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Shape Dependent Wave Force and Bending Moment of Offshorewind Substructure System

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Abstract: *In this study, analytical study to improve structural safety of the CFMP (Concrete Filled Multi-Piles) based offshore wind hybrid substructure system was carried out. Firstly, in order to optimally arrange the multi-piles at the upper part, diffraction analyses were carried out for the three multi-piles arrangement cases. Then, in order to minimize wave-induced bending moment at the substructure, diffraction analysis and structural analysis were carried out for the four cases substructure system of a mono-pile and three hybrid cases. As the results of diffraction analysis for the three multi-piles arrangement cases, maximum wave force of five multi-piles case indicated about 30% lower level than that of mono-pile case. Therefore, multi-piles arrangement of hybrid substructure was decided as five multi-pilescase. As the results of bending moment calculation at the critical bending points, wave-induced bending moment of hybrid cases decreased about 75.3 ~ 79.4 % for the extreme wave loading. Integrated bending moment of three hybrid cases including wind-induced bending moment decreased about 18.8 ~ 24.6 % comparing with the mono-pile case. As the results of bending moment calculation at the foundation pile head, integrated bending moment of the concrete base height 8.0 m was similar with the mono-pile and of the concrete base height 6.0 m decreased about 4.4 %, respectively. Therefore, in order to certify the same level of the structural safety for the hybrid substructure of this study, it was found that the critical height of the concrete base was the 8.0 m. In this case, structural safety at the foundation pile has the same level with the mono-pile case. However, structural safety at the multi-pile (upper) part has the enhanced safety level comparing with the mono-pile.*

Keywords: *Offshore wind, Substructure, Shape, Hybrid, Wave force, Moment*

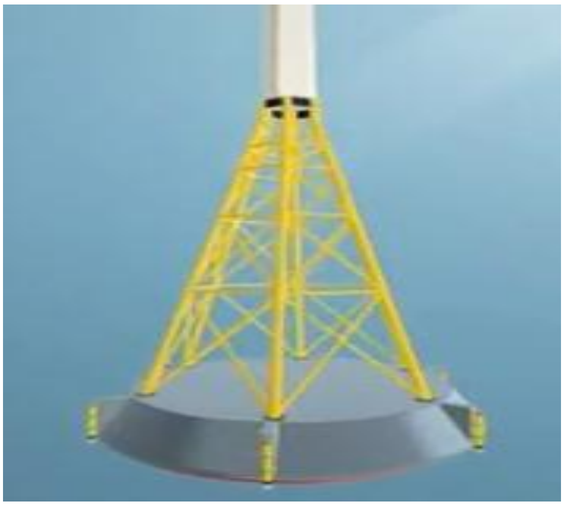
1. Introduction

Offshore wind substructure system should have a structural safety against to the harsh offshore conditions of wind, wave, and tidal. Also, in order to satisfy overturning stability, gravity based substructure system should be required to have sufficient foundation resistance and self-weighting resistance to resist to the overturning efficiently.

In order to improve structural safeties of offshore wind substructure system, it is important to reduce wave force subjected to the substructure system and to improve strength, stiffness, and vibration resistance of substructure system [1,2]. Also, recently, in order to improve wind energy availability and economic efficiency, the capacity of wind turbine is drastically increasing. According to the increasing of offshore wind turbine capacity from 2.0~3.0MW to 5.0~10.0MW, substructure system also should be large-sized. However, since the increasing of the size of substructure system to improve strength and stiffness or to corresponding to the large capacity of wind turbine disadvantages to the wave forces subjected to the substructure system because of the larger cross-sectional area, it needs to optimally arrange cross-section of substructure system so as to satisfy both low-hydrodynamic force and high-structural capacity of strength, stiffness, and vibration resistance. Also, in order to improve overturning stability of substructure system, it is advantage to increase self-weight of substructure system [3,4, 5] and to lower center of gravity. However, since the increasing of self-weight of substructure system influence on the construction costs, it needs to optimally control the self-weight of substructure system.

