Smart Systems and Green Energy (2024)
Clausius Scientific Press, Canada

DOI: 10.23977/ssge.2024.060101
ISSN 2523-904X Vol. 6 Num. 1

Design and Analysis of a Novel offshore Gravity Energy Storage Support Structure Based Wind Power Jacket Foundation

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Keywords: Gravity Storage; Offshore Wind Power; Jacket Foundation; Structural Design

Abstract: Energy storage technology is one of the important means to address the impact of large-scale offshore renewable energy grid integration on grid security. In recent years, gravity energy storage(GES) technology has attracted widespread attention. To apply this new type of energy storage technology to the ocean, this paper proposes a novel offshore GES support structure based on the foundation of wind turbine jacket structures, according to the structural characteristics of the new GES system. To verify the feasibility of the support structure, it is proposed to construct it in a certain sea area. Based on the hydrogeological conditions of the sea area and the data of wind turbine units, the preliminary dimensions of the structure are determined. A finite element model is established using SACS software based on the structural dimension parameters, and static and modal analyses are performed to check whether the structure meets the requirements for strength, deformation, and frequency. According to the calculation results, all requirements are met, preliminarily verifying the feasibility of the structure.

1. Introduction

As the proportion of offshore renewable energy generation, primarily wind power, increases in the power system, the intermittent, volatile, and random nature of marine renewable energy generation poses significant challenges to the safety and economic efficiency of the power system. Energy storage serves as one of the effective means to address these issues [1]. Currently, there are various forms of energy storage technology, such as electrochemical storage, flywheel storage, and pumped hydro storage [2]. In recent years, based on the working principle of pumped hydro storage, scholars at home and abroad have proposed a new GES technology. This energy storage technology is simple in principle, unaffected by climate and terrain. As a purely mechanical form of storage, it has a long lifecycle and generates no pollution during operation, attracting widespread attention. According to the characteristics of the new gravitational energy storage technology, the storage capacity is mainly determined by the height and the weight of the mass. The distance from the seabed to the sea surface provides a natural height difference, making the application of the new gravitational energy storage technology in the ocean possible [3].

This article proposes a novel offshore gravitational energy storage technology scheme, based on the foundation of wind turbine jacket structures, integrating a new gravitational energy storage system to form an integrated "wind power + storage" structure, as illustrated in Figure 1. Currently, research on new gravitational energy storage systems for marine applications is still in the early stages of exploration internationally, but integrated systems based on jacket support structures are relatively common. Wang Shiming [4] et al. proposed an integrated structure of wind and tidal energy based on a jacket foundation, incorporating a horizontal axis water turbine into the foundation of the jacket and using ANSYS software to analyze displacement deformation and stress distribution under extreme conditions, verifying the feasibility of the design scheme. Jiang Junjie and others [5] combined wind turbine jacket foundations with aquaculture cages to conduct static and dynamic analyses of the structure under wind, wave, and current loads, verifying the feasibility of using the jacket as a support structure for aquaculture cages. Wang Chang [6] et al. integrated a wave energy device with an offshore platform jacket, and through comparative analysis, confirmed that the structure could meet engineering requirements under combined wind, wave, and current loads.

This paper introduces a novel offshore gravitational energy storage support structure based on the foundation of wind turbine jackets. The structure size will be determined based on the proposed design materials, and Bentley's offshore design software, SACS, will be used for modeling and structural analysis to verify the feasibility of the offshore new gravitational energy storage support structure, providing support for the marine application of new gravitational energy storage systems.

