New development of cost-efficient Multi-pile Concrete Foundation (MCF) for offshore wind turbine

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ABSTRACT

A hybrid type of cost-efficient supported structure combined with concrete cone and steel shaft has been developed for wind turbine farms. A new type of structure which is supported by driven piles, termed Multi-pile Concrete Foundation (MCF), is suggested. Finite element analyses for support structures under hydrostatic load are carried out, using both a shell and frame element of the XSEA program. The Morrison equation with three dimensional wave load is applied in XSEA simulation software, which are particularly directed at concrete structures. The optimized structures based on the preliminary design concept resulted in an efficient structure, which reasonably reduces fabrication costs.

Keywords: Offshore wind turbine, fine element analysis, Multi-pile concrete foundation, hybrid

1. Introduction

From past to present, most offshore wind farms have used steel foundations; however, the main disadvantage of steel foundations are high corrosion and costs. On the other hand, government sectors in some countries have developed new materials to prevent these problems. In Denmark, using concrete material in the ocean has been developed, and used with success [1]. Not only is the construction cost of concrete foundation cheaper, at half the steel foundation cost, concrete structure can also be installed rapidly, and the period is shorter, than in the case of a steel jacket structure. Additional advantages of concrete material are its durability, low maintenance, resistance to abrasion, and higher damping properties [2]. Prestressed concrete provides specific advantages of durability, low cost maintenance, rigidity against buckling, fatigue properties under a large number of loadings, freedom from vibration, ease of repair of local damage, and resistance to fire and external explosion.

Gravity foundations using prestressed concrete are already used in wind farms at depths up to 27 meters. Each comprises a hollow conical stem, and a circular raft footing, with continuous reinforcement of passive and prestressed steel. The dimension of the stem is designed to provide the required anchoring for the tower. This prestressed concrete transfers the overturning bending moments to the raft. Thus, the dimension of the raft footing is determined by the overturning moment at the foot of the stem, and the allowable bearing pressures on the seabed [3]. It is therefore site-specific; for deeper water, greater wind loads, more severe sea states and weaker seabed, a greater diameter is needed. However, the basic design of a circular raft stiffened by prestressed concrete radial ribs, which transfers the overturning moment from the foot of the stem to the seabed, remains the same for all applications. The fatigue design study of a concrete framed tripod structure is suggested by J. Grünberg et al. [4].

In this paper, the optimum foundation selection is a function of the variables of water depth, turbine size, and wind farm location conditions. As the water depth and turbine size increase in weak soil foundation, the applicability of the gravity base foundation becomes limited by the heavy gravity loading. Therefore, the concrete gravity foundation and driven-pile has been developed, to abolish the disadvantage of each type of foundation. This limit is further constrained by the concept design of a new hybrid model, termed Multi-pile concrete foundation (MCF). This structure responds with an optimum solution for shallow and deep water level. The general arrangement of substructure was studied, and investigated through behavior and natural frequency analyses. The objectives of the study were to assess of new hybrid structures: (1) the acceptable natural frequencies of the structure; and (2) the behavior of the structure under environmental loads, with principle attack angles. In this paper, the characteristics of sea conditions of a demonstration offshore wind farm in the west sea of Korea are considered [5]. In addition, a wind energy conversion system with a concrete substructure is fully modeled, using the finite element method to simulate the various conditions.

2. Design environment and analytical model

The new innovative concept of an offshore wind turbine substructure, shown in Figure 1, is developed by using concrete material. The starting point of the design basis of the structural concept is to use static analysis under the extreme environmental parameters and loads of the west sea of Korea.