In Japan, NEDO (New Energy and Industrial Technology Development Organization) has been developed hybrid gravity type of substructure system. This type was designed by adopting the advantages of the gravity and jacket system, as presented in Fig. 1(a), and reported to reduce overturning moment about 80% compared to the typical gravity type [6]. This type was constructed as offshore wind condition observation tower in June, 2012 [6]. In France, Rockmat Ltd. also has been developed hybrid jacket type of substructure system for the rocky seabed [7]. This type was similar with the NEDO's hybrid gravity type, as presented in Fig. 1(b). This system adopted flexible cofferdam bags system to easily flat uneven seabed by injection the concrete and to simply uninstall substructure system after the service life. Korea goverment plan to construct large offshore wind farm at southern-western Korean sea. However, this area has disadvantages of harsh wave, typhoon, and soft soil conditioms. Therefore, it is very important to disign substructure system safely against to the harsh offshore environmental loads.

(a) NEDO (Japan)



(b) Rockmat (France)

Fig1. *Hybrid types substructure system*

In this study, analytical study to improve structural safety of the CFMP (Concrete Filled Multi-Piles) based offshore wind hybrid substructure system was carried out. CFMP based hybrid substructure system was designed to reduce wave force and to improve structural safety against to the harsh offshore condition. Firstly, in order to optimally arrange the multi-piles at the upper part, diffraction analyses were carried out for the three multi-piles arrangement cases and wave forces subjected to the upper part of the substructure were compared with each other. Then, in order to minimize wave-induced bending moment at the substructure system, diffraction analysis and structural analysis were carried out for the four substructure system of a mono-pile and three hybrid cases and structural behaviors were compared with each other.

2. ANALYSIS MODEL

2.1 CFMP based Hybrid Substructure System

In order to reduce wave forces subjected to the substructure, it needs to optimally arrange cross-sectional area of substructure system. In order to improve structural capacity, it is important to improve strength, stiffness and vibration resistance of substructure system. Also, in order to improve overturning stability of substructure system, it is advantage to increase self-weight of substructure system and to lower center of gravity. In addition, in order to reduce installation cost, it needs to optimally control the self-weight of substructure system and to install without large capacity offshore crane during the installation.

In this study, CFMP based offshore wind hybrid substructure system was introduced, as presented in Fig. 2. CFMP based hybrid substructure system was designed to reduce wave force subjected to the substructure, to improve structural safety against to the harsh offshore condition, and to reduce installation cost [8, 9].In order to reduce wave force subjected to the substructure system, multi-piles system was adapted. Also, in order to improve structural strength, stiffness, and vibration resistance of substructure system, multi-piles system filled with the concrete. Therefore, CFMP based hybrid substructure system was designed so as to satisfy both low-hydrodynamic force and high-structural capacity of strength, stiffness, and vibration resistance.

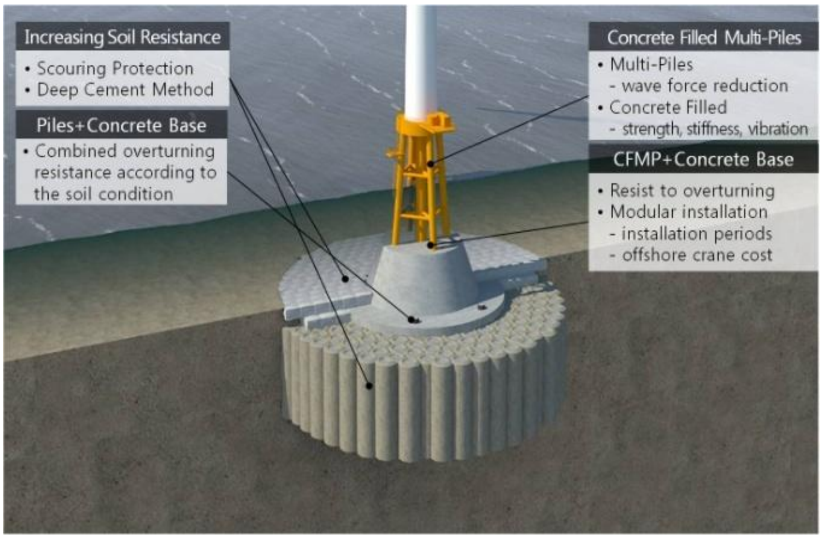


Fig2. *CFMP based hybrid substructure system*

In addition, in order to improve overturning stability of substructure system, the bottom part of substructure system consists of the concrete base. The gravitational restoring force of the concrete base resist to the overturning combined with the foundation piles. Namely, combining force of the concrete base and foundation piles resist to the total overturning moment. This concept has an advantage that two components of gravitational restoring force and foundation piles resistance can be apply alternatively according to the seabed soil condition from the soft to the rock.

