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Foundation Types of Fixed Offshore Wind Turbine

Yun Jae Kim[1], Jin-wook Choe[2], Jinseok Lim[2] and Sung Woong Choi[3]

[1]*Master course student, Department of Mechanical System Engineering, Gyeongsang National University, Tongyeong, Korea*
[2]*Senior researcher, Power Cable Research Center, Korea Electrotechnology Research Institute, Changwon, Korea*
[3]*Professor, Department of Mechanical System Engineering, Gyeongsang National University, Tongyeong, Korea*

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ABSTRACT: *Offshore wind turbines are supported by various foundations, each with its considerations in design and construction. Gravity, monopile, and suction bucket foundations encounter geotechnical issues, while jacket and tripod foundations face fatigue problems. Considering this, a gravity foundation based on a steel skirt was developed, and a monopile foundation was analyzed for Pile-Soil Interaction using the p–y curve and 3D finite element method (3D FEM). In addition, for suction bucket foundations, the effects of lateral and vertical loads were analyzed using 3D FEM and centrifuge tests. Fatigue analysis for jacket and tripod foundations was conducted using a hotspot stress approach. Some hybrid foundations and shape optimization techniques that change the shape to complement the problems of each foundation described above were assessed. Hybrid foundations could increase lateral resistance compared to existing foundations because of the combined appendages, and optimization techniques could reduce costs by maximizing the efficiency of the structure or by reducing costs and weight. This paper presents the characteristics and research directions of the foundation through various studies on the foundation. In addition, the optimal design method is presented by explaining the problems of the foundation and suggesting ways to supplement them.*

1. Introduction

Countries worldwide adopted the Paris Agreement to cope with climate change. The South Korean government announced its “Renewable Energy 3020 Plan” to reduce greenhouse gas (GHG) emissions, which are the leading cause of climate change. According to the plan, the total renewable energy generation is targeted at 20% with 63.8 GW by 2030 by supplying more than 95% of new facilities with clean energy, such as solar and wind power (Ministry of Trade Industry and Energy, 2017). According to the Global Wind Energy Council (GWEC, 2022), the offshore wind market is expected to grow rapidly. In 2021, 21.2 GW of offshore wind capacity was added, and a total capacity of 316 GW is expected to be supplied with a 16.7% increase in 2030.

In the case of onshore wind power in domestic and overseas wind markets, there are limited sites for constructing large power complexes. The construction causes noise, radio interference, and visual inconvenience, resulting in complaints. The interference of the surrounding geographic features also reduces wind speed, decreasing energy efficiency. In the case of offshore wind power, it is easy to construct large power generation complexes compared to onshore wind power, and the construction causes fewer complaints. It also provides high energy efficiency because the wind speed is 70% higher on average than onshore wind power (Park et al., 2021). Despite this, offshore wind power is difficult to install because of the complex marine environment and requires higher installation costs than onshore wind power. In particular, the foundations of offshore wind turbines (OWTs) increase design costs because of their large and robust design to withstand the loads of the marine environment. The installation and foundation design costs of OWTs are 20% and 12.5% higher, respectively, than those of onshore wind turbines, as shown in Fig. 1 (Guo et al., 2022). In addition, the foundations of OWTs increase in size and weight as the water depth increases, which increases the design cost significantly. Therefore, the selection and optimal design of a foundation type suitable for the water depth are the most important factors in effectively reducing costs (Oh et al., 2018).

OWTs are generally divided into fixed and floating types, which are classified into foundations with various shapes based on the water depth. Therefore, it is important to select a foundation considering the location and purpose. Gravity and monopile foundations with simple

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Corresponding author Sung Woong Choi: +82-55-772-9103, younhulje@gnu.ac.kr

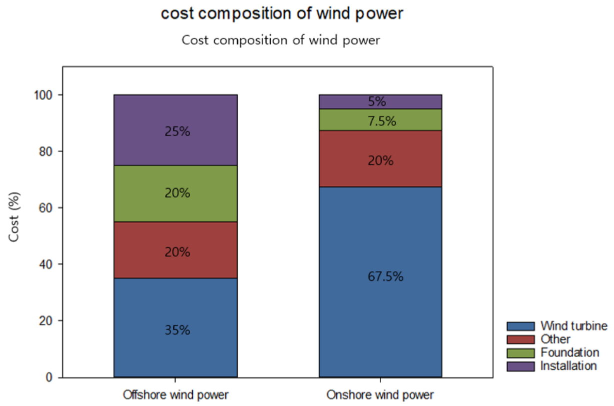

Fig. 1 Cost of onshore wind turbine and offshore wind turbine (Guo et al., 2022)

structures are installed mainly in the shallow sea (0 to 30 m), but gravity foundations are not installed for 3MW or higher OWTs because of the heavy weight and transport costs. Many design cases for monopile foundations have been reported because of the larger power generation capacity and higher installation depth than gravity foundations. In the case of monopile foundations, however, larger diameter piles are applied as the depth and capacity increase, increasing costs due to the increased amount of steel. Therefore, multipod-type (jacket and tripod) foundations are installed mainly in transitional waters (30 to 50 m) and deep waters (50 to 200 m) (Oh et al., 2018).

Li et al. (2020) examined the costs of various foundations for 5MW OWTs. The costs included design, production, and installation, which were expressed in Euro (€) as of 2016. In depths of 30 to 39 m, the costs were found to be 864, 972, 918, and 1024 k€/MW for gravity, steel monopile, steel jacket, and tripod foundations, respectively. Gravity foundations showed the most economical cost, but a maximum cost of 1247 k€/MW may occur considering additional submarine preparation costs. Therefore, jacket-type structures were considered the most economical for 5MW OWTs.

Extending the mechanical life of OWTs, which are significantly affected by the surrounding environment, requires a consideration of the factors involved in the design and construction processes and an understanding of the basic shape of the structure (Jiang, 2021). For OWTs, it is necessary to identify the characteristics of foundations and their technological problems.