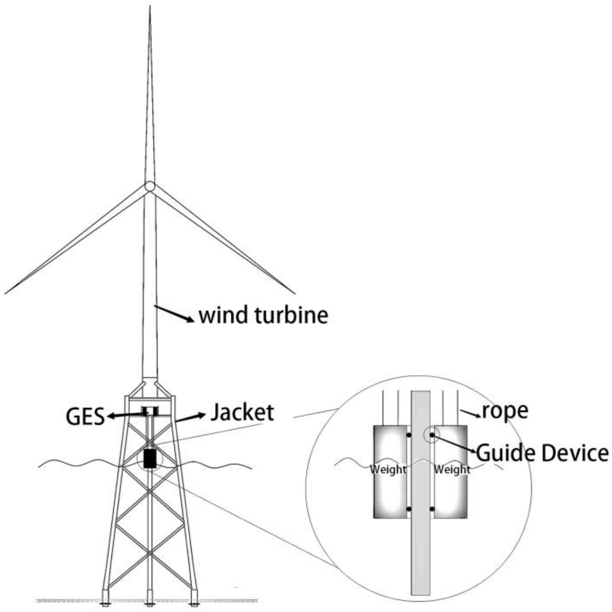

Figure 1: Schematic diagram of an ocean GES design scheme

2. Design Materials

2.1 Geological Overview

The target sea area selected for this study is located in the Jiangsu maritime area, which is part of the southern Yellow Sea. The seabed terrain is gentle, with seabed elevations ranging from -38.5m to -40.3m, and the natural mud surface elevation is taken as -39.5m. Based on the survey, the specific distribution of soil layers and their physical and mechanical parameters are as shown in Table 1.

Table 1 Geological Parameters.

ID	Soil Type	Thickness(m)	Effective Unit Weight (KN/m3)	Soil Friction Angle(°)	Undrained Shear Strength(Kpa)	Soil-Pile Friction Angle(°)
①	Clay	5.0	16.5	-	35	-
②	Silty Clay	9.5	17.3	-	70	-
③	Sand Slit	7.2	17.2	-	85	-
④	Clay	11.5	17.4	-	45	-
⑤	Clayey Silt	11.2	17.6	-	50	-
⑥	Silty Silt	13.3	18.2	36	-	31
⑦	Clayer Silt	12.5	18.5	-	80	-
⑧	Clay	13.8	18.7	-	120	-

2.2 Wind Turbine Information

2.2.1 Basic Parameters of the Wind Turbine Unit

This paper selects a 3MW unit manufactured by a domestic wind turbine manufacturer, consisting of a rotor, hub, nacelle, and tower. The diameter of the wind turbine rotor is 110m, with the hub center at a height of 106.5m. The total weight of the rotor and nacelle is 170 tons, with the overall center of gravity located 1.8m above the top of the tower and 1.1m forward of the axis. The wind turbine type is IEC Class II A. According to the operating parameters provided by the manufacturer, the turbine's cut-in speed is 6.51rpm, and its cut-out speed is 15.96rpm, corresponding to a 1P distribution range of 0.109 to 0.266Hz, and a 3P distribution range of 0.356 to 0.798Hz. The tower is composed of three sections with a total length of 77.8m, with specific parameters as shown in Table 2.

Table 2: Parameters of the Tower Segment.

Site	Top diameter (m)	Bottom diameter (m)	Thickness (mm)	Height (m)	Flange attachment quality (kg)
Top	3.07	3.9	20	32.1	4865.4
Middle	3.9	4.5	28	30.8	7468.6
Bottom	4.5	4.5	51	14.9	18708.7

2.2.2 Wind Turbine Loads

The loads on the wind turbine are provided by the turbine manufacturer, as shown in Table 3. The loads are applied at the base of the tower.

Table 3: Wind turbine loads.

Load Cases	F_X (KN)	F_Y (KN)	F_Z (KN)	M_X (KN m)	M_Y (KN m)	M_Z (KN m)
Extreme Conditions	-935	-72	-4540	3280	-86100	-1145
Normal Operating Conditions	510	-22	-4640	4130	45410	472

2.3 Design Environmental Factors

In the targeted sea area, the average sea level is 0.24m above the national elevation benchmark. Based on the natural mud surface value from the geological conditions, the design water depth for this project is 39.74m. According to the "Hydrological Standards for Harbors," the design water level regulations and values are as indicated in Table 4. The tidal currents in the project area belong to regular semidiurnal tides. Assuming that the design current speed in the target sea area does not change with water depth, the design current speed for a recurrence period of 50 years is taken as 1.25m/s. The wind speed at a height of 10m, occurring once in 50 years for an average of 10 minutes, is 37.5m/s. Due to the lack of complete design wave data, the wave elements at different water levels will all use the wave height and period for a 50-year recurrence period. Based on meteorological data, the design wave height is taken as the H1% wave height of 11.3m, with a corresponding wave period T of 9.8s, and wave forces are calculated using the Stokes 5th wave theory [7].

Table 4: Design Water Level Parameters.

