground surface, and \( A \) is a nondimensional constant related to the loading condition. The unloading and reloading effects of the steady-state hysteretic response of soil were characterized by the backbone curve. The amplitude-dependent damping was considered for analysis of the response of the monopile foundation.

A brief review of the theory and mechanisms of the instability of offshore foundations has been presented by FuPing et al. [68]. The behavior of various types of offshore foundations, including piles, spud cans, gravity bases, suction caissons, and plate anchors, was studied. The different study aspects, such as flow-structure-soil coupling processes, constitutive modeling of cyclic behaviors of marine sediments, and the spatial variability of marine soil properties, were investigated. The coupled influences of wind, waves, currents, and tidal loads were found to be crucial features for the dynamic responses of offshore foundations. Quite often, scouring of the upper seabed surface initiates a loss of bearing capacity. The authors suggested that advanced constitutive models ascertain the cyclic behavior of marine soils through hysteresis, degradation of strength and stiffness, irrecoverable plastic deformation, and the generation of excess pore water pressure. Finally, the uncertainties in deep water subsoil characterization due to inadequate geotechnical investigations because of limited accessibility would also initiate the failure of offshore foundations if not properly designed.

Reder et al. [69] conducted a series of case studies on the failure data analysis of OWTs, including the failure of supporting foundation systems. Yoon et al. [70] conducted a reliability study of laterally loaded pile foundations supporting OWTs using response surface and simulation methods. A Monte Carlo simulation procedure was adopted in the analyses, and the piles were modeled as a vertical beam supported by a series of discrete nonlinear springs. A case study was conducted on the soil bed in the Yellow Sea of Korea. The study indicated that the probabilistic analysis was more reasonable for monopile design, compared to the deterministic approach. Additionally, the internal friction angle of marine soil influenced the lateral response of monopiles significantly.

Chen and Gilbert [71] carried out a reliability analysis on failures of offshore pile foundations due to hurricanes. The failure of piles due to base shear and overturning were
identified and bias factors were introduced using the Bayesian calibration model. The existing design methodology was found to be improved, considering the failure modes and incorporating the suggested reliability analyses.

Extensive case studies conducted by Su et al. [72] indicated higher failure rates of OWTs associated with weather factors. Average failure rates of various components of OWTs were studied (see Table 1). Comparative studies of failure patterns of offshore and onshore wind turbines were carried out by Dao et al. [73] through reliability analysis.

Table 1. Offshore wind turbine components.

| Mechanical     | Components         | Civil          |
|---------------|--------------------|----------------|
| Brakes        | Sensors            | Foundations    |
| Hydraulics    | Electric System    | Access Ladder  |
| Gear Box      | Entire Unit        | Structure      |
| Pitch/Blade   | Drive Train        |                |
| Hub           |                    |                |

Asgarian et al. [74] numerically investigated the consequences of foundation response on steel jacket offshore platform failure modes subjected to wave loading. The in-situ soil data relevant to the Persian Gulf region were utilized and their influences on the failure mode and ultimate strength of an existing offshore platform were studied by performing static pushover analysis. The p-y curves approach was applied to quantify the pile-soil interaction. For quantification of wave loading, hydrodynamic analysis was employed by Morison’s equation [75]. It was observed that the soil condition, wave loading pattern, and pile sizes were the most significant factors in the failure mode of offshore platforms. Weaker piles would lead to the formation of plastic hinges at the piling platform, while the increased moment of inertia of the pile cross-section would initiate the buckling of braces before foundation failure. Reduction in the depth of penetration was found to produce pull-out of piles. The relevant differential equation for wave loading on piles is expressed by:

$$\frac{\partial F_w}{\partial t} = \pm \frac{\pi^2 \rho_w D h^2}{2T^2} (f_s \cos^2 \theta - f_{\mu} \sin \theta)$$  (10)

where $F_w$ is the wave force, $t$ is the time, $\rho_w$ is the seawater density, $h$ is the wave height, $T$ is the wave time period, $f_s$ and $f_{\mu}$ are the functions of drag coefficient and mass coefficient, and $\theta = 2\pi t/T$.

Li et al. [76] analyzed the failure envelope of bucket foundations due to torsion through numerical study. It was observed that the nondimensionalized failure envelopes of bucket foundations under different torsional loads almost coincide, which indicates a limited influence of the magnitude of torsion on the shape of the failure envelope.