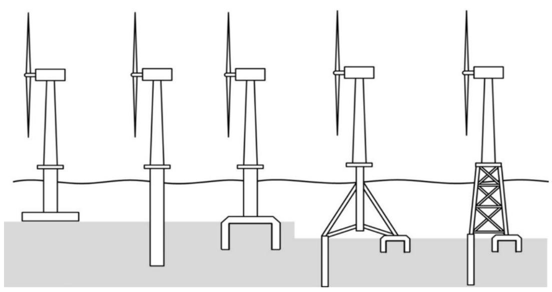

Fig. 2 Foundation types of fixed offshore wind turbines (Oh et al., 2018)

This study examined the foundations of fixed OWTs. The foundations were divided into gravity, monopile, jacket, tripod, and suction bucket types, as shown in Fig. 2. The benefits and limitations of the shape were explained for each foundation, and the results of previous studies and the latest research trends were examined. Technological problems, design, and methodologies were discussed based on the results of previous studies on each foundation, and research directions were presented. In addition, an optimal design method with improved reliability was presented based on research trends.

2. Characteristics of Fixed Offshore Wind Turbine Foundations

2.1 Gravity-Based Foundation

Gravity-based foundations are the foundation type first applied to OWTs. They have benefits, such as inexpensive material cost and easy installation via transport after onshore production, because they consist of materials that can be obtained easily, such as concrete and steel (Saleem, 2011).

Gravity-based foundations can be classified as shown in Fig. 3. These foundations are divided mainly into three types. Vindeby (Barthelmie et al., 1996) and Middelgrunden (Larsen et al., 2005) are first-generation gravity-based foundations. They are solid reinforced concrete structures with large-diameter slabs with no holes and cells. This type can be designed only for very shallow depths of 3 to 7 m (Esteban et al., 2019). For the second-generation gravity-based foundations, Rodsand1(4C Offshore, 2020), which was commissioned in 2003, was applied to a depth of 6 to 10 m. Rodsand2 (4C Offshore, 2020) and Karehamn (4C Offshore, 2020) were also commissioned in 2010 and 2013 and applied to 6 to 12 m and 6 to 20 m depths, respectively. The second-generation gravity-based foundations are similar to the first generation but have holes or cells in the slab (Esteban et al., 2019). A representative third-generation gravity-based foundation is Thornton Bank 1 (Mengé and Gunst, 2008). The foundation was commissioned in 2009 and applied to an 18 to 24 m depth. The third-generation gravity-based foundation has a narrow cylindrical shape for the upper part and a conical shape for the lower part to directly transfer the load of the turbine to the bottom slab. This foundation consists of hollow steel pipes submerged in the seabed after being designed on land, and the empty space is filled with ballast at the installation location (Mengé and Gunst, 2008). Blyth, which was recently commissioned in 2017, is located at a 35 m depth and has a similar shape to that of Thornton Bank. Unlike Thornton Bank, Blyth (ICE, 2017) is towed to the final position by a tugboat using the “float and submerge” technique to save transport costs. Table 1 lists the gravity-based foundations mentioned in this section through references (Esteban et al., 2019; 4C Offshore, 2020).

2.2 Monopile

Monopiles, the most commonly used support structures, are easy to produce and install because a large-diameter pile is connected to piling

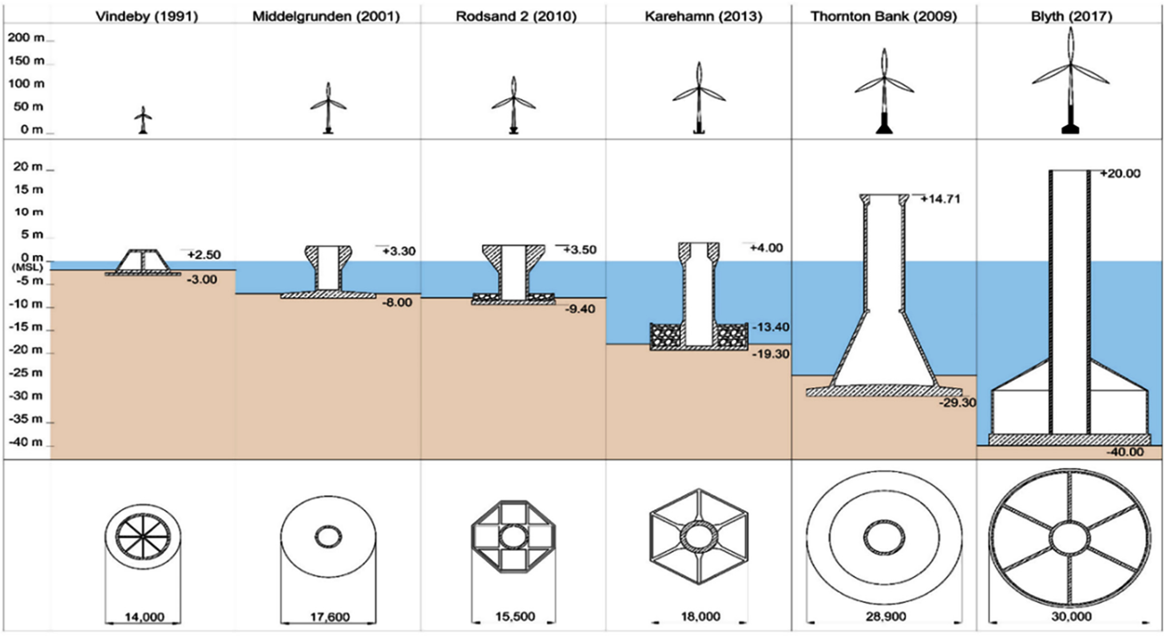

Fig. 3 Fixed offshore wind turbine, gravity-base foundation (Mathern et al., 2021)

Table 1 Development and characteristics of gravity-base foundation

Name	Year	Total power (MW)	Depth (m)	Distance (km)
Vindeby	1991	4.95	2–4	2
Middelgrunden	2001	40	4–8	2–3
Rodsand 1	2003	166	6–12	10
Thornton Bank	2009	30	18–24	30
Rodsand 2	2010	207	7.5–12.5	8
Karenhamn	2013	48	3.8	3.8
Blyth	2017	41.5	35	5.7

with grout. They are economically beneficial at depths of less than 30 m (Saleem, 2011). The structure is completed with grout, which is high-strength concrete for joining the upper tower, after installing a single large-diameter pile, a steel cylinder with a high thickness, using the piling method.

