Overview of Geotechnical factors for Onshore Wind Turbine foundation

Sodom Bali Reddy

balireddy23@gmail.com

Abstract: Wind turbine foundations represent a critical component in the renewable energy infrastructure and require specialized geotechnical considerations due to unique loading conditions and operational requirements. This review paper examines the geotechnical factors affecting onshore wind turbine foundation design, including site investigation procedures, soil-structure interaction effects, foundation types, design standards, construction challenges, and environmental considerations. The paper synthesizes current knowledge from academic research, industry practices, and design standards to provide a comprehensive overview of geotechnical engineering principles specific to wind energy infrastructure. Key findings indicate that foundation gapping limitations and cyclic loading considerations often drive design decisions rather than traditional bearing capacity requirements, with soil stiffness and dynamic properties being paramount for ensuring operational frequency requirements. The review emphasizes the critical importance of comprehensive site characterization and the evolving design approaches needed to accommodate increasingly larger wind turbines.

Keywords: Wind turbine foundation; Geotechnical and Geophysical survey; Gapping; Cylic loading

---

1. Introduction

The global wind energy sector has experienced unprecedented growth, with wind turbines becoming increasingly large and sophisticated to maximize energy capture efficiency [1]. Modern onshore wind turbines can reach heights of 130-200 meters with rated capacities ranging from 3-6 MW, imposing unique challenges on foundation design that differ significantly from conventional civil engineering structures [2-3]. Unlike traditional buildings or bridges, wind turbines experience substantial dynamic loads, significant overturning moments, and cyclic loading patterns that can their operational lifetime [4-5].

Geotechnical engineering plays a fundamental role in wind turbine foundation design, as the soil-structure interaction directly influences the dynamic behavior of the entire turbine system [6]. The foundation must not only provide adequate bearing capacity and stability but also maintain specific stiffness requirements to prevent resonance between the turbine's operational frequencies and the natural frequency of the soil-foundation-structure system [7]. This requirement makes wind turbine foundations uniquely sensitive to soil properties and geotechnical conditions.

Poor geotechnical investigation and foundation design have led to delays and cost overruns at European wind farms, emphasizing the critical importance of proper geotechnical assessment and design practices [7].

This review paper aims to provide a comprehensive overview of geotechnical factors affecting onshore wind turbine foundation design, synthesizing current knowledge from research, industry practice, and design standards to guide future developments in this rapidly evolving field.

2. Site Investigation and Characterization

2.1. Geotechnical Investigation Requirements

Wind turbine foundation design requires comprehensive geotechnical investigations that extend beyond traditional site characterization approaches[8]. The unique loading conditions and operational requirements of wind turbines necessitate specialized investigation procedures that provide both static and dynamic soil properties. Unlike conventional structures, wind turbines require site-specific investigations at each turbine location due to the variability of soil parameters and their direct impact on foundation performance[9].

The geotechnical investigation process typically follows a phased approach aligned with project development stages. During the feasibility phase, desk studies and preliminary site reconnaissance provide initial assessment of geotechnical risks and site suitability. The preliminary design phase requires more detailed investigations including boreholes, in-situ testing, and laboratory analysis to develop preliminary foundation designs. The detailed design phase involves targeted investigations to refine design parameters and calibrate constitutive models for advanced analysis[10].

2.2. Investigation Methods and Techniques

Standard Penetration Testing (SPT) remains a fundamental component of wind turbine site investigations, providing soil classification, bearing capacity parameters, and settlement characteristics. The Standard Penetration Test allows defining soil nature and resistance to penetration, with N-values serving as the basis for empirical correlations to determine soil properties essential for foundation design.

Cone Penetration Testing (CPT) provides continuous profiles of tip resistance, sleeve friction, and pore pressure, enabling detailed soil stratification and parameter determination. For wind turbine applications, Seismic Cone Penetration Testing (SCPT) integrates seismic sensors to measure shear wave velocity (Vs), which directly relates to small-strain shear modulus (Gmax) - a critical parameter for dynamic analysis[11].

Geophysical methods play an increasingly important role in wind turbine site characterization. Multichannel Analysis of Surface Waves (MASW) provides shear wave velocity profiles essential for determining dynamic soil properties and foundation stiffness calculations[12].