Scheu et al. [77] analyzed different failure modes of OWTs, including failure of mechanical components in turbines, substructure catastrophe, or foundation failure. The extensive case studies provided updated information about the critical failure modes of OWTs.

5. Design Techniques

The design techniques for the OWT monopile foundation should take into account the complex static and cyclic load characteristics together with the failure mechanisms. Although significant contributions have been made in the past to this study aspect [78–82], there is still a knowledge gap. Adopting an appropriate design technique for a monopile foundation necessitates consideration of different factors, including geographical
location, imposed loads originated by super-structural dead weights, aerodynamic and hydrodynamic forces, and subsoil characteristics [83].

Haiderali and Madabhushi [84] carried out a three-dimensional finite element modeling of monopiles for OWT, considering combined vertical, horizontal, and moment loads. The shear force, bending moment, and deformation characteristics of large-diameter monopiles in offshore wind farms were studied in detail.

Scharff and Siems [46] conducted a feasibility study on monopile foundations at a greater water depth in the North Sea. The fatigue limit state design was found to be more appropriate for the increase in water depths. It was concluded that the monopile foundation has significant advantages and can be used in greater water depths, especially for turbines with lower mass and low-speed rates.

Kallehave et al. [85] reviewed the available techniques for optimal monopile design of OWT. They described the state-of-the-art optimization approaches applied to the design of the monopile support structures and identified the main factors for incorporating more accurate engineering methods. They suggested that such optimization could be achieved partly through introducing new technologies and partly through the upgrading of existing techniques, together with cost-effectiveness.

Arshad and O’Kelley [86] provided a state-of-the-art review of the geometric design of monopile-supporting OWTs. The structural, geotechnical, and environmental issues were taken into consideration, including loading conditions relevant to the ocean environment. The soil-pile interactions under cyclic loadings involving plastic strain accumulation were also included. A typical design example was also presented in the paper. The paper recommended the target areas for future research in the wind energy sector to facilitate improved design techniques for monopile foundations.

Kim et al. [87] carried out a review of the monopile design of OWT. They found that a relatively shallower offshore condition demands the adoption of a jacket structure with a monopile for OWT, which necessitates appropriate foundation design against critical loading conditions. In offshore environments, the application of lateral load and moment on monopiles was found to be predominant compared to conventional vertical loads. Therefore, the focus of the work was to design an OWT foundation with particular reference to considering the lateral cyclic loading conditions.

Arany et al. [88] presented a simplified design technique for OWT based on the necessary field data, including loading characteristics, turbine properties, and subsurface characteristics. A flowchart of the proposed design technique was also given to visualize the complex design methodology. The method was validated with available field data and a typical design example with the site conditions in London was presented. The relevant load-displacement correlations were expressed in matrix form as follows:

\[
\begin{bmatrix} F \\ M \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} \rho \\ \theta \end{bmatrix} \tag{11}
\]

where, \(F\) and \(M\) are lateral force and moment, \(\rho\) and \(\theta\) are the relevant lateral displacement and rotation, and \(S_{ij}\) are the elements of the stiffness matrix.

Srikanth et al. [89] presented a simplified design technique for monopile-supporting OWT for the state of Gujarat, India. The work aimed at developing appropriate configurations for the commercial viability of monopiles under offshore conditions. A nonlinear static analysis was conducted, taking into account the hydrodynamic and aerodynamic forces under varying water depths, velocities, and subsoil conditions. The loading conditions simulated in the monopile design, as proposed by the authors, are portrayed in Figure 5. The suggested design technique yielded the required diameter and embedded depth of the monopile under the input design parameters. A series of design curves were recommended, and parametric studies were conducted.
As stated earlier, the design of monopiles supporting OWTs requires consideration of numerous critical combinations of loadings. The design loads were classified as permanent loads (i.e., dead weights of structural and mechanical components of the turbine), variable loads (i.e., forces initiated by rotating components of turbines, installation effects, etc.), environmental forces (usually waves, wind, current and incidentally earthquakes, tides, snow, etc.), and accidental loads (for example, ship impacts, fire, explosions, etc.). As recommended by several researchers, the design should be essentially an iterative process and be completed only upon satisfaction of all applicable design load cases and limit states set by appropriate design standards. Appropriate formulations of static and cyclic pile-soil interaction through calibrated p-y curves for marine soils under monotonic and dynamic conditions via a series of axial, lateral, and torsional nonlinear springs were found to be the most commonly adopted technique in OWT monopile design [90–92]. Based on recent studies and recommendations, a comprehensive flowchart of the design of a monopile supporting a typical OWT is given in Figure 6.