Monopile foundations are affected by lateral loads because of the vertical cylindrical structure. Lateral loads reduce the bearing capacity of the foundation and decrease soil stiffness due to the soil deformation around the foundation. The optimal pile diameter must be determined to secure bearing capacity because lateral loads vary depending on the the water depth (Achmus et al., 2009). The design of the natural frequency that can avoid resonance with the forced frequency generated under environmental loads is also essential to minimize fatigue damage (Andersen et al., 2012; Lombardi et al., 2013). In the design stage, the natural frequency varies according to the stiffness of the foundation and the strength and stiffness of the soil, and it can be transformed by external dynamic loads. The change in stiffness of the foundation and soil must be considered in the design stage because this shortens the life of the structure.

Lombardi et al. (2013) conducted a series of model tests to examine the changes in the natural frequency and attenuation of the monopile OWT foundation under continuous environmental loads. They also expressed the soil strain (ϵ_s) around the foundation as a dimensionless number using three parameters to identify the natural frequency due to soil deformation as expressed in Eq. (1). The early changes in natural frequency were measured using a free vibration test. The changes in natural frequency according to the forced frequency and soil strain under cyclic loads were examined. According to the research results, the natural frequency was reduced most significantly as the ratio (f_f/f_n)) of the forced frequency (f_f) to the natural frequency (f_n) approached one. In addition, when only the soil strain (ϵ_s) was adjusted in a structure where the ratio (f_f/f_n)) approached one under the same cyclic loading condition, the natural frequency of the structure decreased by 37% and 0.02% at soil strain (ϵ_s) values of 34% and 0.02%, respectively. This shows that the deformation of soil has a significant impact on the stiffness of the structure. Monopile foundations are significantly affected by the surrounding soil. Therefore, it is important to identify the life of the structure from the relationship between the foundation and soil.

$$\epsilon_s = f(\frac{P}{GD^2}) \quad \frac{F}{[FL^{-2}][L]^2} \tag{1}$$

where ϵ_s, P, D, and G are the soil strain, horizontal load acting on the foundation, diameter of the pile, and shear modulus of the soil, respectively.

2.3 Jacket-Based Foundation

Jacket-based foundations have long been used for oil and gas mining facilities. OWTs have been designed based on them at a depth of 30 to

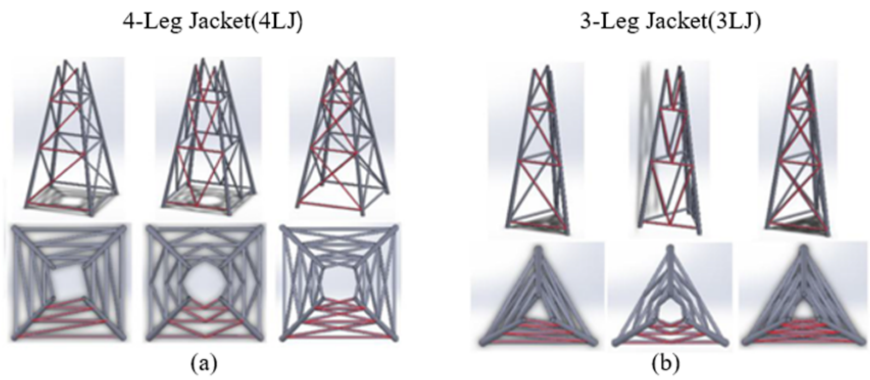

Fig. 4 Various types of jacket foundations (Chen et al., 2016)

80 m owing to their solid and stable characteristics. Jacket-based foundations distribute loads with multiple legs. Hence, they have higher structural stability than other OWT foundations (Wang et al., 2018).

Hao and Liu (2017) compared the impact prevention performance among the monopile, tripod, and jacket foundations for OWTs. They concluded that the jacket type has optimal impact prevention performance because of the highest performance in the collision force and damage area.

Jacket-based foundations improve the axial capacity by connecting the lower structure and the wind turbine using grout. The upper part of the jacket is combined with the tower through the transition piece. The lower part of the jacket is formed by three to four legs under axial and bending loads as well as X, V, and Z-braces that connect the legs, as shown in Fig. 4. The weight and stiffness of jacket-based foundations as well as their dynamic response under external loads vary according to their shape. Therefore, it is vital to find the optimal geometry with stability considering marine characteristics according to the design location for jacket-based foundations (Shi et al., 2013; Chen et al., 2016).

Shi et al. (2013) compared the dynamic responses of jacket-based foundations with X and Z braces according to their weight and marine environment. The marine characteristics were considered based on a depth of 30 m in the southwest sea of Korea, and deterministic and probabilistic simulations were performed for 5MW OWTs. According to the research results, jackets with X-braces showed higher performance in terms of dynamic response, and Z-braces also showed a dynamic response that met design standards. Therefore, designing jackets with relatively lighter Z-braces is more appropriate.