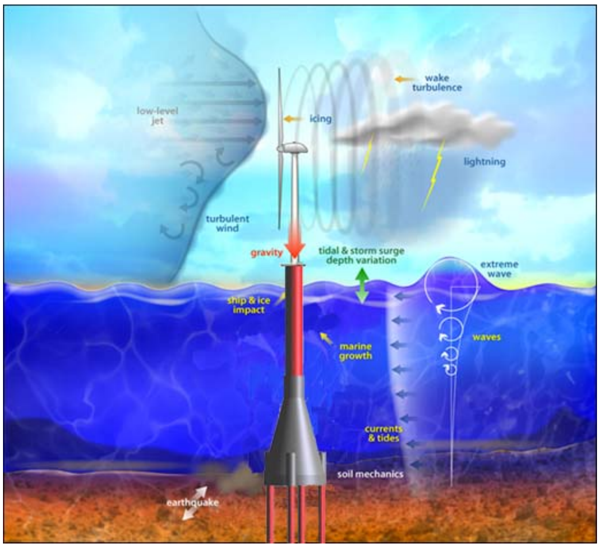
The geometry of the concrete structure with piles support is shown in Table 1, for the structural analysis in XSEA. The concept model from the conventional gravity based foundation is developed by modifying the concrete material and structural configuration. The concrete substructure is composed of central concrete-steel structure, steel shaft, concrete wing and concrete leg sleeves.

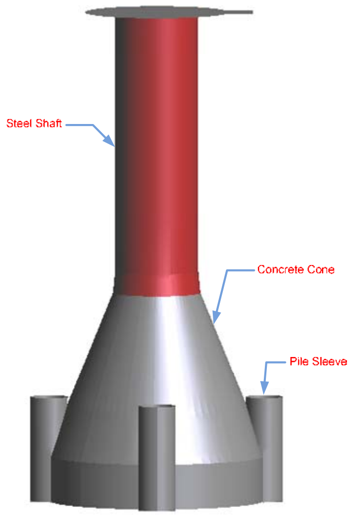
Table 1. Geometry of concrete substructures

Structural Components	Elevation from (m)	Elevation to (m)	Length (m)	Outer Dia. (m)
Concrete Cone	0.00 (base)	15.00 (base)	15.00	15.00
Concrete Sleeve	0.00	7.00	7.00	3.00
Steel Shaft	15.00	33.00	18.00	6.60

3. The Environmental condition

The metocean condition is applied to the sub-structure for primary design, using the extreme condition. The objective is the feasibility study that the structure is able to withstand storm attack. The applicability of the load case refers to extreme turbulent wind as an abnormal turbine operation mode. The 1 hour mean wind speed, significant wave height, water level, storm surge heights, Tide height and current speed magnitude are assigned with 50 year-return period.





(1-1) Modified from NREL report figures (1-2) MCF Substructures

Figure 1. Multi-pile Concrete Foundation (MCF) in offshore wind turbine

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3.1 Wind modeling

The mean wind velocity is determined by a database in which values are recorded near the site, and evaluated and applied to the substructure and tower above the water surface. The wind model analysis is the variation of the mean velocity, with a height of 10 meter over a horizontal surface of homogeneous roughness, describe by the exponential power law. This is given by [6].

$$\mathrm{u(z)} = \mathrm{U}_{10}(\mathrm{H}) \cdot \left[\frac{z}{H}\right]^{\alpha} \quad \mathrm{u(z)} = \mathrm{U}_{10}(\mathrm{H}) \cdot \left[\frac{z}{H}\right]^{\alpha}$$

3.2 Hydrodynamic Modeling

Offshore turbines are those whose foundation may be subjected to hydrodynamic loading. The offshore wind turbine substructure is subjected to hydrodynamics that depend on the foundation system and water depth for the offshore turbine installation. In this case, they consist of current and wave loading.