Figure 5. Loading condition simulation in monopile design.
6. **Brief Overview**

The above studies show significant progress on the subject of failure mechanisms and design techniques of monopile foundations for OWTs. The main research findings have been sequentially summarized as follows:

(a) Structural failures of OWTs are mostly initiated by extreme environmental and climatic conditions that lead to structural instability and buckling failure. Researchers observed that monopile foundations perform better than fixed gravity-based foundations.
since the latter is susceptible to liquefaction and base instability initiated by the generation of resonant frequencies by rotating components of the turbines.

(b) Apart from structural and foundation failures, other modes of failure are quite common in OWTs. These include mechanical failures of the rotor, gearbox, sensors, and control systems, power transmission failures, wear and tear of gear systems and blade shells, etc.

(c) Monopiles are widely considered an effective foundation for OWTs. Owing to the cyclic nature of imposed environmental loading, mainly originating from waves and wind, degradation of pile capacity with increased displacement initiated by a progressive deterioration in strength and stiffness of soft marine soil in the vicinity of the pile-soil interface is obvious. The pattern of such degradation is different in clay and sand.

(d) Owing to the complexity of imposed dynamic and cyclic loading in axial, lateral, and torsional directions, the failure mechanism of monopile foundations is complex. Such failure may be induced by a sufficient reduction in the factor of safety against ultimate failure, increased pile displacements introducing unacceptable serviceability, scouring, and erosion due to an adverse environmental impact on the surrounding subsoil, or buckling of pile-substructure joints.

(e) Although several researchers suggested various design recommendations, a complete design methodology associated with appropriate charts and curves for OWT monopiles is yet to be available.

A summarized form representing the above contributions has been included in Table 2.