The CFMP and the concrete base connect with the grouting at the sea condition. This modular installation method can become possible substructure installation by using only small capacity's offshore crane, instead of large capacity's offshore crane which is very expensive and too difficult to rent, and resulting in reducing total construction cost [9].

2.2 Turbine and Environmental Load

In this study, NREL 5.0 MW turbine model was selected for the structural safety analysis of CFMP based hybrid substructure system and tower model resulting from Upwind project [10], which was designed corresponding to the NREL 5.0 MW turbine model, was applied. The total weights of turbine and tower models were about 350 and 220 ton, respectively. The hub height is 82.5m from MSL (Mean Sea Level) and the tower length is 68.0 m. The height of substructure is 32.0 m from seabed and the water depth is 20.0 m.

At the structural safety analysis, design code IEC 61400-3 [11] for the wind turbine system was adopted and structure analysis was carried out according to the ultimate design loads condition 6.1(a) and 6.2(a), as presented in Table 1. DLC 6.1(1) and 6.2(a) present ultimate limit states for the parked (standing still or idling) state and grid loss state, respectively. Environmental loads of wind and wave for the southern-western sea of the Korea peninsular were processed and summarized in Table 2. Extreme wind loads subjected to the blade, nacelle, and tower were calculated based on the wind speed of return period 50 years. Extreme wave force subjected to the substructure was calculated based on the wave height and period of return period 50 years.

Table1. *Design load cases (DLC) for ultimate limit state*

DLC	Condition	Wave	Wind
IEC 61400-3-(6.1a)	Parked standing still or idling	Extreme	Extreme
IEC 61400-3-(6.2a)	Grid loss	Extreme	Extreme

Table2. *Environmental loads*

	Wind	Wave	Limit state
Normal	7.7 m/s	H_w=1.52m, P_w=6.2sec	Fatigue limit
Extreme	41.6 m/s	H_w=13.76m, P_w=15.0sec	Ultimate limit

3. MULTI-PILES ARRANGEMENT DEPENDENT WAVE FORCE

3.1 Multi-Piles Arrangement Models

Table3. *Details of multi-piles arrangement cases*

	Mono (1)	Multi (1)	Multi (2)
No. of piles	1 EA	5 EA	9 EA
D (m)	8.0	0.94 (D1), 3.0 (D2)	0.71 (D1), 1.25 (D2)
I (kN/m3)	9.073	9.081	9.006

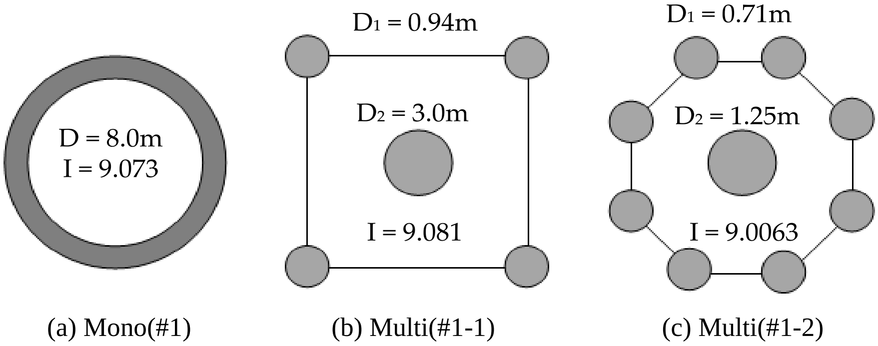


Fig3. *Hybrid substructure shape to the multi-piles arrangement*

In order to investigate wave force subjected to the substructure according to the multi-piles arrangement and to decide optimal multi-piles arrangement of CFMP based hybrid substructure, diffraction analysis were carried out for the three multi-piles arrangement cases, Mono(1), Multi(1): five multi-piles, and Multi(2): nine multi-piles, as presented in Fig. 3.Three multi-piles arrangement cases were designed to have a similar cross-sectional moment of inertia (I) so as to have a similar structural performance, as presented in Table 3.The moment of inertia of Multi(1) and Multi(2) cases were determined assuming the multi-piles filled with the concrete of the 30 MPa. Based on the diffraction analysis, wave forces subjected to the three multi-pile arrangement cases were compared with each other and optimal multi-piles arrangement of hybrid substructure was decided.

