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How Port, Waterway and Coastal Engineering Inject "Core Strength" into Offshore Wind Power

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Abstract. Offshore wind power is a powerful engine driving the development of renewable energy. However, the complex marine environment brings challenges such as high construction difficulty, difficult operation and maintenance, and high costs, which seriously affect the high-quality development of the offshore wind power industry. As an interdisciplinary major integrating knowledge of marine environmental dynamics, geotechnical engineering, structural engineering, port planning and logistics management, Port, Waterway and Coastal Engineering actively empowers all aspects of the offshore wind power industry chain. This paper deeply analyzes the core engineering challenges faced by the development of offshore wind power, systematically elaborates on the core technical contributions and innovative solutions of the Port, Waterway and Coastal Engineering major in key links such as offshore wind farms, helps offshore wind power march into the deep-sea era, and promotes the high-quality and low-energy-consumption development of the offshore wind power industry.

Keywords: Port and Waterway, Coastal Engineering, Offshore Wind Power, Foundation Structure, Operation and Maintenance Support

1. Introduction

As an important part of the clean energy system, the development of offshore wind power continues to accelerate towards deep and far seas, large-scale and large-capacity, which is a powerful weapon to promote the green and low-carbon transformation of energy and the realization of the "dual carbon" goals. In the process of offshore wind power development and construction, Port, Waterway and Coastal Engineering plays an irreplaceable fundamental and supporting role, and is the basic guarantee for promoting the high-quality development of the offshore wind power industry.

Ports serve as the fulcrum for the whole life cycle of offshore wind power. The deep-water berths, heavy lifting capacity and broad land area of high-quality ports can provide good conditions for the transportation of large wind power equipment such as ultra-long blades, heavy towers and giant jacket foundations required in the manufacturing, assembly, storage and operation of offshore wind power. Waterway engineering is equivalent to the "highway" of offshore wind power. Through pre-investigation and planning, dredging, trenching and daily maintenance in the later period, it provides safety guarantee for the entry and passage of large special ships such as transportation and installation ships and operation and maintenance ships, and transports wind power equipment and

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staff to the wind farm site. Coastal engineering is mainly used in the construction of wind farms, such as using coastal protection facilities to defend against the impact of wind and wave scouring; Equipped with special offshore construction platforms, berthing facilities and submarine cable landing points, it can complete the laying of wind turbine foundations and submarine cables as well as the whole life cycle operation and maintenance at sea; Since the long-term operation of wind farms needs to be carried out in sea areas far from the shore, Port, Waterway and Coastal Engineering provides strong support for the construction of the entire project. Port, Waterway and Coastal Engineering are the key to the smooth progress of offshore wind power engineering construction. They play an important role in improving the degree of construction and operation and maintenance support, ensuring the safety of offshore wind power personnel and equipment, reducing the construction, operation and maintenance costs, risks and development intensity of offshore wind power, and acting as the unsung heroes of the large-scale and commercialization of offshore wind power.

2. The rise of offshore wind power and engineering challenges

2.1. Strategic status and development trend of offshore wind power

Facing climate change, actively implementing the "dual carbon" action has become a common consensus of all mankind. Wind power, a clean energy with mature technology and continuously decreasing costs, is further promoting the development of offshore wind power from land to the vast ocean. Due to many advantages such as higher and more stable wind speed, weaker turbulence, no occupation of land resources and proximity to coastal load centers in offshore wind farms, wind power generation has great potential. The global offshore wind power installed capacity has achieved rapid growth. Europe is the leader, and the Asia-Pacific region, especially China, has caught up from behind and become another driving force for the development of offshore wind power. The "14th Five-Year Plan for Renewable Energy Development" proposes: actively promote the clustered development of offshore wind power, and accelerate the construction of deep-sea wind power demonstration projects [1]. China has a long coastline and abundant offshore wind energy resources. It has identified offshore wind power as a national strategic emerging industry, vigorously developed offshore wind power projects, and actively promoted the development of the wind power equipment industry. According to data from GWEC [2], China's new offshore wind power installed capacity in 2024 accounted for 50.47% of the global new installed capacity, ranking first in the world for 7 consecutive years; by the end of 2024, China's offshore wind power grid-connected installed capacity reached 41.27 million kilowatts, accounting for 50.3% of the global total, exceeding the sum of the second to fifth place countries, and ranking first in the world for 4 consecutive years.