**Table 2. Summarized existing contributions.**

| Study Aspect             | Authors                                      | Brief Contributions                                                                 |
|-------------------------|----------------------------------------------|-------------------------------------------------------------------------------------|
| Offshore pile-soil interaction | Basack and Dey [22]                          | Numerical model on a single pile in the sand under cyclic lateral load.               |
|                         | Bush and Manuel [28]                         | Alternative models for monopile foundations in shallow water.                        |
|                         | Kirsch and Klingmüller [29]                 | Statistical and illustrative analysis with low strain integrity test methods.       |
|                         | Chao et al. [31]                            | Capacities of pile shafts driven in dense sands.                                     |
|                         | Abdelkader et al. [32]                      | Design recommendations for offshore wind turbines using a 3D nonlinear finite approach. |
|                         | Nair et al. [33]                            | Multipile foundations can occasionally improve the overall stability of OWTs, although they are not always cost-effective. |
|                         | Gho et al. [34]                             | Offshore wind turbine substructures are eccentrically jacketed to withstand environmental stresses. |
|                         | Ravichandran et al. [35]                    | Design and optimization procedure for piled raft foundation in clayey and sandy soils. |
|                         | Randolph [36]                               | Analysis of pile-soil interaction under axial cyclic stress using hysteresis.        |
|                         | Matlock [37]                                | Modeling of building frame base that supports pile groups in cohesive soil.          |
|                         | Bhattacharya et al. [43]                    | Interaction between the foundation and the soil and structure under complicated loads. |
|                         | Scharff and Siems [46]                      | Monopile foundations are feasible at locations in the North Sea with sea depths of up to 35 m. |
|                         | Seo et al. [47]                             | Wind and wave time-history analysis with multiple force-induced soil-structure-interaction. |
|                         | Boominathan et al. [48]                     | Dynamic and static lateral load analysis in a single pile implanted in soft clay.    |
|                         | Carswell et al. [49]                        | Wind and wave loading on a monopile foundation using probabilistic approaches.       |
|                         | Asumadu et al. [50]                         | Instabilities in the monopile foundation are caused by waves.                       |
|                         | Shirzadeh et al. [51]                       | The damping on cyclic pile-soil interaction for an OWT monopile was estimated using laboratory model tests and computational analyses. |
|                         | Negro et al. [52]                           | Uncertainties in the structural design of offshore wind farms.                      |
| Failure mechanism | Design techniques |
|-------------------|-------------------|
| Doherty and Gavin [53] | Studied pile-soil interaction under lateral load for monopole design in offshore wind farms. |
| Chen et al. [54] | Monopile mechanisms deform under the influence of existing and a fifth-order Stokes wave. |
| Dai et al. [55] | Monopile offshore foundation failure mechanisms under unidirectional and multidimensional stresses. |
| Schaffer [56] | Dynamic analysis of monopile foundation. |
| Marzuni et al. [57] | Extensive cyclic triaxial tests on liquefaction potential of sandy and silty soil. |
| Tang et al. [58] | Bias, inaccuracy, and reliability assessments of the capacities and performances of axially and laterally loaded piles. |
| Aggarwal et al. [59] | For three jacket platforms and three caissons, field-based capacity analysis and calibration of predictions with observed behavior were performed using Bayesian updating. |
| Fan and Meng [60] | To investigate the failure processes of pile foundations in various loading planes, numerical finite element calculations in three dimensions were carried out. |
| Cuellar et al. [61] | The soil surface subsides as a result of the increasing sand density, and pile behavior becomes significantly stiffer. |
| Bi et al. [62] | A survey is carried out, which includes data collection and statistical analysis. To quantify the failings of the WTG. |
| Zhang et al. [63] | The Dongtai wind farm’s typhoon wind field is modeled using a classical autoregressive model and a regional power-spectrum-density model. |
| Banerjee et al. [64] | OWT stochastic dynamic study of soil-structure interaction performance with frequency dependence. |
| Beuckelaers [65] | Discussion of how a kinematic hardening model may be applied to the present design process for sand-based wind turbine monopiles. |
| FuPing et al. [67] | Piles, spud cans, gravity bases, suction caissons, and plate anchors were all discussed. |
| Reder et al. [68] | To address concerns linked to WT failure assessments, an updated version of an existing OWT taxonomy is introduced. |
| Yoon et al. [69] | A response surface and simulation methodologies for an OWT monopile foundation were used to investigate the sensitivity of monopile design parameters. |
| Chen and Gilbert [70] | The existing design technique might be improved by taking the mechanism of failure into account for a more consistent degree of reliability. |
| Su et al. [71] | The field-based study was used to assess the reliability of components. |
| Dao et al. [72] | Systematic evaluation of reliability data and investigation of the effects of reliability on energy costs. |
| Asgarian et al. [73] | OpenSees software was used to develop a numerical model that considered pile-soil-structure interaction, jacket member buckling, and post-buckling behavior. |
| Morison’s equation [74] | The force exerted by surface waves on a pile is composed of two components: a drag force and an inertia force. |
| Li et al. [75] | The effects of torsion and aspect ratio on combined bearing capabilities are investigated. |
| Scheu et al. [76] | To improve maintenance efforts, 337 failure mechanisms have been discovered and analyzed. |
| Scharff and Siems [46] | If the logistical obstacles of moving huge masses are overcome, monopile foundations can be built for water depths that exceed the existing limits of practical experience. |
| Haiderali and Madabhushi [83] | The behavior of monopiles placed in clays were evaluated using 3D finite element calculations. |
| Kallehave et al. [84] | Optimization strategies are applied to the design of existing wind farms and monopile support structures. |
The review article included information on the geometric design, nominal size, and structural and environmental loading.

Review of offshore foundation design for wind turbine towers, with emphasis on the lateral behavior of monopiles.

Based on the relevant data, a simplified method of carrying out monopile design was presented.

Based on multivariable linear regression analysis, a simpler design technique for monopile support structures under high loading conditions is described.

7. Research Directions

Past studies indicate that the time-dependent effects influence pile behavior through soil aging or alterations in soil stress, increasing its capacity and stiffness [93,94]. Offshore piles, however, are subjected to progressive degradation under the composite action of wind and wave loading [26]. These two opposing phenomena govern the behavior of offshore pile foundations, which necessitates failure mechanism analysis and the development of an optimal design philosophy [1].

Specific research directions and needs relevant to OWT monopile foundations are sequentially presented below.

1. An extensive laboratory investigation, followed by theoretical analyses, on the monopile-soil interactive performance under composite actions of static and cyclic loads under axial, lateral, and torsional modes is crucial. To simulate the actual site conditions, it is essential to submerge the monopile under water, and the time pattern and modes of applied loads should be computer-regulated and controlled by an actuator based on appropriate field data.