3.2.1 Current model

The most common currents considered in offshore structural analysis are tidal currents. The magnitude and direction of the tidal currents at the tower surface are generally estimated from local field measurement, the direction of the current reversing with the rise and fall of the tide. The ocean current caused by tidal wave propagation in shallow water can be characterized by a practically horizontal velocity field, in which intensity is slowly increased and decreased by the water depth. The variation of current velocity with depth is given by [8]

$$\mathrm{v(z)} = v_{tide}(z) + v_{wind}(z) \quad \text{Where} \quad v_{tide}(z) = v_{tide0} \cdot \left[\frac{h+z}{h}\right]^{1/7}, \quad v_{wind}(z) = v_{wind0} \cdot \left[\frac{h_0+z}{h_0}\right]^{1/7}$$

3.2.2 Wave modeling

The force exerted on a sub-structure by surface waves was considered by Morison (1950). The excitation force is created by drag term and inertia term. These two terms are seen to be proportional to the square of the water velocity and acceleration, respectively. The values of velocity and acceleration are calculated from an appropriate wave theory. By applying a regular wave with period, wave height and water depth to the Regular wave theory selection diagram [7], a seven order stream function wave theory is selected to be used in this case. The general stream function wave form is illustrated below,

where, $$\psi = cz + \sum_{n=1}^{N} X(n) \cdot \sinh\left(nk(z+d)\right) \cdot \cos(nkx)$$

3.3 Turbine Loading

In this research, 5MW of wind turbine under wind excitation cause the loading conditions to the offshore substructure. Top tower loads are applied to the substructure, as shown in the table below. Yaw bearing fore-after shear force, yaw bearing side-to-side shear force, yaw bearing axial force, rotating yaw bearing roll moment, rotating yaw bearing pitch moment and yaw bearing yaw moment are applied quasi-statically at the top of the tower in the x, y and z directions, respectively [8].

Fx	Fy	Fz	Mx	My	Mz
(kN)	(kN)	(kN)	(kNm)	(kNm)	(kNm)
1.21E+02	-2.94E+01	3.40E+03	1.24E+02	-8.58E+01	-1.44E+03

3.4 Self Weight Modeling

The dead load or permanent load is the sum of the loads that are relatively constant over time, including the self-weight of the structure itself. The designer can also be relatively sure of the magnitude of dead loads, as they are closely linked to the density and quantity of the construction materials. The self-weight of the offshore wind turbine structure is analyzed by using the commercial software XSEA. The structural weight is automatically calculated by the self-weight module of XSEA to be equal to 1,173 Ton. Shell and frame element are used to apply to the concrete-steel sub-structure and beam part, respectively.

3.5 Environment site parameters

Extreme wave conditions are assumed for a recurrence period of 50 years per wave direction. A parameter of hydrodynamic load for finite element analysis, considering the characteristics of a candidate site, is introduced. To select the parameter for a wind farm, not only wind resources, but also diverse factors, including the water depth and the use of the sea, must be taken into account. Through an analysis of these factors, the Korea Electric Power Corporation Research Institute (KEPCO Research Institute) has determined that the area near the island Wi-do in the West Sea (Yellow Sea) is the optimal site for a demonstration offshore wind farm. The metocean parameter data are represented in the table below, which is given by Ref. [5]

Water depth	Surge + Tide Height	Effective water Depth	Significant Wave Height	Wave Period	Wind Speed (1hr @ 10m)	Current Speed