Laboratory testing focuses on both static and dynamic soil properties. Standard tests include grain size analysis, Atterberg limits, unit weight determination, and unconfined compression tests[13]. Specialized dynamic testing includes cyclic triaxial tests to evaluate soil behavior under repeated loading conditions and small-strain stiffness measurements using bender elements or resonant column testing[14].

2.3. Critical Geotechnical Parameters

Wind turbine foundation design requires specific geotechnical parameters that may not be routinely determined for conventional structures. Soil bearing capacity must account for both ultimate and serviceability limit states, with typical requirements ranging from 250 kPa to several MPa depending on foundation type and soil conditions.

Shear modulus and damping characteristics are critical for dynamic analysis and frequency calculations. The soil stiffness directly affects the natural frequency of the soil-foundation-structure system, which must be designed to avoid resonance with turbine operational frequencies (typically 1P and 3P frequencies)[15].

Settlement parameters including both immediate elastic settlement and long-term consolidation settlement must be evaluated. Differential settlement is particularly critical for wind turbines, as even small foundation tilting can affect turbine alignment and operational efficiency[16].

Cyclic loading parameters are essential for evaluating soil behavior under millions of load cycles. This includes cyclic strength, accumulated strain characteristics, and potential for soil degradation under repeated loading[17].

3. Foundation Types and Selection Criteria

3.1 Shallow Foundation Systems

Spread footings or gravity foundations represent the most common solution for onshore wind turbines in competent soil conditions. The selection of shallow foundations is generally appropriate when soil layers at shallow depths demonstrate adequate strength and deformation characteristics to resist turbine loads. This foundation type is preferred due to its simplicity, cost-effectiveness, and well-established construction practices[18].

3.2 Deep Foundation Systems

Piled foundations become necessary when shallow soil layers lack sufficient bearing capacity or stiffness, or when settlement requirements cannot be met with shallow foundations. Deep foundations for wind turbines can include driven piles, drilled shafts, or combination pile-raft systems.

Single large-diameter drilled shafts represent an efficient deep foundation solution, with studies showing that 0.70-meter diameter single piles can provide cost-effective support while requiring minimal construction time[19]. Pile foundations typically cost 1.5-2.5 times more than shallow foundations but may be necessary in poor soil conditions[20].

Pile-raft foundations combine the load distribution benefits of a shallow foundation with the deep load transfer capacity of piles. This hybrid system allows both the raft and pile group to contribute to load resistance, optimizing foundation performance in variable soil conditions[21].

3.3 Specialized Foundation Systems

Rock-anchored foundations provide an economical solution when competent bedrock is encountered at relatively shallow depths[22]. This system allows significant reduction in foundation dimensions and concrete volume by utilizing post-tensioned anchors to provide uplift resistance[23].

3.4 Foundation Selection Criteria

Foundation selection depends primarily on geotechnical conditions, with soil strength and stiffness being the governing factors[24]. Competent bedrock typically allows rock-anchored solutions, while average soil conditions support shallow foundations, and weak or deformable soils necessitate deep foundation systems[25].

Economic considerations play a significant role, with average foundation costs ranging from 5% of total turbine cost for shallow foundations in competent soils to 27.8% for deep foundations in poor soil conditions[26]. The selection process must balance technical requirements with economic constraints while ensuring long-term performance and safety.

4. Soil-Structure Interaction and Dynamic Considerations

4.1 Dynamic Loading Characteristics

Wind turbines experience complex dynamic loading patterns that distinguish them from conventional structures[27]. The primary loading components include:

- 1P loading from rotor imbalance at the rotational frequency (typically 0.2-0.5 Hz)
- 3P loading from blade-tower interaction at three times the rotational frequency
- Wind loading with broad-band frequency content including tower shadow effects
- Emergency shutdown loads that can impose significant transient loading

These loading patterns result in millions to billions of load cycles over the turbine's 20-30 year operational life, making fatigue and cyclic loading considerations paramount in foundation design[28].

4.2 Soil-Structure Interaction Effects

The interaction between wind turbine foundations and surrounding soil significantly affects the dynamic response of the entire system[29]. Foundation impedance functions describe the relationship between applied loads and resulting displacements, accounting for frequency-dependent soil stiffness and damping characteristics[30].