Chen et al. (2016) conducted dynamic analysis and local buckling analysis of various types of jackets that support OWTs, as shown in Fig. 4. The dynamic response was analyzed under normal and extreme conditions because the dynamic analysis of jacket-based foundations is affected by environmental loads, such as wind, tides, and waves. Local buckling analysis of jacket foundations was verified through numerical simulation and scale models. All jacket foundations provided safe values in terms of the critical load and local buckling strength. The results may vary according to the location. Hence, additional dynamic analysis and fatigue analysis are required.

2.4 Tripod

Tripod foundations that can support structures in a wide range are installed at approximately 25 to 50 m depths. Tripod foundations showless resonance by waves because of the high stiffness, and their natural frequency can be adjusted (Lozano-Minguez et al., 2011). Tripod foundations provide triangular support using the cylindrical steel tube column in the center and three legs and braces. They are favorable for securing safety because the central column transfers the load of the structure to pile sleeves through diagonal braces (Saleem, 2011). They are, however, vulnerable to fatigue damage because of the complex structure as with jacket-based foundations. Thus, accurate calculations are required. In addition, the three piles must be designed against extreme load cases to prepare for changes in weather conditions, wind, and waves, which are marine environmental conditions that occur in all directions. In particular, fatigue damage must be examined under FLS conditions (Ma et al., 2018).

2.5 Suction Bucket

The suction bucket is a lid-shaped bucket with a large venthole. When installed in soil, the suction bucket adheres to the soil due to the

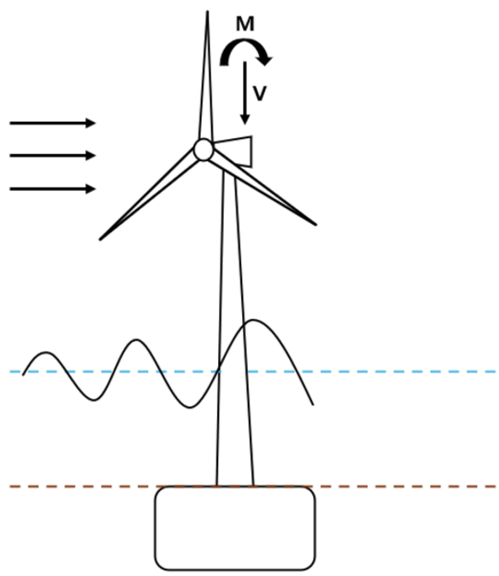

Fig. 5 Fixed offshore wind turbine, suction bucket (Wang et al., 2017a)

pressure difference caused by the vacuum, increasing the bearing capacity of the structure. The suction bucket is designed to have a larger diameter and a shorter length than monopile foundations (Fig. 5), and it applies to a depth of up to 60 m (Wang et al., 2018).

Suction bucket foundations involve less vibration and noise than other foundations installed through piling. They are economically beneficial because of the short construction period. They are also easy to remove when their application is finished because they are installed by introducing seawater (Byrne and Houlsby, 2003). Suction bucket foundations, however, are sensitive to lateral loads, which alter the bearing capacity, deflection, and rotation of the structure. Therefore, research is required to understand and respond appropriately to structural effects. It is also necessary to consider design conditions according to the soil characteristics because they significantly affect the suction bucket.

3. Problems and Analysis of Fixed Offshore Wind Turbine Foundations

3.1 Geotechnical Problems with Fixed Offshore Wind Turbine Foundations

Geotechnical problems with fixed OWT foundations mainly occur from gravity, monopile, and suction bucket foundations that correspond to single foundations. For gravity-based foundations, a gravity-based structure is usually installed after digging the seabed. Therefore, their design can be limited by the soil characteristics. In particular, obtaining sufficient bearing capacity on soft or weak soil is difficult. Lateral loads have a dominant influence on monopile and suction bucket foundations. Lateral loads reduce the bearing capacity of the foundation by decreasing the stiffness of the soil around it, but they also cause local scour. Therefore, it is necessary to identify the characteristics of soil and the displacement of the foundation under external loads, considering the damage caused by the foundation–soil interaction before design. In this regard, geotechnical problems with each foundation were mentioned in this section for gravity, monopile, and suction bucket foundations significantly affected by soil. Solutions and analysis methods to address the problems were presented through papers that dealt with them.

3.1.1 Geotechnical problems with gravity-based foundations and solutions

For gravity-based foundations, a gravity-based structure is usually installed after digging the seabed. This involves detailed work under the sea, and a pipe or other equipment is used to dig the seabed. The gravity-based structure is then placed at the precise location. For gravity-based foundations, soil erosion on the seabed by the tides or waves is prevented by scour protection, a structure to protect the bottom surface of the seabed. Scour protection is placed around the gravity-based structure with stones or rocks to strengthen its stability. Gravity-based structures are difficult to install on poor-quality soil because their bottom structure is located on top of the seabed. Thus, seabed preparation must be performed for terrain and soil quality to improve the bearing capacity (Esteban et al., 2015). During seabed preparation, it is necessary to examine the soil characteristics and remove soil with low bearing capacity. The soil must also be leveled to install gravity-based foundations, incurring additional costs and economic losses. A gravity-based foundation based on a steel skirt is being developed to address these problems. This can significantly reduce the need for seabed preparation by injecting concrete into the empty space between the foundation and the seabed (Mathern et al., 2021).

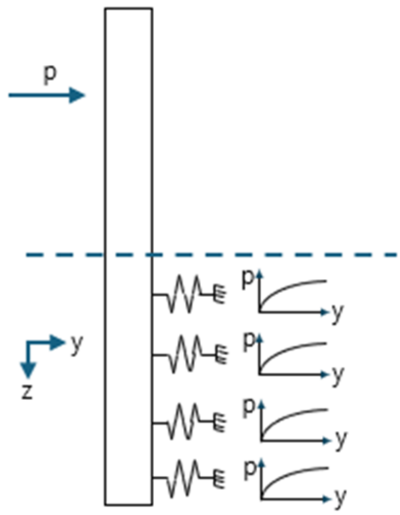

Fig. 6 *p*–*y* curves method (Sunday and Brennan, 2021)

3.1.2 Monopile-soil problem and analysis method

Monopile foundations are embedded in the soil. Therefore, it is necessary to reflect their dynamic behavior in the design because of the nature of marine structures. The soil around a monopile foundation has different stiffness and shear strength depending on the drainage condition, which has a significant impact on the displacement of the foundation. For safe design, this needs to be considered through pile-soil interaction (PSI) analysis.