(m)	(m)	(m)	(m)	(sec)	(m/s)	(m/s)
15	2.9	17.9	7.22	11.90	25.00	1.55

4 The analysis result

4.1 Natural frequency analysis

In general, the nacelle generates electricity on offshore wind turbine structure by inducing the rotor's rotation, having the characteristic of rotational frequency effects. An operational wind turbine is subjected to harmonic excitation from the rotor. The rotor's rotational frequency is the first excitation frequency, and is commonly referred to as 1P. The second excitation frequency to consider is the blade passing frequency, often called 3P (for a three-bladed wind turbine), at three times the 1P frequency. The turbine manufacturer advises an additional safety margin of 10% for the lower boundary and upper boundary. Outside the additional safety margin, the dynamic response due to turbine loading is neglected. Therefore, the natural frequency of the design should not coincide with the rotational frequency of the turbine (1P), or the blade passing frequency (3P). If the natural frequency is in the same interval, resonance will occur, with significant fatigue damage (even failure) as a consequence. The first natural frequency of the MCF is 0.970, which is in the safety margin of the Stiff-Stiff zone, as shown in Figure 2. Generally, a concrete structure is designed in the Stiff-Stiff range design, which is cost-effective, and has good durability. Moreover, the concrete gravity base design has the natural frequency of 0.95 Hz, which is nearly same as this new concept structure. However, the MCF has less weight and cost than the gravity base foundation, which is good for an in situ construction site. For fatigue consideration, sea states with a high frequency (0.10 Hz.) of occurrence have the largest effect. These are generally relatively short waves. Because waves have various periods, they span a wide range in the frequency band. Thus, it shows that this structure will not be damaged by wave or blade.

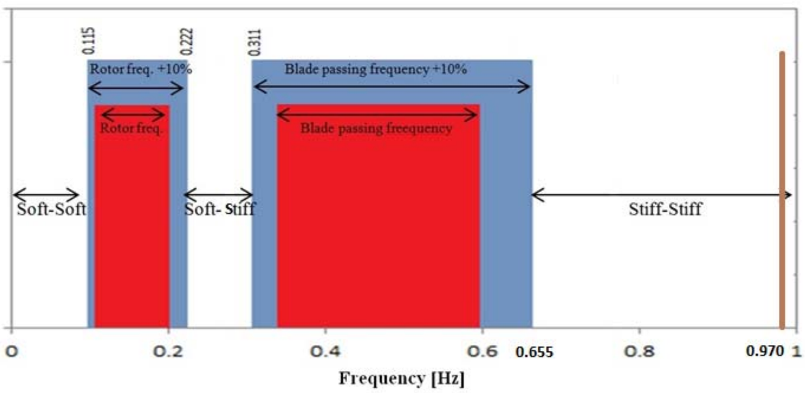

Figure 2. Design ranges for the fundamental frequency of the support structure

Furthermore, the XSAE program provides a mathematical model to calculate the Eigen-vector. In this paper (refer Table 2), five modes shape are illustrated, to see the realistic physical behavior of the MCF in Figure 3.

Table 2. Natural frequency and Natural period

Mode	Axis	Natural Frequency	
		Frequency (Hz)	Period (sec)
1st-Mode	X-axis	0.970	10.300
	Y-axis	0.970	10.300
2nd-Mode	X-axis	3.256	0.307
	Y-axis	3.257	0.307
3rd-Mode	X-axis	7.223	0.138
	Y-axis	7.224	0.138
4th-Mode	Twist	11.590	0.086
	Twist	12.290	0.086
5th-Mode	X-axis	13.080	0.076
	Y-axis	13.140	0.076