2.2. Core engineering bottlenecks in the development of offshore wind power

Harsh environmental conditions: Strong winds, huge waves, ocean currents, tides, sea ice, earthquakes and corrosion pose serious threats to structural safety.

Short construction window period: Due to the limitation of time and geographical conditions, the window period for efficient and safe construction is very short, and the difficulty is conceivable.

Significant large-scale trend: The single-unit capacity of wind turbines has gradually increased (exceeding 15MW), the blade length has exceeded 100 meters, and the tower height is also over 100 meters, which has put extreme requirements on manufacturing, transportation and hoisting.

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Deep-sea challenge: Projects are developing towards areas with better wind resources and larger development space, moving towards deep and far seas (water depth > 50m), which requires new foundation types, construction technologies, grid connection methods, operation and maintenance support, etc.

Great cost pressure: The initial investment and operation and maintenance costs are relatively large (CAPEX and OPEX respectively), and cost reduction and efficiency improvement are the eternal pursuit of industrial development.

High requirements for ecological and environmental protection: Minimize negative impacts on the marine environment, fishery and shipping.

2.3. Empowerment opportunities for the port, Waterway and Coastal Engineering major

The research objects of the Port, Waterway and Coastal Engineering major include hydrodynamics, sediment movement, geology and engineering structures in the coastal zone and offshore areas. Its core capabilities lie in: deeply understanding and predicting the mechanism of complex marine environmental loads (waves, currents, winds, tides, ice, earthquakes, etc.) acting on engineering structures; mastering the key technologies for the design and construction of large underwater foundations under complex geological conditions (soft soil, sand soil, rock); being able to grasp port planning, waterway regulation, terminal design, dredging and reclamation, etc., and providing important infrastructure support for the berthing, transfer and assembly of large equipment; being good at engineering technologies such as shore protection engineering, erosion control and ecological restoration. These aspects are closely combined with offshore wind power construction, making it a key technical support discipline that can empower the offshore wind power industry and realize the high-quality development of offshore wind power.

3. Core empowerment areas: full-chain support from site selection to operation and maintenance

3.1. Accurate site selection and engineering geological survey guarantee

Scientific route selection is the premise for the success of the project.

Macro site screening: Refer to historical marine observation data (such as statistical data of waves, tides, ocean currents, wind speed and direction), regional geological background data, and comprehensively consider factors such as wind energy resource evaluation, marine functional zoning, shipping, military and ecological red lines to initially screen the site areas suitable for development and construction.

Micro position optimization: Within the site, it is necessary to complete high-resolution topographic and geomorphological surveys (multi-beam, side-scan sonar), engineering geological surveys (geological drilling, CPT, geophysical prospecting) and geophysical exploration. The main work is to carry out these basic tasks.

Accurate detection of seabed topography and shallow geological conditions: Identify unfavorable geological conditions such as sand waves, sand ridges, eroded trenches, buried ancient rivers, shallow gas and bedrock undulations, and evaluate their impact on foundation construction.

Detailed division of engineering geological units: Accurately grasping the spatial distribution, physical and mechanical properties (strength, modulus, permeability) and dynamic parameters (liquefaction potential, etc.) of each soil/rock layer is the basic condition for foundation type selection and design.

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Assessment of geological disaster risks: Identify landslides, fault activity, sand liquefaction, scouring pit development areas, etc., which can provide disaster prevention references for site optimization and engineering design.

Geotechnical engineering analysis and parameter determination: Use professional knowledge and experience to analyze research data, conduct statistical analysis, and obtain reliable parameters (pile side friction resistance, end resistance, horizontal subgrade coefficient, foundation bearing capacity) and evaluate the uncertainty of parameters.