In general, the *p*–*y* curve that used a beam, which is the nonlinear Winkler (1867) foundation model, is used for PSI according to the guidelines of the American Petroleum Institute (API, 2000). As shown in Fig. 6, The *p*-*y* curve of API represents the relationship between the subgrade reaction (p) and lateral pile displacement (y) by replacing the stiffness of soil with the stiffness of a spring. Many studies have dealt with PSI for monopile foundations through the *p*–*y* curve (Bisoi and Haldar, 2014; Sunday and Brennan, 2021).

Bisoi and Haldar (2014) investigated lateral pile displacement in undrained clay under cyclic loads. They also compared and analyzed lateral pile displacement in uniform soil with a constant shear strength along the depth and non-uniform soil with varying shear strength through the *p*–*y* curve. They reported that the lateral pile displacement in the non-uniform soil was 60% larger than that in the uniform soil when a wind speed of 25 m/s was applied as a lateral load under the resonance condition ($f_f/f_n = 1$).

Fig. 7 Coupled spring model to consider the effect of the foundation (Jung et al., 2015)

The API (2000)-based *p-y* curve is an empirical interpretation of piles with a diameter of up to 2.0 m. This curve may underestimate the soil stiffness and overestimate lateral pile displacement for monopiles with large diameters (Bekken, 2009). Therefore, some researchers presented PSI analysis methods based on the three-dimensional continuum-based finite element method (3D FEM) (Jung et al., 2015; Liu and Kaynia, 2022).

Jung et al. (2015) conducted SSI analysis of monopile foundations using Abaqus software based on 3D FEM. They examined the lateral displacement curve for a later load using a coupled spring model (Zaayer, 2002), as shown in Fig. 7. Monopile foundations were modeled using 3D solid elements. The behavior of sand and clay was simulated using the Mohr–Coulomb model (Hearn and Edgers, 2010) and the Tresca model (Jeanjean, 2009), respectively. When the FEM model and the *p*–*y* curve were compared, the foundation moment showed a slight difference of less than 4%, but the measured slope of the pile head was more than 14% higher in the FEM model. Therefore, researchers proposed the application of FEM modeling when there are problems with the service life of OWTs because of the high slope.

Liu and Kaynia (2022) conducted a 3D FEM analysis of the PSI of monopile foundations using the SANISAND-MSu model. The SANISAND-MSu model (Liu et al., 2020) analyzes the displacement of the monopile under lateral cyclic loads through 3D FEM analysis by simulating the circulation behavior of sand under drained and undrained conditions. When the pile displacement in sand under drained and undrained conditions was compared, the measured pile displacement in sand was larger under undrained conditions. The severe deformation of soil and reduced soil stiffness caused by the accumulation of pore water pressure significantly affected the pile displacement. Therefore, it is essential to examine the drainage condition of soil for the safe design of monopile foundations.

3.1.3 Local scour at monopile foundations

Local scour occurs around monopile foundations because of severe changes in environmental load. Scouring around monopile foundations is caused by current, waves, and a combination of current and waves. The shear stress near the soil changes when sediment moves from a monopile foundation. Local scour occurs when the critical shear stress of the soil is exceeded. The cyclic loads caused by environmental loads can also cause local scour by reducing the strength and stiffness of soil and promoting the interaction between the pile and soil. Such local scour decreases the bearing capacity of monopile foundations and may destroy the structure (Guan et al., 2022). Therefore, many studies have examined the effects of scour protection to prevent local scour (Askarinejad et al., 2022; Zhang et al., 2023).

Askarinejad et al. (2022) conducted a centrifuge test to examine the scour protection effect for monopiles. This test was conducted on scour prevention layers corresponding to five times (5D) and seven times (7D) the monopile diameter. Under monotonic loading conditions, the lateral resistance of the pile foundation increased by more than 30% for the scour prevention layer of 5D, and the difference in lateral resistance from the scour prevention layer of 7D was less than 5%. Regarding the effects of the scour prevention layer of 5D under cyclic loads, the cumulative deflection decreased by more than 50% compared to the monopile foundation with no scour prevention layer. Hence, the scour protection layer significantly affects the stability of monopiles.

Zhang et al. (2023) explained more than 20 methods to protect monopile foundations from scour based on previous studies. They mentioned the benefits and shortcomings of various scour protection methods, considering the scour protection effect, safety, cost, environmental impact, and additional effects.

3.1.4 Suction bucket-soil problem and analysis method

Suction bucket foundations are mostly sensitive to lateral loads, as with monopile foundations, which significantly reduces the bearing capacity of the structure by deflecting and rotating the structure and causing changes in the soil characteristics. Suction bucket foundations require further analysis because the vertical load and moment affect the final bearing capacity. Therefore, research on effective responses to these effects is required to maintain structural stability.

Wang et al. (2017a) conducted a centrifuge test to examine the lateral support behavior of suction bucket foundations under static and cyclic loading conditions. They analyzed the lateral displacement of the structure under static and cyclic lateral loads considering the soil condition and the aspect ratio of the foundation. Under cyclic lateral loads, the lateral displacement increased rapidly in the early cycles, and it tended to change slowly as the number of cycles increased. In particular, the fifth cycle represented approximately 2/3 of the total displacement.