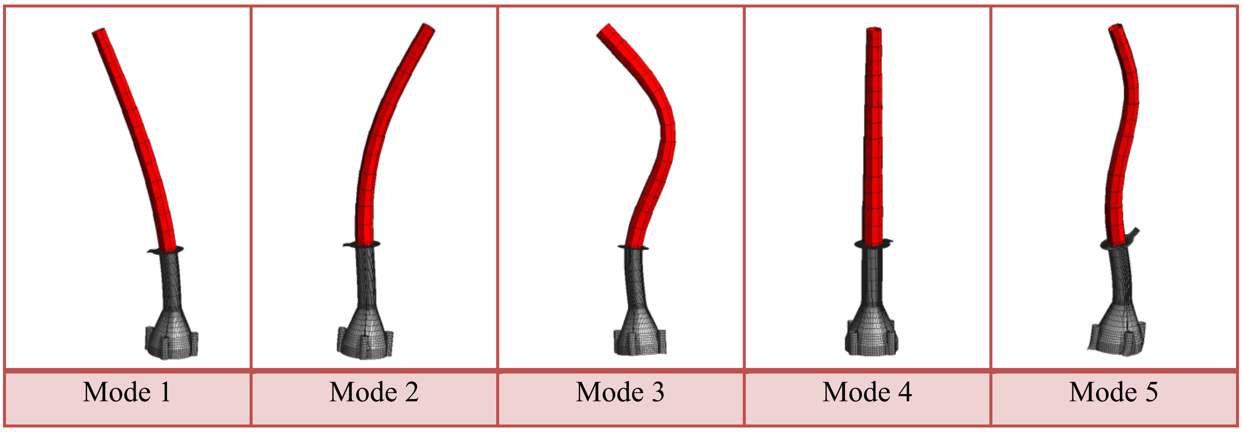

Figure 3. Mode shapes simulation of the MCF

4.2 Load combination analysis

The load combination of wind, wave, current, turbine and self-weight loads is completed by the superposition method. Load combination cases are selected by attack angle, as shown in Figure 3. Due to the symmetry of the Multi-piles concrete foundation along the x and z axis, load cases were reduced from 8 to 2 load cases, as illustrated in Figures 4 and 5, respectively. In this paper, loads are automatically combined, by using the XSEA offshore simulation program, which provides the load combination analysis of the sea state to apply to the offshore wind turbine sub-structure.

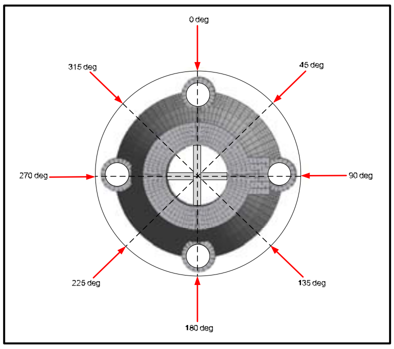

Figure 4. Load Direction Cases

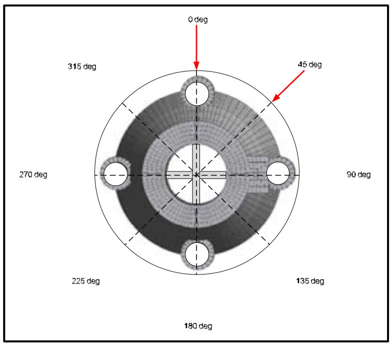

Figure 5. Principle Load Simulations in XSEA

Based on the properties of the MCF, this structural modeling strategy is characterized by the use of a four nodes shell element called XShell-4-ANS, to model the concrete structure and steel shaft. Moreover, a frame element called XFrame is used to model the concrete cross beam of the bottom structures. These two elements are selected, based on the characteristic and dimension of the structure. The finite element analysis is analyzed by applying the hydrostatic load based on the Morrison equation, and turbine load, at the top, and body of the structure, respectively.

According to the analysis, the response of the MCF system during the quasi static loading is illustrated by the deformation and stress distribution over the entire body of the structure. Applied load combinations are varied along the attack angle direction. Figs. 6 and 7 illustrate the characteristic of its response in the simulation. In the present analysis, the displacement of the structure at the top of tower has been considered as the main parameter. The top of the tower is displaced 0.1267 and 0.1251 meters in the direction of 0 and 45 degrees at the top of tower, respectively. Since, there is no verification for the top tower displacement; the vertical deflection that is given in the design code [6] is used to check the requirement. Due to the design code, the allowable vertical deflection is 2L/200, where L is the length of cantilever beam. Therefore, the allowable value is 2*101/200=1.01 meters, at the top of the tower.

Due to the earlier mentioned structural model, the stress and displacement contour are presented. The acting loads considered in this analysis were self-weight, wave and top tower load. In this case, the wave load was applied horizontally to the structural alignment. The wind load was calculated according to the procedure described on the Definition of a 5-MW reference wind turbine for offshore [9]. The computed Bending stress contour is shown with the MCF from the XSEA [9] program, where the stress distribution can be seen in the outer zone, not just in its value, but even in its sign. The inner zone of the steel shaft receives compressive stress (B), due to the combination load. On the other hand, the outer zone of the shaft is in tensile stress state (A), since the outer zone is elongated.