3.2 Wave force

The result of the diffraction analysis was provided in Fig.4 and maximum wave force and design wave forces per unit wave height for the extreme and normal wave conditions were provided in Table 4. As the results of diffraction analysis for the three multi-piles arrangement cases, maximum wave forces for the Mono(1), Multi(1), and Multi(2) were about 1018.03, 715.32, and 737.50kN/m, respectively. Wave forces of multi-piles cases indicated about 70 ~ 72% level than that of mono-pile case. The wave forces of multi-piles cases, Multi (1) and Multi (2), indicated a similar wave forces with each other. The maximum wave forces occurred at the wave periods of8.2, 8.9, and 8.8sec for the three multi-piles arrangement cases, respectively. Considering the extreme and normal wave periods of this study were about 15.0 and 6.2 sec, respectively, as presented in Table 2, the wave force of Multi(1) case: five multi-piles was indicated the lowest wave force among the three cases, about 75% of the mono-pile case at the extreme wave condition and about 57% at the normal wave condition.

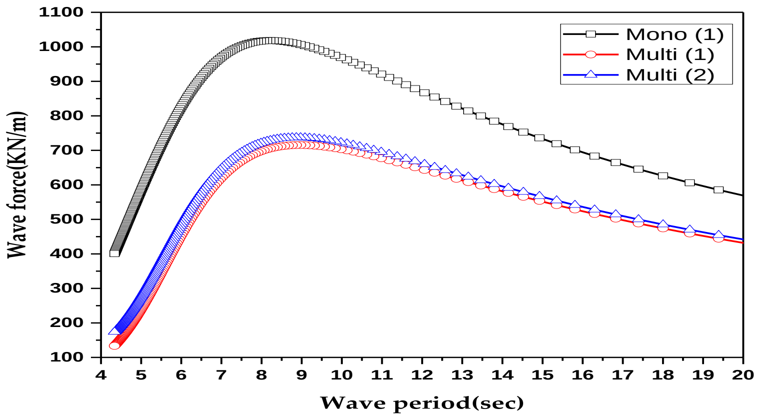


Fig4. *Wave forces according to the arrangement of multi-piles*

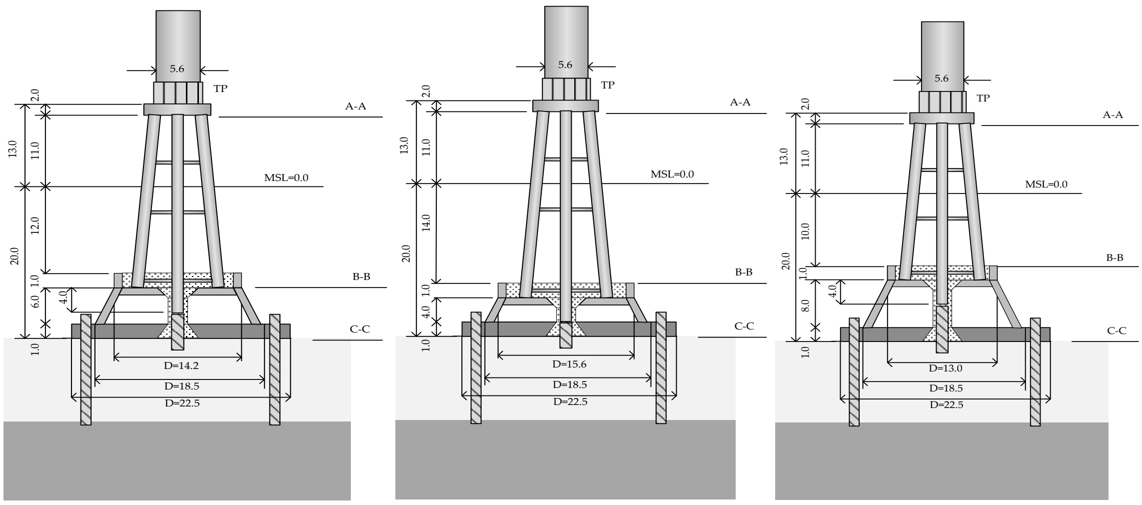
Table4. *Wave forces of multi-piles arrangement cases*

	Mono(1)	Multi(1)	Multi(2)
Max.	1,018.03 (1.00)	715.32 (0.70)	737.50 (0.72)
Extreme	736.27 (1.00)	553.65 (0.75)	567.16 (0.77)
Normal	866.21 (1.00)	497.37 (0.57)	528.12 (0.61)