3.2. Marine foundation structure: the cornerstone of safety and economy

Foundation type selection decision: According to various factors such as water depth, geological conditions, environmental loads, wind turbine characteristics and construction conditions, scientifically selecting the foundation form is the optimal solution (in Table 1, the key technical parameters and engineering characteristics of the five major foundation types for offshore wind power).

Monopile foundation: The most widely used and technically mature. The core of the design is to accurately calculate the internal force (bending moment, shear force), deformation (deflection) in the pile body under complex loads (wind turbine electrodynamic load + extreme environmental load), pile-soil interaction (P-Y curve), pile driving (prediction of penetration depth and hammering energy, etc.), and fatigue life; Port and coastal engineers are proficient in pile dynamics and pile driving analysis.

Jacket foundation: Suitable for areas with large water depth or poor geological conditions (deeply buried hard layers). Core: Spatial frame structure optimization, joint fatigue check, foundation-seabed interaction, installation and leveling measures; Possessing very strong port and coastal engineering design experience.

Gravity foundation: Adopted in special geology (hard bottom) or places that need ballast to resist floating and sliding. The main design contents include: foundation bearing capacity and settlement calculation, anti-overturning and anti-sliding stability analysis, control of floating transportation, towing and sinking to the bottom, and foundation-seabed contact surface. Port and coastal engineers have a large number of design experiences in gravity wharves and breakwaters.

Suction bucket foundation: A foundation type suitable for sandy or cohesive soil seabeds. The main research contents of this foundation are: bucket structure design, simulation and control of negative pressure penetration process (avoiding soil plugging and bucket buckling), and long-term service performance (bucket tightness, equivalent stiffness and deformation of the bucket under cyclic loads).

Floating foundation: [3] Used in deep-water environments (> 50-60m), and the technology is still in the development stage, including spar-type, semi-submersible type, tension leg type, etc. Its design mainly involves the design and analysis of the mooring system, floating body motion response, and dynamic cable design. Since such projects mostly use mooring systems, floating body hydrodynamics and other contents, port and coastal engineers are usually good at such work.

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Table 1. Key technical parameters and engineering characteristics of the five major foundation types for offshore wind power

Foundation Type	Applicable Water Depth	Core Design Elements	Key Technical Indicators
Monopile Foundation	0-30m	Pile-soil interaction (P-Y curve), pile driving control, fatigue life calculation	Pile top deflection ≤ H/200, penetration error ±5cm
Jacket Foundation	30-50m	Spatial frame topology optimization, joint fatigue check, installation and leveling	Steel consumption reduced by 15%, flatness < 1/500
Gravity Foundation	Any water depth (hard bottom)	Foundation bearing capacity calculation, anti-sliding stability analysis, floating transportation control	Settlement < 30mm, anti-sliding safety factor ≥ 1.5
Suction Bucket Foundation	0-30m	Negative pressure penetration control, bucket buckling suppression, long-term tightness maintenance	Penetration speed 8m/h, soil plug control error ±2kPa
Floating Foundation	> 50m	Mooring system design, motion response (RAO), dynamic cable deflection control	Mooring cable breaking strength ≥ 1500kN, deflection angle redundancy 30%

3.3. Ports: hubs for large equipment and operation and maintenance bases

Requirements for specialized wind power terminals:

Bearing capacity: Meet the requirements for stacking and transferring super-heavy (over 1000-ton foundations, towers) and super-large (100-meter-level blades) components, and design super-large load terminal structures, heavy pavements, large crane rail beams, etc.

Water depth conditions: Provide sufficient water depth at the terminal front and approach channel to ensure the safe draft of large transport ships (deck transport ships or installation ships), which requires frequent dredging work.

Port land area: Provide sufficient space for installation (blade assembly, tower section pairing, nacelle assembly) and pre-assembly. The site should be flat and suitable for the travel and precision assembly of heavy equipment, as well as meeting the applicable foundation requirements.

Supporting facilities: Heavy lifting equipment such as gantry cranes and crawler cranes, as well as large automobile passages, power supply and distribution systems, lighting devices and berthing and mooring equipment.