Water Level	1985 National Elevation Datum	depth of water
Extreme High Water Level	2.58	42.08
Design High Water Level	1.48	40.98
Design Low Water Level	-1.48	38.02
Extreme Low Water Level	-1.60	37.90

2.4 Energy Storage System Structural Loads

Considering the structural features of the new gravitational energy system, which is characterized by a significant overall weight and dynamic properties during operation, this paper focuses on the loads generated by the energy storage system structure, including the self-weight and live loads of the storage system. The proposed total weight of the new gravitational energy storage system structure is 150 tons, primarily comprising the system's transmission mechanism, steel cables, and weights. This portion of the weight will be added to the middle of the support platform deck using the "footprint weight" module in SACS software, and then converted into "load" by adding gravitational acceleration. The live load primarily considers the dynamic loads generated during the energy storage system structure's speed change process on the working platform and the movement of personnel during system maintenance. The value of this part of the load refers to the live load value of the elevator machine room floor specified in the "Code for Design of Building Structures" GB50009-2021, which is $8KN/m^2$.

3. Structural Design

The support structure discussed in this paper mainly includes three major parts: the transition section, foundation, and substructure, as illustrated in Figure 2. The transition section utilizes a braced design, consisting of a main cylinder, braces, horizontal links, radial rods, and short leg columns. The upper tower is connected to the top of the main cylinder through a flange, with the main cylinder connected to the leg columns via radial rods and horizontal links. To effectively transfer loads and ensure the safety of the transition section structure, braces extend upward from the positions of the links and leg columns to support the sides of the main cylinder. In practical engineering, the connection between the brace and the main cylinder should have an external reinforcement ring to increase the contact area [8]. Additionally, a steel beam work platform is set between the short leg columns to accommodate the new gravitational energy storage system structure. To avoid the impact of tide or waves on the bottom of the platform, the work platform is located 13.5m above the elevation benchmark, as required by the standards [9].

The foundation is composed of three layers of X-braces and five guide columns, with the four outer main guide columns in a double diagonal symmetrical shape, preliminarily set at a slope of 1:8. Besides, a central guide column for the energy storage system structure is designed in the middle of the support structure and connected to the work platform as part of the support structure. The distance between the main guide columns at the top of the foundation is 14m.

The substructure consists of five steel tubular piles to ensure the stability of the guide columns; these will be fixed to the seabed using a pile foundation. The pile tops are located 3m above the natural mudline, with a pile foundation depth of 55m. The outer four main piles have a diameter of 1.8m and a wall thickness of 35mm, and the central guide column pile has a diameter of 1.5m with a wall thickness of 35mm. Given the structural characteristics, the substructure construction will use a piling method first, hence the foundation and substructure will be connected by grouting. The structure materials are planned to be Q345 steel, with material properties as shown in Table 5.