Liu et al. (2014) analyzed the support behavior of the bucket foundation in drained silty sand through Abaqus version 6.10. They examined the bearing capacity of suction bucket foundations according to the aspect ratio by dividing the vertical load (V), horizontal load (H), and moment (M) into single loads, secondary combined loads (VH, VM, and HM), and a tertiary combined load (VHM). They reported that the vertical load decreased the displacement and rotation of the bucket and increased the horizontal bearing capacity and moment capacity by strengthening the foundation-soil interaction.

Wang et al. (2019) conducted a centrifuge test of the vertical bearing capacity of suction bucket foundations. They also compared the numerical approach with the data of the actual test model to estimate the bearing capacity of the suction bucket foundation. In the centrifuge test results, the bearing capacity of the presented foundation was higher than that obtained through the numerical approach. The results emphasized the difference between numerical modeling and actual experimental data and evaluated the bearing capacity of the suction bucket foundation in real terrain.

Wang et al. (2017b) conducted a centrifuge test to evaluate seismic response because the soil liquefaction caused by an earthquake can significantly decrease the strength and stiffness of soil. They also conducted research on resistance to liquefaction according to the aspect ratio. They reported that the resistance to soil liquefaction increased as the aspect ratio increased.

3.2 Fatigue Damage Analysis Method for Fixed Offshore Wind Turbine Foundations

Fatigue damage problems with fixed OWT foundations mainly occur from jacket and tripod foundations corresponding to multi-pile foundations. Jacket and tripod foundations have structural stability compared to other OWT foundations because of the complex structure that combines legs and braces, but they are vulnerable to fatigue damage caused by external loads. Fatigue damage occurs mostly at tubular joints, i.e., welded joints. The fatigue life of tubular joints must be estimated because the fatigue life of structural joints determines the design life. Therefore, this section focuses on analysis methods for the fatigue damage of jacket and tripod foundations in this section.

3.2.1 Fatigue damage analysis method for jacket foundations

For jacket foundations, the welded joints, in combination with legs and braces, are referred to as tubular joints. When a stress concentration occurs at the tubular joints under long-term cyclic loads, it can be difficult to secure fatigue resistance and structural safety. Therefore, it is important to evaluate the fatigue damage of tubular joints. Many studies have conducted fatigue analysis to evaluate fatigue damage using the hot spot stress (HSS) approach according to the guidelines of DNVGL-RP-C203 (2016), as shown in Fig. 8 (Ju et al., 2019; Marjan and Hart, 2022).

The HSS approach is used to evaluate fatigue damage at eight points located around a tubular joint, including the axial load for external loads and bending inside and outside the plane, according to the guidelines of DNV (2016). At these points, HSS formulas were expressed as Eq. (2).

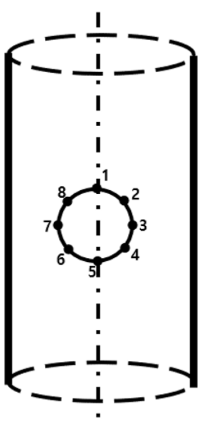

Fig. 8 Positions of hot spots in tubular joints (DNV, 2016)

$$\sigma_1 = SCF_{AC}\,\sigma_x + SCF_{MIP}\sigma_{my} \tag{2}$$

$$\sigma_2 = \frac{1}{2}(SCF_{AC} + SCF_{AS})\sigma_x + \frac{1}{2}\sqrt{2}\,SCF_{MIP}\sigma_{my} - \frac{1}{2}\sqrt{2}\,SCF_{Mop}\sigma_{mz}$$

$$\sigma_3 = SCF_{AS}\,\sigma_x - SCF_{MoP}\sigma_{mz}$$

$$\sigma_4 = \frac{1}{2}(SCF_{AC} + SCF_{AS})\sigma_x - \frac{1}{2}\sqrt{2}\,SCF_{MIP}\,\sigma_{my} - \frac{1}{2}\sqrt{2}\,SCF_{MoP}\,\sigma_{mz}$$

$$\sigma_5 = SCF_{AC}\,\sigma_x - SCF_{MIP}\,\sigma_{mz}$$

$$\sigma_6 = \frac{1}{2}(SCF_{AC} + SCF_{AS})\sigma_x - \frac{1}{2}\sqrt{2}\,SCF_{MIP}\,\sigma_{my} + \frac{1}{2}\sqrt{2}\,SCF_{MoP}\sigma_{mz}$$

$$\sigma_7 = SCF_{AC}\sigma_x + SCF_{MoP}\sigma_{mz}$$

$$\sigma_8 = \frac{1}{2}(SCF_{AC} + SCF_{AS})\sigma_x + \frac{1}{2}\sqrt{2}\,SCF_{MIP}\sigma_{my} + \frac{1}{2}\sqrt{2}\,SCF_{MoP}\sigma_{mz}$$

where σ_x is the axial load, and σ_{my} and σ_{mz} are the maximum nominal stresses caused by bending inside and outside the plane, respectively. SCF_{AC} and SCF_{AS} are the stress concentration factors at the crown and saddle for the axial load, respectively. SCF_{MIP} and SCF_{MoP} are the stress concentration factors for the internal and external moments of the plane, respectively. SCFs in Eq. (2) are used for HSS formulae through the Efthymiou equation (Efthymiou, 1988).

Ju et al. (2019) conducted a fatigue analysis of the tubular joints of jacket foundations. They calculated the HSS at eight points around the tubular joints and used the rain-flow counting method (Amzallag et al., 1994) to express the average stress under random loads.

Marjan and Hart (2022) conducted a time-series fatigue analysis of tubular joints through the Sesam software, a marine structure analysis software program, to examine the fatigue life of jacket foundations. They calculated fatigue life through the HSS approach according to the guidelines of DNV (2016). They also used Miner's rule (Miner, 1945) to calculate the total damage of each tubular joint and confirmed the position of the joint with the largest fatigue damage.