Dynamic soil stiffness is generally nonlinear and frequency-dependent, typically simplified using springs and dashpots in engineering analysis. The shear modulus (G) decreases from small-strain values (Gmax) as cyclic shear strain increases, while damping increases correspondingly. Design practice typically uses reduced G values based on anticipated strain levels of 10^-2 to 10^-3 for wind turbines[31].

Soil-structure interaction modeling ranges from simplified spring-dashpot systems to advanced three-dimensional finite element models. The SR (Sway-Rocking) model provides an intermediate approach that captures foundation flexibility effects while remaining computationally efficient.

4.3 Natural Frequency Considerations

Frequency placement represents a critical design consideration for wind turbines[32]. The fundamental natural frequency of the soil-foundation-structure system must be positioned to avoid resonance with dominant excitation frequencies. Three frequency ranges are typically considered:

- Soft-soft design: Natural frequency below 1P range
- Soft-stiff design: Natural frequency between 1P and 3P ranges
- Stiff-stiff design: Natural frequency above 3P range

Foundation stiffness directly influences natural frequency placement and may require iterative design to achieve appropriate frequency separation. Changes in soil properties due to cyclic loading can alter natural frequencies over the turbine's operational life[33].

4.4 Cyclic Loading Effects

Soil behavior under cyclic loading presents unique challenges for wind turbine foundations[34]. Depending on soil type and stress conditions, cyclic loading can result in:

- Strain hardening in dense sands, leading to increased stiffness and natural frequency
- Strain softening in loose sands or clays, resulting in decreased stiffness
- Accumulation of permanent deformations affecting foundation alignment

Foundation stiffness degradation due to cyclic loading must be considered in long-term performance assessment. The extent of degradation depends on soil properties, stress levels, and number of load cycles experienced[35].

5. Design Standards and Codes

5.1 International Design Standards

IEC 61400 series represents the primary international standard for wind turbine design. IEC 61400-1 addresses wind turbine design requirements including load calculations and safety factors [36]. The recently published IEC 61400-6:2020 specifically addresses tower and foundation design requirements, providing unified guidance for wind turbine structural design[24].

IEC 61400-6 represents a significant advancement in wind turbine foundation standards, addressing the previous lack of internationally accepted design references.

DNV guidelines provide comprehensive coverage of wind turbine design requirements[37]. Key DNV standards include:

- DNVGL-ST-0126: Support structures for wind turbines
- DNVGL-ST-0437: Load and site conditions for wind turbines
- DNVGL-RP-0416: Corrosion protection

5.2 National and Regional Standards

European standards including Eurocodes provide the structural design framework for wind turbine foundations in European markets. EN 1997-1 (Eurocode 7) [38] addresses geotechnical design requirements, while EN 1992 covers concrete design aspects[39].

American standards include ASCE/AWEA RP2011 "Recommended Practice for Compliance of Large Land-Based Wind Turbine Support Structures"[40]. This document provides US-specific guidance while referencing IEC standards for load calculations.

National variations exist in different countries, with examples including:

- German DIBT guidelines providing alternative to IEC standards
- French CFMS recommendations for wind turbine foundations
- Chinese FD 003-2007 standard for wind turbine design

5.3 Fatigue Design Requirements

Concrete fatigue represents a critical design consideration due to the high number of load cycles experienced by wind turbine foundations. Over a typical 20-year operational life, foundations can experience up to 10^8 load cycles, potentially causing concrete fractures at stress levels below static ultimate capacity[24].

Fatigue design standards show significant variation in approach and requirements. Comparison between NS-EN 1992-1-1:2004, Model Code 2010, and DNV-OS-C502 reveals substantial differences in predicted fatigue life, with DNV-OS-C502 generally considered most suitable for wind turbine foundation applications.

Steel fatigue requirements apply to anchor bolts, embedded plates, and reinforcement details[41]. Eurocode 3-9 provides fatigue assessment procedures for steel structural elements commonly employed in wind turbine foundation design[42].

6. Environmental and Seismic Considerations

6.1 Seismic Design Requirements

Seismic loading has gained increased attention as wind turbine deployment expands into earthquake-prone regions. Earthquake strong ground motions constitute a significant component of the multi-hazard environment affecting wind turbines. Combined wind-earthquake loading can result in structural demands exceeding those from extreme wind events alone[43].