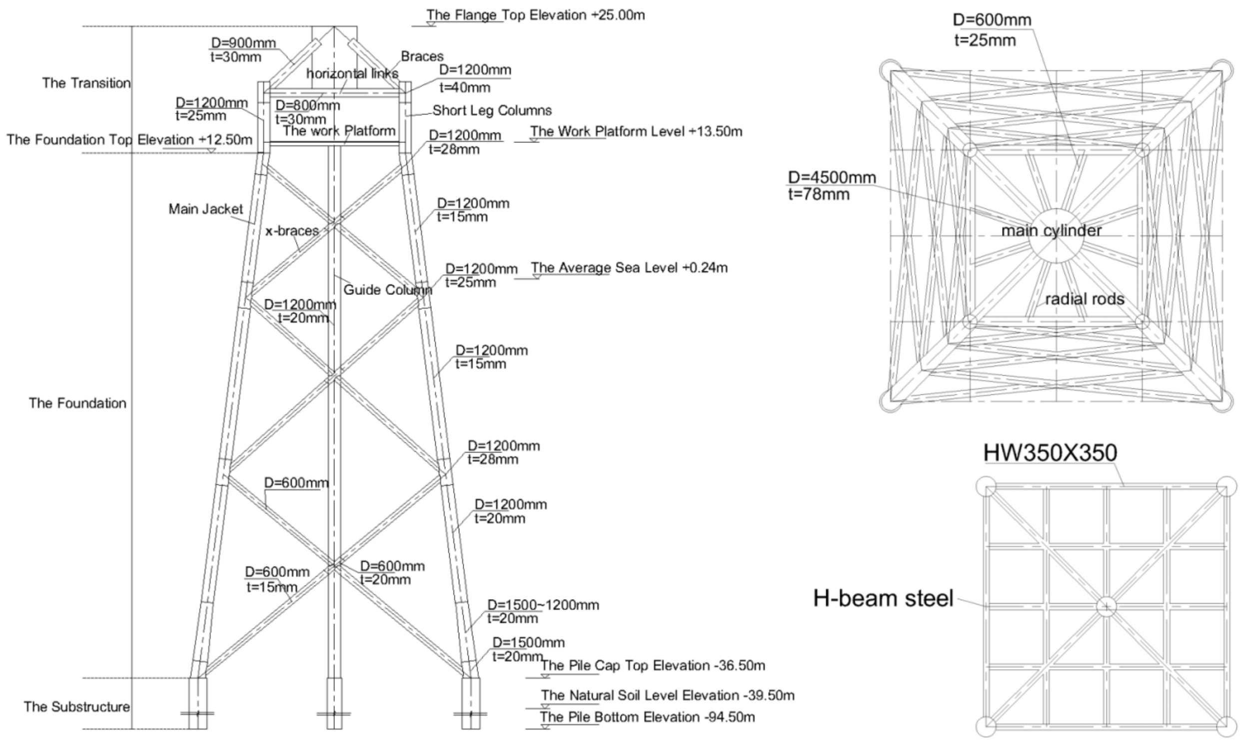

Figure 2: Basic Dimensions of the Support Structure.

Table 5: Material properties.

Steel Grade	Elastic Modulus(N/mm^2)	Shear Modulus(N/mm^2)	Density(kg/m^3)
Q345	206000	79000	7850

4. Structural Analysis

4.1 Static Analysis

The structural static check will be based on the limit state design method. This involves checking the structural strength under extreme load conditions at the limit state of bearing capacity, as well as checking the foundation's bearing capacity and structural deformation under normal operating load conditions at the normal use limit state. For extreme load conditions, load combinations will use basic combinations of extreme loads from the wind turbine unit and other relevant loads. Under normal operating load conditions, standard combinations of normal operational loads from the wind turbine unit and other relevant loads should be applied [10]. According to standard [9], different load subdivision and combination coefficients for various checking contents will be selected. Additionally, combinations of wind, wave, and current should consider four water level conditions —extreme high water level, design high water level, design low water level, and extreme low water level—along with the impact of water level changes on buoyancy. Due to the lack of reliable data on the direction of environmental loads such as wind, waves, and currents, this paper selects 0°, 45°, 90°, 135°, and 180° as the angles for calculation and analysis, maintaining consistency in the direction of action.

This paper will conduct static and dynamic checks of the new offshore support structure using SACS, a marine engineering design and analysis software developed by Bentley Company. First, based on the structural design parameters, finite element modeling of the support structure will be established in SACS using pipe elements, as shown in Figure 3. The upper wind turbine unit, including the tower, is not included in the structural modeling, and the wind turbine loads are applied at the top of the structure flange in the form of point loads, provided by the wind turbine manufacturer. Next, loads will be applied in combination with the design materials and relevant load combination content. Finally, a pile-soil file will be established based on the distribution of soil layers at each level, using p-y curves, q-z curves, and t-z curves to simulate the nonlinear interaction between the pile foundation structure and the soil [11].

Figure 3: The Finite Element Modeling of the Support Structure.

Table 6: Structural Results of the Support Structure Member Strength.

<table>
<tr><th>Projack</th><th>UC_{max}</th><th>Projack</th><th>UC_{max}</th><th>allowable value</th></tr>
<tr><td>Top Layer Main Jacket</td><td>0.48</td><td>Brace</td><td>0.84</td><td rowspan="6">1</td></tr>
<tr><td>Middle Layer Main Jacket</td><td>0.49</td><td>Horizontal Links</td><td>0.24</td></tr>
<tr><td>Bottom Layer Main Jacket</td><td>0.60</td><td>Radial Rods</td><td>0.55</td></tr>
<tr><td>Top x-Brace</td><td>0.19</td><td>Main Cylinder</td><td>0.48</td></tr>
<tr><td>Middle x-Brace</td><td>0.36</td><td>Short Leg Columns</td><td>0.33</td></tr>
<tr><td>Bottom x-Brace</td><td>0.42</td><td>Guide Columns</td><td>0.60</td></tr>
</table>

Table 7: Pile Foundation Bearing Capacity and Structural Deformation Results.