3.2.2 Fatigue damage analysis method for tripod foundations

Tripod foundations are vulnerable to fatigue damage because of the complex structure, as with jacket foundations, and stress concentration occurs at tubular joints. Therefore, determining the fatigue life by accurately calculating fatigue damage for tripod foundations is also important.

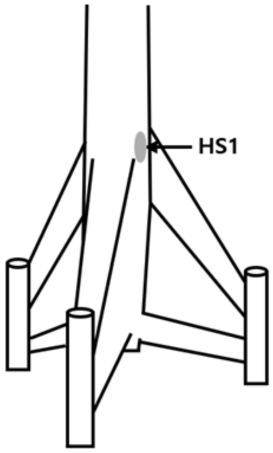

Fig. 9 Location of fatigue damage in tripod foundation (Ma et al., 2018)

Ma et al. (2018) conducted finite element analysis using the ABAQUS software for a 6MW OWT based on a tripod foundation. They examined the loads of the marine environment considering the ultimate limit state (ULS), serviceability limit state (SLS), and fatigue limit state (FLS) at the design location. They presented the maximum cross-sectional area equivalent stress distribution and lateral load for the three piles of the tripod foundation under ULS conditions and examined the deflection distribution of the three piles under SLS conditions. Under FLS conditions, the largest fatigue damage occurred at the tubular joint (HS1) between the central column and the brace, as shown in Fig. 9.

Yeter et al. (2015) performed a time-domain fatigue damage assessment for tripod foundations under various environmental load conditions. They derived the dynamic response spectrum under environmental loads using a high-speed Fourier transform and obtained the average stress through the rain-flow counting method (Amzallag et al., 1994), considering cyclic loads. Yeter et al. (2015) also calculated fatigue damage using the S–N approach. The largest fatigue damage was observed from the tubular joint between the central column and the brace. The accurate fatigue life was obtained by comparing the fatigue lives obtained using the rain-flow counting method, the Dirlik method (Dirlik, 1985), and the Narrow-band solution (Bendat, 1964).

Lu et al. (2023) introduced the Stress Influence Matrix (SIM) to simplify the fatigue analysis of tripod foundations. The SIM approach considers the cyclic loads from external loads and expresses the unit force and moment in each component direction using a matrix. Approximately 25 minutes were required to obtain the fatigue analysis results using this proposed method, which could efficiently reduce the calculation time.

4. Shape Changing Techniques for Fixed Offshore Wind Turbine Foundations

In fixed OWTs, studies have been conducted to address problems with each foundation, as described in section 3. Despite the considerable research efforts, there are still limitations to fully overcoming chronic problems with OWT foundations. Single foundations (gravity, monopile, and suction buckets) are easy to manufacture and install and have economic benefits at shallow depths. Owing to the structural characteristics, however, they are sensitive to lateral loads and soil characteristics, which limits the design depth. Multi-pile foundations (jacket and tripod) have structural stability because of the complex structure, but they involve considerable fatigue damage and design cost. Therefore, some researchers have attempted to address chronic problems with wind turbine foundations by changing their geometry. Among them, hybrid foundations and optimization techniques have attracted attention. Hybrid foundations solve existing geotechnical problems, such as interactions with soil and local scour, by combining them with foundations or attaching appendages. In addition, optimization techniques allow optimal geometry by reducing the weight along with the safety and performance of the structure. Therefore, this section presents research on hybrid foundations and optimization techniques, which address chronic problems with previous foundations through changes in geometry.

4.1 Hybrid Foundations

In recent years, various studies have been conducted on hybrid foundations, which changed the geometry by attaching appendages around the foundations or in combination with foundations to address geotechnical problems, such as lateral loads and local scour. Hybrid foundations can provide larger lateral capacity than conventional ones and increase lateral resistance with combined appendages.

Kim and Kim (2018) proposed a hybrid pile-type concrete foundation composed of steel shafts and a concrete base to overcome the geotechnical limits of conventional monopile and gravity-based foundations. This foundation overcame the heavy weight of concrete and the shortcomings of installation cost by introducing steel shafts while maintaining the low cost and safety of concrete. They also conducted quasi-static analysis and natural frequency analysis to verify the validity of the hybrid foundation and found that the allowable displacement and stress met the conditions.

Chen et al. (2020) proposed a hybrid foundation by attaching a broad and shallow bucket skirt to a monopile foundation. For this foundation, the bucket is placed on soil, and the water inside is then discharged to make the bucket adhere to the seabed. The monopile is stably fixed to the seabed after passing through the center of the bucket. The two components are then combined using a grout material. They compared the behavior of the hybrid foundation under static and dynamic loads with that of conventional monopiles to examine its performance. The hybrid foundation exhibited excellent lateral displacement, rotation, and bending moment performance compared to conventional monopiles.

Li et al. (2020) examined a foundation that combined pile-wheel-bucket. A vertical load was applied to the bucket by loading gravel or stone on the wheel to increase frictional force. In the monotonic loading test, the final bearing capacity of the hybrid foundation was

100 to 300% higher than that of conventional monopile foundations. Li et al. (2022) introduced the discrete continuum numerical approach to identify the behavior of a hybrid pile-bucket foundation under circulatory lateral loads. Numerical modeling was based on a 3D discrete-continuum coupling approach that combined the discrete element method (DEM) and the finite difference method (FDM). They compared the hybrid foundation with conventional monopiles under 20,000 loading cycles to identify its displacement under cyclic lateral loads. The cumulative displacement of conventional monopiles was smaller in the first 30 cycles, but it exceeded the cumulative displacement of the hybrid foundation after 250 cycles. They suggested that the hybrid foundation can provide higher performance over the long term.

4.2 Optimization Technique to Reduce the Weight of Structures

As the power generation capacity of fixed OWTs increases, their design depth also increases. Therefore, foundations have evolved into more complex forms to meet the load conditions in the marine environment, which causes economic losses. Therefore, many studies have attempted to give foundations the optimal geometry by meeting the design conditions and reducing weight through optimization design.