Seismic analysis approaches range from simplified response spectrum methods to detailed time-history analysis. The response spectrum method requires consideration of low structural damping characteristics typical of wind turbines and soil-structure interaction effects[44]. Modified damping correction factors have been developed specifically for wind turbine structures with damping ratios significantly lower than conventional buildings.

Operational considerations during seismic events present unique challenges. Emergency shutdown procedures triggered by seismic activity impose additional structural demands while the system must simultaneously resist earthquake loading. The combination of emergency braking loads and seismic forces can control foundation design in earthquake-prone regions.

6.2 Liquefaction Susceptibility

Soil liquefaction represents a critical hazard for wind turbines in seismically active regions with saturated cohesionless soils. Liquefaction can cause significant loss of foundation bearing capacity and lead to excessive tilting or settlement. Assessment of liquefaction potential requires evaluation of soil characteristics, groundwater conditions, and expected seismic intensity[45].

Foundation performance in liquefiable soils has been investigated through centrifuge modeling and numerical analysis. Research indicates that monopile foundations may experience earthquake-induced rotation exceeding allowable thresholds in liquefiable conditions. Alternative foundation systems such as outrigger foundations or ground improvement techniques may be necessary in high liquefaction risk areas.

Mitigation strategies for liquefaction hazards include ground improvement techniques such as stone columns, deep soil mixing, or vibro-compaction. These methods can increase soil density and drainage capacity, reducing liquefaction potential while improving foundation performance.

6.3 Climate Change Impacts

Environmental loading considerations are evolving as climate change affects weather patterns and extreme event frequencies. Changes in precipitation patterns and soil moisture content can affect foundation stability and bearing capacity. Rising groundwater levels may alter soil properties and increase liquefaction susceptibility in coastal areas.

Extreme weather events including increased storm intensity and frequency require consideration in foundation design. Wind turbines must be designed to withstand not only normal operational loads but also extreme weather conditions that may exceed historical records.

7. Construction Challenges and Quality Control

7.1 Construction Challenges

Mass concrete effects present significant challenges in wind turbine foundation construction.Temperature gradients can develop massive internal stresses leading to structural cracking if not properly controlled.

Reinforcement congestion complicates concrete placement and quality control. Wind turbine foundations require sophisticated anchor bolt assemblies and heavy reinforcement to resist overturning moments. This congestion can lead to segregation, poor consolidation, and void formation around critical anchor elements.

Construction tolerances become increasingly critical with larger turbines requiring precise foundation geometry. Tower-foundation interface requirements demand strict dimensional control to ensure proper load transfer and equipment alignment.

7.2 Quality Control Procedures

Fresh concrete testing forms the foundation of quality control programs. Standard tests include slump or flow testing for workability assessment, air content measurement, and compressive strength evaluation through cylinder sampling. For mass concrete applications, temperature monitoring using thermocouples is essential to control thermal effects.

Non-destructive testing (NDT) provides comprehensive assessment of concrete quality without compromising structural integrity. Common NDT methods include:

- Ground-penetrating radar for reinforcement location and void detection
- Ultrasonic testing for concrete uniformity and crack assessment
- Impact-echo testing for thickness verification and delamination detection

- Core drilling for strength verification and petrographic analysis

Temperature control plans are essential for mass concrete placements. These plans specify concrete mix design requirements, placement procedures, curing methods, and temperature monitoring protocols to prevent thermal cracking.

7.3 Performance Monitoring

Structural health monitoring (SHM) systems provide continuous assessment of foundation performance throughout operational life. Monitoring parameters include:

- Strain measurements using embedded vibrating wire gauges
- Settlement monitoring through precise leveling or automated systems
- Tilt measurements using inclinometers or tiltmeters
- Crack monitoring using crack meters and visual inspection

Real-time monitoring systems enable early detection of structural issues and optimization of maintenance schedules. Wireless sensor networks can transmit data from multiple foundation locations to centralized monitoring systems. This approach enables proactive maintenance strategies and extends foundation service life.

Foundation performance assessment requires correlation between measured behavior and design predictions. Long-term monitoring data provides validation of design assumptions and enables optimization of future foundation designs.

8. Emerging Technologies and Future Trends

8.1 Advanced Analysis Methods

Three-dimensional finite element modeling is becoming standard practice for complex foundation systems. Advanced constitutive models can capture nonlinear soil behavior, cyclic loading effects, and soil-structure interaction more accurately than simplified methods.