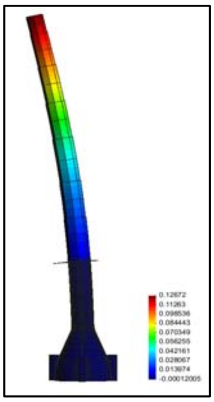

Figure 6. Displacement contour

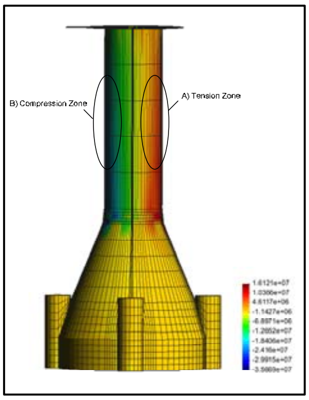

Figure 7. Bending stress contour.

5. Conclusion

Although offshore wind turbine structures are traditionally created from steel for almost the entire structure, concrete has also been used in wind farms. Recently, the wind offshore industry has recognized the great possibilities offered by concrete material. As compared to steel, there are many advantages: of lower maintenance and lower fabrication costs, longer life of the structure and better motion behavior. A new innovative technology of wind turbine substructure, termed the Multi-pile Concrete Foundation (MCF), is suggested in this paper, which is developed from the conventional gravity based foundation and driven pile. The structural analyses show that it can withstand the allowable displacement in the extreme condition. In addition, natural frequency analysis is also used. There are many reasons to compute the natural frequencies and mode shapes of a structure. All of these reasons are based on the fact that real eigenvalue analysis is the basis for many types of dynamic response analyses, which will be the further study of this structure. The result of eigenvalue analysis of Multi-piles concrete foundation can confirm that this structure is in the safety range to avoid resonance. In conclusion, it is possible to infer that the new concept of foundation design in this paper can withstand the extreme condition in the west sea of Korea.

Further study, involving optimum design by hydrodynamic and aerodynamic load, is required to develop a stable model. The basic design, transportation and installation method of the MCF to be installed in the West Korean Sea will also be studied. Moreover, the pile size can be studied from the reaction at the supports of structure, under the load conditions.

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REFERENCES

[1] P. Volund, “Concrete is the future for offshore foundations”, Wind Engineering, Vol. 29 (2005).

[2] H. C. Cotton, “Materials Requirements for Offshore Structures”, Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 282, No. 1307 (1976).

[3] W. Brook-Hart, P. A. Jackson, M. Meyts, P. Sayer, “Competitive Concrete Foundations For Offshore Wind Turbine”, Gifford (2008).

[4] J. Grünberg, J. Göhlmann, C. Ertel, “Concrete Foundations for Offshore Wind Energy Converters subjected to fatigue loading”, Institute of Concrete Constructions, University of Hannover, Copenhagen Offshore Wind (2005).

[5] K.-Y. Oh, J.-Y. Kim, J.-S. Lee, “Preliminary evaluation of monopole foundation dimensions for an offshore wind turbine by analyzing hydrodynamic load in the frequency domain”, KEPCO Research Institute, Korea (2012).

[6] DNV-OS-J101, “Design of Offshore Wind Turbine Structures”, Det Norske Veritas, offshore standard (2011).

[7] DNV-RP-C205, “Environmental Conditions and Environmental Loads”, Recommended Practice, Det Norske Veritas, offshore standard (2007).

[8] J. Jonkman, S. Butterfield, W. Musial, and G. Scott, NREL/TP-500-38060, “Definition of a 5-MW Reference Wind Turbine for Offshore System Development” , National Renewable Energy Laboratory (2009).

[9] XSEA: www.xfinas.com, Konkuk University (2013).