Kaveh and Sabeti (2018) performed an optimization design for jacket foundations using Colliding Bodies Optimization (CBO), a heuristic algorithm. They dealt with 20 design variables, including the diameter and thickness of the foundation. When the proposed algorithm was applied, the weight of the substructure decreased to 2,742.9 kN, which is approximately half of the initial structure.

Motlagh et al. (2021) optimized a jacket foundation by performing WCF and CF optimization using genetic algorithms. WCF optimization involves optimizing stress and buckling within a structure, and CF optimization minimizes the fatigue damage considering all design conditions. Consequently, WCF optimization reduced the initial weight of the jacket foundation by 15%, and CF optimization that considered fatigue damage decreased the weight by 13%.

Tian et al. (2022) designed an optimal jacket foundation by applying a three-step topology optimization technique using the Optistruct optimization module of the HyperWorks software. In the first step, the stiffness of the structure was maximized, and its weight was reduced through mathematical calculations. In the second step, the stress state of the jacket was optimized, and shape optimization was performed by determining the optimal jacket node positions. In the final step, the overall volume was reduced through size optimization. The structure was simplified through this optimization process, and the weight of the optimized structure was 38.24% lower than that of the initial model.

Lu et al. (2023) designed a tripod foundation using the topology optimization technique. They also analyzed the static and dynamic behavior of the structure, considering external loads, including wind and waves. They compared the optimized structure with the existing structure, considering natural frequency, ultimate strength, and fatigue strength. The optimized structure exhibited a weight reduction effect of 16.29%.

Tian et al. (2024) proposed a topology optimization technique considering fatigue damage for a jacket structure. The proposed optimization technique reconstructed the optimization computational formula through the P-norm formula used in stress-based topology optimization methods. This could reduce the volume of the structure by approximately 14.58% while meeting the fatigue life.

5. Conclusions

This study examined the gravity, monopile, jacket, tripod, and suction bucket foundations for fixed offshore wind turbines (OWTs). The benefits and shortcomings of each foundation type were analyzed comprehensively using the results of previous studies and the latest research. Technological problems were presented based on the results of studies on each foundation type, and studies on optimization design methods that improved reliability were presented. The comprehensive analysis of each foundation type can be summarized as follows.

(1) For gravity-based foundations, the substructure is located on top of the seabed. Therefore, it is necessary to investigate the soil characteristics before installation and remove soil with low bearing capacity to secure sufficient bearing capacity. The soil also needs to be leveled for the installation of gravity-based foundations. A gravity foundation based on a steel skirt is being developed to address these problems. The need for seabed preparation can be reduced significantly by injecting concrete into the empty space between the foundation and the seabed.

(2) Monopile foundations are significantly affected by the surrounding soil, and it is important to assess the life of the structure from the relationship between the foundation and soil. In general, the pile–soil interaction (PSI) was examined through the p–y curve that used a beam, which is the nonlinear Winkler (1867) foundation model. Nevertheless, the curve may underestimate soil stiffness and overestimate lateral pile displacement for monopiles with large diameters. Therefore, research has been conducted on PSI analysis methods based on the three-dimensional continuum-based finite element method (3D FEM).

(3) Jacket-based foundations involve significant fatigue damage because stress concentration easily occurs at tubular joints under long-term cyclic loads. Therefore, it is necessary to assess the fatigue life of the structure by evaluating the fatigue damage of tubular joints. Many studies conducted fatigue analysis using the hot spot stress (HSS) approach for fatigue damage assessment. In addition, the rain-flow counting method was used to express the average stress under random loads, and total damage was calculated using Miner’s rule. Time-series fatigue analysis was conducted using Sesam software, a marine structure analysis software program, to examine fatigue life through the latest research.

(4) Tripod foundations also showed the most severe fatigue damage at tubular joints, and the largest fatigue damage occurred at the tubular joint between the central column and the brace. Therefore, the Dirlik method (Dirlik, 1985) and narrow-band solution (Bendat, 1964) can

obtain the fatigue life by accurately calculating the fatigue damage at the position. In addition, the SIM was presented to simplify fatigue analysis through the latest research.

(5) Suction bucket foundations are most sensitive to lateral loads, which alter the bearing capacity, deflection, and rotation of the structure. Suction bucket foundations require further analysis because the vertical load and moment affect the final bearing capacity. Many studies revealed the effects of lateral and vertical loads through 3D FEM and centrifuge tests. Under cyclic lateral loads, the lateral displacement increased rapidly in the early cycles, and it tended to change slowly as the number of cycles increased. The vertical load decreased the displacement and rotation of the bucket and increased the horizontal bearing capacity and moment capacity by strengthening the foundation-soil interaction.

For OWTs, foundations that directly affect the system performance and stability must be designed to meet conditions that can respond to various environmental loads and external factors. Some researchers examined hybrid foundations with geometry change and shape optimization techniques to address the problems with each foundation type described above. Hybrid foundations can provide larger lateral capacity than conventional ones and increase lateral resistance with combined appendages. Optimization techniques can maximize the efficiency of structures or reduce costs through weight reduction under given conditions using mathematical modeling and algorithms.

This study identified the characteristics and research directions of fixed structures and presented the optimal substructure design methods for each purpose. These results are expected to be used as basic data for the design of OWT structures.

Conflict of Interest

Sung Woong Choi serves as a journal publication committee member of the Journal of Ocean Engineering and Technology, but he had no role in the decision to publish this article. No potential conflict of interest relevant to this article was reported.

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Author ORCIDs

Author name	ORCID
Kim, Yun Jae	0009-0006-7814-8410
Choe, Jin-wook	0000-0002-4629-6789
Lim, Jinseok	0009-0009-8098-0312
Choi, Sung Woong	0000-0001-7285-4257