Multi-physics modeling integrates structural, geotechnical, and fluid dynamics analysis to capture the full complexity of wind turbine loading. These approaches enable more accurate prediction of foundation performance under combined environmental loading.

8.2 Ground Improvement Technologies

Advanced ground improvement techniques are expanding options for challenging site conditions. Methods such as controlled modulus columns, rigid inclusions, and deep soil mixing provide alternatives to traditional deep foundations. These technologies can modify soil properties to enable shallow foundation solutions while controlling costs.

Bio-cementation and other emerging ground improvement technologies offer potential for sustainable soil modification. These methods may provide environmentally friendly alternatives to traditional chemical stabilization approaches.

8.3 Smart Foundation Technologies

Instrumented foundations incorporating sensors and monitoring systems from construction phase through operational life represent an emerging trend. These systems provide continuous feedback on foundation performance and enable adaptive maintenance strategies.

Self-healing concrete and other advanced materials may improve foundation durability and reduce maintenance requirements. Integration of these technologies could extend foundation service life and reduce lifecycle costs.

9. Conclusions

This comprehensive review of geotechnical factors for onshore wind turbine foundations reveals the complex interplay between soil conditions, structural requirements, and operational demands that characterize this specialized field. Several key conclusions emerge from the analysis:

Unique Design Requirements: Wind turbine foundations differ fundamentally from conventional structures due to their dynamic loading characteristics, cyclic load patterns, and frequency requirements. Traditional geotechnical design approaches must be modified to address these unique challenges, with foundation gapping and fatigue often controlling design decisions rather than conventional bearing capacity limits.

Critical Site Investigation: Comprehensive geotechnical investigation extending beyond standard practice is essential for wind turbine projects. Site-specific investigations at each turbine location are necessary due to soil variability impacts on foundation performance. Integration of geophysical methods, dynamic testing, and specialized laboratory procedures provides the detailed soil characterization required for optimal foundation design.

Foundation System Selection: Foundation selection depends primarily on soil conditions, with shallow foundations preferred in competent soils and deep foundations or ground improvement necessary in poor conditions. The economic impact of foundation selection can range from 5% to 27.8% of total project costs, emphasizing the importance of appropriate geotechnical assessment and foundation optimization.

Soil-Structure Interaction: Dynamic soil-structure interaction effects significantly influence wind turbine performance and must be carefully considered in design. Natural frequency placement, foundation stiffness requirements, and cyclic loading effects require specialized analysis approaches beyond conventional geotechnical practice.

Evolving Standards: The development of international standards such as IEC 61400-6 represents significant progress in wind turbine foundation design guidance. However, continued standardization efforts are needed to address emerging challenges associated with larger turbines and more demanding site conditions.

Construction and Quality Control: Specialized construction procedures and quality control measures are essential for wind turbine foundations. Mass concrete effects, reinforcement congestion, and precise dimensional requirements demand enhanced construction practices and comprehensive quality assurance programs.

Environmental Considerations: Seismic loading, liquefaction potential, and climate change impacts require increasing attention in wind turbine foundation design. Multi-hazard assessment approaches and adaptive design strategies will become increasingly important as the industry expands into more challenging environments.

Future Directions: Emerging technologies including advanced analysis methods, ground improvement techniques, and smart foundation systems offer potential for improved performance and reduced costs. Integration of real-time monitoring systems and adaptive maintenance strategies represents a promising direction for foundation lifecycle management.

The geotechnical challenges associated with wind turbine foundations will continue to evolve as turbines become larger and deployment expands into more challenging site conditions. Success in addressing these challenges requires continued advancement in site investigation techniques, analysis methods, design standards, and construction practices. The interdisciplinary nature of wind turbine foundation engineering demands close collaboration between geotechnical engineers, structural engineers, and wind energy specialists to optimize performance while managing costs and risks.

As the renewable energy sector continues its rapid growth, the role of geotechnical engineering in enabling successful wind energy projects will become increasingly critical. The lessons learned from current practice, combined with ongoing research and technological advancement, provide the foundation for meeting future challenges in this dynamic and essential field.

Funding: This research received no external funding.