Projack	Maximum calculated value	allowable value
Compressive Bearing Capacity(KN)	13547.6	16322.4
Tensile Bearing Capacity(KN)	7110.2	17775.5
Mudline Rotation(°)	0.1	0.5
Mudline Horizontal Displacement(mm)	9.6	20
Flange Surface Rotation(°)	2.87/1000	4.36/1000
Vertical Settlement(mm)	4.4	100

According to the results shown in Tables 6 and 7, all have met the requirements of the standards. The main guide pipes, serving as the primary load-bearing components of the jacket-style structure, are responsible for transmitting all forces to the foundation. In the transition section, the members connecting to the main cylinder body, including the braces and spokes, receive significant wind turbine loads transferred to the flange at the top of the main cylinder body. Since the braces and spokes are directly connected to the main cylinder body's members and are the first to be subjected to the load, it indicates that the transition section's structural form in this paper has not effectively transferred the upper wind turbine load to the lower part, suggesting that the structure could be optimized further.

4.2 Modal Analysis

In addition to satisfying static analysis under design conditions, structural design must also ensure that the natural frequencies of the entire structure are far from the excitation frequencies of environmental loads to avoid structural resonance [12]. For wind loads, the controlling frequencies are the rotor's rotational frequency (1P) and three times the rotor's rotational frequency (3P). For wave loads, the controlling frequencies include wave frequencies and other low-frequency excitations. The current stage of the design only verifies the excitation caused by the rotation of the upper wind turbine unit.

Using SACS software for modal analysis, it is first necessary to create a pile-soil super element file to simulate the boundary conditions of the equivalent soil spring on the support structure's foundation. Next, based on the tower parameters in the wind turbine data, the overall structural model is established. The wind turbine unit is modeled using concentrated mass points connected to the top of the tower with massless rigid rods. The structural modes obtained from the modal analysis are shown in Table 8 and Figure 4.

Table 8: The First Ten Natural Frequencies of the Support Structure.

Model	Frequency(Hz)	Model	Frequency(Hz)	Model	Frequency(Hz)
1	0.317	2	0.318	3	1.181
4	1.181	5	1.817	6	2.153
7	2.223	8	2.337	9	2.354
10	2.384				

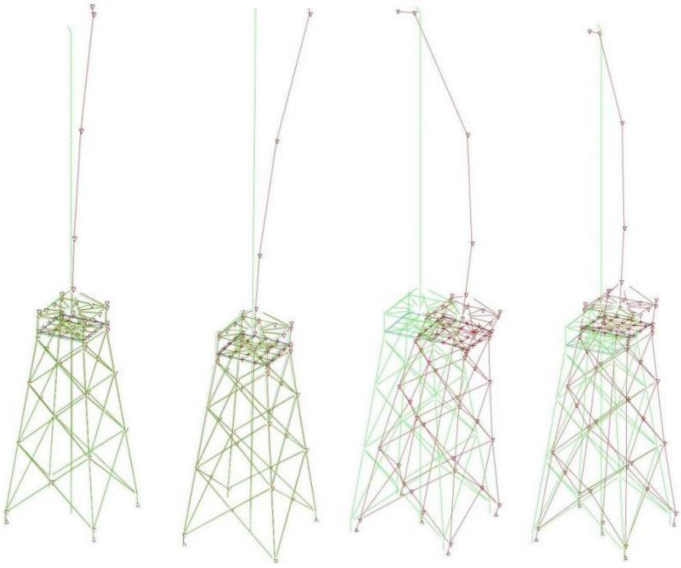

Figure 4: The First Four Modes Shapes of the Support Structure.

Based on Table 8, the first-order frequency of the support structure is 0.317Hz. Given the wind turbine information previously discussed, including the distribution range for the wind turbine unit's 1P and 3P, and considering a 10% safety margin [13], it is evident that the first-order frequency of the support structure does not fall within these ranges, satisfying the requirements of the modal analysis.

5. Conclusion

This paper has conducted a preliminary discussion on a new type of gravitational energy storage support structure based on the foundation of offshore wind turbine jackets, verifying the feasibility of the structure. In addition to the original environmental loads such as wind, waves, and currents, the offshore wind turbine support structure must also consider the impact of the new gravitational energy storage system structure. This paper simplifies the energy storage system loads, applying them as static loads on the support structure. Using SACS software for static and modal analyses, the structural strength, deformation, and frequency results all meet the standard requirements. However, the design of the new offshore gravitational energy storage support structure presented in this paper is still in its preliminary stage, and further research is needed, including fatigue analysis under dynamic load conditions and optimization of structural dimensions and parameters.

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