Core functions:

Storage and transfer of large components: Efficiently organize the whole process logistics of wind turbine components from the manufacturing plant to the terminal yard and then to the ship. Pre-assembly of key components: Complete the docking of blades with hubs and multi-section towers at the terminal to reduce offshore operation time and risks.

Mother port for construction ships: Provide berthing, supply, wind shelter and maintenance support for wind power installation vessels (WTIV), large crane ships, cable laying ships, transportation and operation and maintenance ships, etc.

Operation and maintenance support base: [4] It is the departure point and logistics support center for operation and maintenance personnel, spare parts and operation and maintenance ships (CTV/SOV) during the long-term operation period. In this area, it is necessary to consider the functions of operation and maintenance ship berthing, personnel transfer, warehousing and logistics, as well as office and living.

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Port site selection and optimization: Combine the conditions of being close to the wind farm, near the terminal near the wind power tower, good wind shelter, good geology and potential for expansion, and combine with existing chemical plants to scientifically and reasonably select the site and general layout.

3.4. Waterways and anchorage areas: the lifeline of construction ships

Waterway design upgrade: Judge whether the current approach channel and the temporary channel connecting the offshore wind farm can pass through special ships such as large wind power installation ships and deck transport ships, and widen, deepen (dredge) and optimize the channel as needed.

Navigation safety assessment: Study the impact of wind and current on ship maneuvering, research and formulate corresponding safe navigation and emergency collision avoidance rules; Use ship maneuvering simulation technology to conduct comprehensive research on ship navigation safety, especially under complex conditions.

Planning of operation anchorage areas for construction ships: Determine to select a safe and stable anchorage area near the wind farm, so that installation ships and other ships can berth, take shelter from wind and wait for the window period during idle time. When determining, factors such as seabed anchor holding power, wind shelter conditions and safety distance should be considered.

3.5. Submarine cable engineering: the "blood vessels" of energy transmission

Route survey and optimization: According to comprehensive geological conditions (avoiding faults, steep slopes, unstable parts), obstacles (sunken ships, reefs, existing pipelines), navigation, fishing net activities, ecologically sensitive areas and other factors, reasonably select the cable route; Port and coastal engineers lead the route survey (geophysical detection, geological sampling) and risk assessment.

Cable laying design: Determine the laying method (burial plow, jet burial, riprap protection) and burial depth requirements (preventing damage from fishing gear and scouring). Design the bending radius protection, span control and landing point structure of the cable.

Scour protection design: Predict the scour risk near the cable trench and landing point, and design effective protection measures (such as riprap, artificial mats, concrete cushions, flexible protection mats).

3.6. Digital and intelligent empowerment

BIM (Building Information Modeling) technology: Applied to the whole life cycle management of wind farms, integrating the information of design, construction and operation and maintenance in series, which can minimize the probability of errors and improve efficiency.

Digital twin: Establish a virtual mapping of the wind farm entity (mainly foundations and submarine cables), and integrate real-time monitoring data (structural response, environmental parameters, scour status) for state evaluation and prediction, as well as operation and maintenance decision support.

Advanced monitoring technology: Use optical fiber sensing (strain, temperature), acoustic monitoring (scour depth) and underwater robots to carry out structural health monitoring and seabed state detection.

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Intelligent construction equipment: Develop and apply intelligent construction ships and machinery with automatic positioning and precise pile driving/installation functions.

4. Deep-sea offshore wind power: a new domain of professional empowerment

Floating foundations become the mainstream: [5] Floating offshore wind power is an inevitable choice for deep and far seas. The main types of floating offshore wind power foundations include semi-submersible type, tension leg type, spar-type and barge type (in Table 2, the comparison of applicable water depth conditions, advantages and disadvantages of four different floating offshore wind power foundation types). Its core lies in: optimizing the hydrodynamic performance and stability of the floating platform; developing a highly reliable and economical mooring system and large holding power/suction anchors, pile foundations and other anchoring foundations suitable for deep-sea geology; solving the fatigue life problem of dynamic submarine cables.