Acknowledgments:

References

[1]. Demirci, H. E. (2023). Geotechnical Preliminary Design of Onshore Wind Turbine Foundations. Erzincan University Journal of Science and Technology, 16(3), 756-781. https://doi.org/10.18185/erzifbed.1306867

[2]. https://nexhs.com/2021/08/24/site-specific-soil-investigation-and-foundation-design-for-wind-turbine/

[3]. https://www.numberanalytics.com/blog/geotechnical-challenges-offshore-wind-farms

[4].

[5]. Bhavana Suresh: Study on stabilization of soil for wind turbine foundation: 2020, https://impressions.manipal.edu/cgi/viewcontent.cgi?article=1029&context=mit

[6]. P. Doherty, K. Gavin, and B. Casey: The Geotechnical Challenges Facing the Offshore Wind Sector: Geo-Frontiers 2011: Advances in Geotechnical Engineering, https://doi.org/10.1061/41165(397)

[7]. Darshan Dipak Bhai Tank and Aakash Rajesh Kumar Suthar: A Study of Onshore Wind Turbine Foundation for Varying Heights in Zone-IV.: International Research Journal of Engineering and Technology (IRJET), 2023, Volume: 10 Issue: 06 | Jun 2023.

[8]. Ben He, Shaoli Yang, Knut H.: Andersen,Soil parameters for offshore wind farm foundation design: A case study of Zhuanghe wind farm, Engineering Geology, Volume 285, 2021, 106055, ISSN 0013-7952, https://doi.org/10.1016/j.enggeo.2021.106055.

[9]. Mr.Vishnu A.J: Challenges in the design of offshore wind turbine foundations, International Journal of Novel Research and Development (www.ijnrd.org)

[10]. Sachin Jindal, Ulvi Rahmanli, Muhammad Aleem, Liang Cui, Subhamoy Bhattacharya,: Geotechnical challenges in monopile foundations and performance assessment of current design methodologies: Ocean Engineering, Volume 310, Part 1, 2024, 118469, ISSN 0029-8018, https://doi.org/10.1016/j.oceaneng.2024.118469.

[11]. How to design foundations for onshore wind turbines

[12]. Malcolm Andrew Hicks: Geotechnical Investigations of Wind Turbine Foundations Using Multichannel Analysis of Surface Waves (MASW):2011, Master of Science in Engineering Geology at the University of Canterbury.

[13]. Imanzadeh S*, Pantet A, Taibi S and Ouahbi T: Soil Behavior Under Onshore Wind Turbine Foundation-Case Study in Brazil Using New French EOLIFT Technology: 2021, 10.31031/ACET.2021.04.000594.