2. The experimental and theoretical results obtained would be utilized to study the appropriate failure mechanisms of OWT monopiles under different mechanical, structural, environmental, and accidental loading stages in various marine subsoil conditions.

3. It is of the utmost necessity to establish a complete and practical design methodology associated with appropriate formulations, charts, and curves for OWT monopile foundations. The above-mentioned theoretical and experimental investigations, together with failure mechanism analysis, are expected to be immensely beneficial for the finalization of such a design recommendation.

The application of suitable computational code and software for the design of OWT piles has become increasingly popular in recent years. For the computation of load-displacement responses and capacity of the offshore monopiles, several computer programs based on FORTRAN are available [22–25]. In the recent past, PLAXIS finite element software has been utilized for the analysis of pile groups under lateral cyclic loads [26]. Utilization of appropriate modern software is important for R & D and commercial purposes [95,96].

Although a recent review [97] carried out an extensive analysis of existing contributions on OWT foundations, this work has highlighted other types of foundations as well, for example, gravity, tripod, and jacket-type footings, apart from monopiles. The current work, on the other hand, carried out an in-depth review of available research and progressive development on the OTW pile foundation with an emphasis on failure mechanisms and design techniques.

A proposed flowchart of an implementation of the above-mentioned research direction is portrayed in Figure 7. This diagram depicts the step-by-step procedure expected to be followed for the proposed research activities.
8. Conclusions

OWTs are widely adopted globally in coastal regions due to the availability of substantial wind energy. In addition to designing the electrical, mechanical, and structural components of the OWTs, the foundation supporting the entire turbine should be appropriately analyzed and designed. Monopile foundations are observed to meet the safety and serviceability requirements of OWTs adequately. The pile-soil interactive performance under critical combinations of complex loads necessitates in-depth research and investigation. In this paper, an extensive review has been carried out on past studies to understand the failure mechanisms and design techniques of monopile foundations supporting OWTs. The entire study has been classified into three distinct categories: pile-soil interaction in an offshore environment, failure mechanisms, and design techniques.

As far as offshore pile-soil interaction is concerned, the past contributions of OWT monopiles revealed progressive deterioration in strength and stiffness of the surrounding subsoil due to compound loading conditions including static dead loads from the superstructure, dynamic loads originated by rotating components of the turbine, environmental loading due to composite actions of the wave, wind, and current, and accidental loading initiated by occasional earthquakes, ship impacts, scouring and erosion, ice and frost action, etc. Among the existing numerical and analytical models, the exponential, stress hysteresis, and p-y curve models have been quite effective. Coupled finite element, boundary element, and computational fluid dynamic modeling were carried out by some researchers, while laboratory model tests were also conducted in parallel. The reliability analysis of the probabilistic approach under serviceability limit state to study the offshore pile-soil interaction was also conducted.

The failure mechanism of monopiles in offshore environments is associated with the ultimate yield of the surrounding soil or by excessive displacement, affecting the serviceability criteria. Owing to the complex stress patterns in the adjacent soil, several analytical and numerical studies were carried out based on deterministic and probabilistic approaches. Significant contributions were made to stochastic dynamic analysis of frequency-dependent failure characteristics of monopiles, including reliability analysis, seismic failure, and instability by typhoons, resulting in multifacet modes of structural and foundation failure.

The design of OWT monopiles requires several aspects, including geographical location, geotechnical and geohydraulic characteristics, dead loads, and live loads, together with environmental conditions incorporating wave, wind, and current, and sometimes seismic conditions. Various researchers suggested different design recommendations for
offshore monopiles, most of which followed iterative techniques. However, such design procedures are not universally applicable. This necessitates the need to conduct extensive theoretical and experimental (laboratory and field-based) research to understand the critical pile-soil interaction, failure mechanisms, and the establishment of an appropriate design methodology.

**Author Contributions:** Conceptualization, S.B. and Z.D.; methodology, S.B. and G.G.; validation, S.B., G.G., and Z.D.; formal analysis, S.B.; investigation, S.B., and Z.D.; resources, S.B. and Z.D.; writing—original draft preparation, S.B., and P.B.; writing—review and editing, S.B. and P.B.; supervision, S.B. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors thankfully acknowledge the infrastructure support received from Pinnacle Educational Trust, NERIST, and Fuzhou University during the preparation of this paper.

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

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