Table 2. Comparison of applicable water depth conditions, advantages and disadvantages of four different floating offshore wind power foundation types

Floating Foundation	Applicable Water Depth Conditions	Advantages	Disadvantages
Semi-submersible Type	Wide applicable water depth range, suitable for water depth above 40m	Convenient installation, good stability, wet towing transportation method, relatively mature technology	The overall structure is large, and the construction structure is relatively complex
Tension Leg Type	Usually applicable to water depth greater than 40m	Good adaptability of wind turbines, less steel consumption for the structure	The tendons bear large loads, and the installation process is complex
Spar-type	Often used in deeper sea areas with water depth greater than 100m	Simple structure, small vertical movement, better stability	Lack of relevant manufacturing and application installation experience in China, and high difficulty
Barge Type	Usually applicable to sea areas with water depth greater than 30m and good sea conditions	Simple structure form, good stability, flexible layout, low cost	Sensitive to wave frequency response, large motion response under extreme weather

Port terminal capacity upgrade: The components of deep-sea projects are larger and heavier, which puts forward great challenges to the bearing capacity, water depth, tonnage of lifting equipment and pre-assembly site of the terminal. It is necessary to build or extensively renovate specialized ports.

Large-scale and specialized construction fleet: Develop next-generation wind power installation ships and heavy crane ships with larger tonnage, higher operation capacity (lifting height, lifting weight), stronger wind and wave resistance and equipped with dynamic positioning (DP) systems. The supporting ports need to accommodate "giants".

Innovation of operation and maintenance mode: [6] Compared with offshore areas, deep-sea areas are farther away, more difficult to reach and have harsher conditions. The operation and maintenance mother port needs to provide larger space, better living conditions, DP and the ability to take off and land aircraft for the operation and maintenance mother ship or accommodation ship. At the same time, it is necessary to use UAVs, unmanned ships and underwater robots to carry out remote inspection and simple maintenance.

With the more urgent demand for power transmission from deep-sea areas, the one-way distance and capacity scale will be larger, which will require more economical and reliable HVDC

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technology. This technology must rely on complex offshore converter station platforms, extremely long-distance submarine cables and a series of more complex engineering and technical means to complete the whole work.

5. Conclusion

With a deep understanding of the complex marine environment and core technical capabilities in geotechnical engineering, engineering structures and port logistics, the Port, Waterway and Coastal Engineering major realizes the overall and comprehensive empowerment of the offshore wind power industry, and becomes a key force to escort the development of the offshore wind power industry. It has overcome the "bottleneck problems" of offshore wind power in terms of precise site selection and design, innovative foundation structures, refined port hub construction, convenient construction and operation and maintenance, and ecological scouring protection, greatly reducing project risks and costs, and providing necessary support conditions for the development of offshore wind power towards large-scale and deep-sea.

It is foreseeable that the Port, Waterway and Coastal Engineering major is the foundation and the main driving force for the development of the offshore wind power industry. Through continuous innovation and practical exploration, it will make great contributions to the large-scale utilization of clean and abundant marine wind energy resources by humans. In China's acceleration of building a modern energy system, it will help complete the carbon neutrality task and provide referential intelligent solutions and application results by forming a sound energy system pattern.

References

[1] National Development and Reform Commission (NDRC), & National Energy Administration (NEA). (2022). 14th Five-Year Plan for Renewable Energy Development (Document No. Fagai Nengyuan [2021] 1445).
[2] Global Wind Energy Council (GWEC). (2025). Global Offshore Wind Report 2025. [Report].
[3] Huang, J. J. (2025). Research on the construction application and optimization of port, waterway and coastal engineering. Pearl River Water Transport, (8), 37-39.
[4] He, B. (2024). Difficulties and optimization strategies of offshore wind power operation and maintenance. China Science & Technology Review, (4), 129-131.
[5] Li, H. J., et al. (2022). Current status and key technologies of deep-sea floating offshore wind power. China Engineering Sciences, 24(3), 10-20.
[6] Wang, S., Liu, S. W., Tian, L., et al. (2024). Challenges and countermeasures for the high-quality development of offshore wind power in China. China Energy, 46(11), 15-23.