[14]. https://sut-us.org/pages_data/files/Integrated-site-characterization-considerations-for-U-S-East-Coast-offshore-wind-developments_637284642420288125.pdf
[15]. J.M. Tinjum, R.W. Christensen,: 2 - Site investigation, characterization and assessment for wind turbine design and construction,: Editor(s): John D. Sørensen, Jens N. Sørensen In Woodhead Publishing Series in Energy, Wind Energy Systems, Woodhead Publishing, 2011, Pages 28-45, ISBN 9781845695804, https://doi.org/10.1533/9780857090638.1.28.
[16]. Recommendations for the design, calculations, installation and inspection of wind-turbine foundations, Revue Française de Géotechnique (RFG), 2012, https://www.geotechnique-journal.org/articles/geotech/pdf/2012/01/geotech2012138-139p51.pdf
[17]. Michail Papagiannis: wind turbine foundations in clay technical and economic considerations for proposals for wind turbine foundations: 2018, master of science with a major in wind power project management, Uppsala university.
[18]. Jeramy C. Ashlock and Vern Schaefer,: FOUNDATIONS FOR WIND TURBINES, ENGR 340 – Fall 2011, https://www.engineering.iastate.edu/~jdm/engr340-2011/ENGR 340 - Foundations 1 - Ashlock - Schaefer.pdf.
[19]. Alshaba, A. A., Hassona, F. A., Hassan, A. M., and Abdelaziz, T. M.,:Settlement of Wind Turbine Resting on Different Foundations Systems in Zafarana Egypt: Indian Geotechnical Journal</i>, vol. 55, no. 2, pp. 730–749, 2025. doi:10.1007/s40098-024-00902-z.
[20]. Filho, H. A. N. C., Avila, S. M., & Brito, J. L. V. de.: Dynamic analysis of onshore wind turbines including soil–structure interaction:2021, In Journal of the Brazilian Society of Mechanical Sciences and Engineering.
[21]. Onshore Structure - NeXHS
[22]. Upendra Kumar Sah and Jun Yang: Importance of higher modes for dynamic soil structure interaction of monopile-supported offshore wind turbines: 2024, Volume53, Issue6, Pages 2006-2031, https://doi.org/10.1002/eqe.4095
[23]. Engineering Wind Turbine Support Structures
[24]. International Electrotechnical Commission, IEC 61400-1 Ed.3: Wind Turbines – Part 6: Tower and foundation design requirements , 2003.
[25]. Børsheim, Håkon: Concrete fatigue of onshore wind turbine foundations:2020, Master thesis, https://hdl.handle.net/11250/2679263
[26]. R. Damiani and D. Davis.: Design Load Basis Guidance for Distributed Wind Turbines:,2024, NREL Technical Monitor: Brent Summerville, https://docs.nrel.gov/docs/fy25osti/91458.pdf
[27]. G. Nikitas a , Nathan J. Vimalan b , S. Bhattacharya: An innovative cyclic loading device to study long term performance of offshore wind turbines: 2015, Soil Dynamics and Earthquake Engineering, pp.154-160, http://dx.doi.org/10.1016/j.soildyn.2015.12.008
[28]. Mike Woebbeking: Development of a new standard and innovations in certification of Wind Turbines, IEC WT 01 vs. IEC 61400-22 , Germanischer Lloyd Industrial Services GmbH 2007
[29]. Bing Li, Kang Rong, Haifeng Cheng, Yongxin Wu: Fatigue Assessment of Monopile Supported Offshore Wind Turbine under Non-Gaussian Wind Field, 2021, https://doi.org/10.1155/2021/6467617.
[30]. Martin Kelm: FOWPI Foundation Design OWF Gujarat, https://niwe.res.in/static/pdf/depart-side-tabs/FOWPI_foundation_design.pdf
[31]. DNV-ST-0126 Support structures for wind turbines, Edition 2021-12
[32]. Industry Best Practice for Wind Turbine Foundations, https://www.dnv.com/article/industry-best-practice-for-wind-turbine-foundations-182221/
[33]. Katsanos, E., Thöns, S., & Georgakis, C. T. (2016). Wind turbines and seismic hazard: a state-of-the-art review. Wind Energy, 19(11), 2113-2133. https://doi.org/10.1002/we.1968
[34]. Oloruntosin Tolulope Joel and Vincent Ugochukwu Oguanobi: Geotechnical assessments for renewable energy infrastructure: Ensuring stability in wind and solar projects, Volume 5, Issue 5, P.No. 1588-1605, May 2024 DOI: 10.51594/estj/v5i5.1110
[35]. Umar Ahad Butt and Takeshi Ishihara: Seismic Load Evaluation of Wind Turbine Support Structures Considering Low Structural Damping and Soil , Structure Interaction, 2012, https://windeng.t.u-tokyo.ac.jp/ishihara/proceedings/2012-2_paper.pdf
[36]. International Electrotechnical Commission (2005), IEC 61400-1 Ed.3: Wind Turbines – Part 1: Design Requirements.
[37]. Ben-Hassine J. and Griffiths D.V. , : Geotechnical Exploration for Wind Energy Projects,2013, Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris.

[38]. EN 1997-1: Eurocode 7: Geotechnical design - Part 1: General rules [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC
[39]. EN 1992-1-1 : Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC]
[40]. American standards include ASCE/AWEA RP2011 "Recommended Practice for Compliance of Large Land-Based Wind Turbine Support Structures
[41]. Hamed Layssi, PhD, PEng; Faird Moradi, and Vahid Shahsavari, : Non-destructive testing of turbine foundations, https://www.windsystemsmag.com/wp-content/uploads/2020/07/0820-IF-1.pdf
[42]. EN 1993-1-9 : Eurocode 3: Design of steel structures - Part 1-9: Fatigue [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC]
[43]. Allan Lion Kristensen: Inspection of concrete in wind turbine foundations.
[44]. Mathern, A.; Magnusson, J.: Lessons Learned from the Construction, Inspection, and Defect Assessment of Reinforced Concrete Foundations for Wind Turbines. Appl. Sci. 2022, 12, 1443. https://doi.org/10.3390/app12031443
[45]. DNV/Risø, : Guidelines for Design of Wind Turbines