4. SUBSTRUCTURE SHAPE DEPENDENT WAVE FORCE

4.1 Substructure Shape Models

In order to investigate wave force subjected to the hybrid substructure according to the concrete base height and to decide optimal concrete base height of hybrid substructure, diffraction analysis were carried out for the four cases: a mono-pile case, Mono (2), and three hybrid cases, Hybrid(1), Hybrid(2), and Hybrid(3), according to the concrete base height, as presented in Fig.5. The diameter D of the mono-pile case was selected as 6.0 m which was typical diameter for 5.0 MW turbine systems [10] since hybrid substructure of this study was designed for the NREL 5.0MW turbine system. Multi-piles arrangement of hybrid substructure was decided as five multi-piles case Multi (1) since the wave force was the lowest among the three multi-piles arrangement cases, as illustrated in Fig. 4. Details of a mono-pile and three hybrid cases were indicated in Table 5. In Table 5, D is the diameter of mono-pile, D1 and D2 are the diameters of the multi-piles, Hpiles is the height of the mono-pile or multi-piles, Hcon's is the height of the concrete base of the three hybrid cases, and Ap is the wave force projection area per length.



(1)Hybrid(a) (2)Hybrid(b) (3)Hybrid(c)

Fig5. *Hybrid substructure shape according to the height of concrete base*

Table5. *Details of concrete base height cases*

	Mono (2)	Hybrid (1)	Hybrid (2)	Hybrid (3)
No. Piles	1 EA	5 EA	5 EA	5 EA
D (m)	6.0	1.2(D_1), 2.0(D_2)	1.2(D_1), 2.0(D_2)	1.2(D_1), 2.0(D_2)
H_{piles} (m)	33.0	27.0	25.0	23.0
$H_{con'c}$ (m)	-	6.0	8.0	10.0
A_P (m/m)	6.0	6.8	6.8	6.8

Three hybrid cases were designed to have the same dimensions of 18.5 and 22.5 m at the concrete base bottom so as to have the same origin for the overturning resistance. Based on the diffraction analysis, wave forces subjected to the four substructure system were compared with each other. Then, wave-induced bending moment was evaluated. Finally, guideline for the concrete base height of hybrid substructure was proposed.

4.2 Substructure Shape Dependent Wave Force

The result of the diffraction analysis was provided in Fig.6 and maximum wave force and design wave forces for the extreme and normal wave conditions were provided in Table6. Wave force subjected to the substructure were explained for three part of the multi-piles (upper) part, the concrete base (bottom) part, and total substructure system, respectively, since the wave forces subjected to the multi-piles (upper) part and the concrete base (bottom) part presented the different tendency.

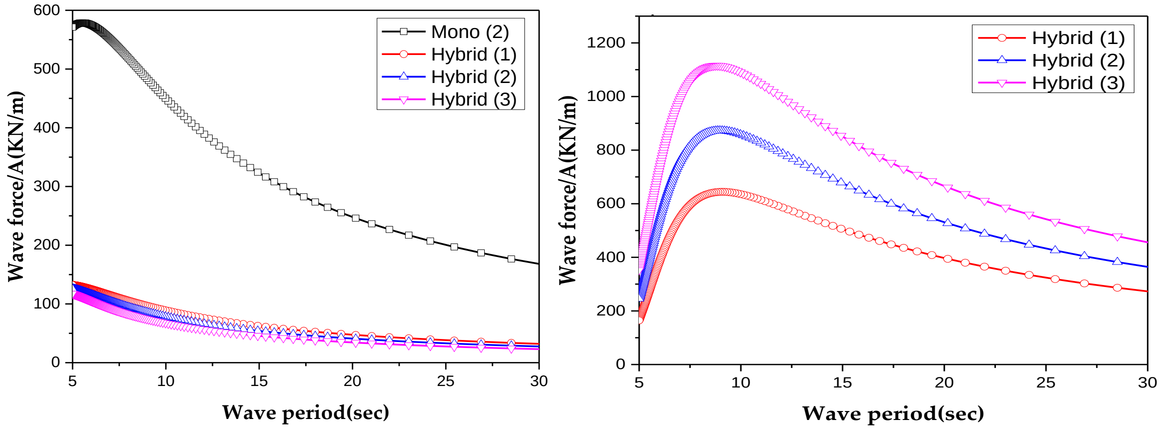


Fig6. *Wave forces of multi-piles (upper) and concrete base (bottom) parts*

Table6. *Wave forces of concrete base height cases*

	Mono (2)	Hybrid (1)	Hybrid (2)	Hybrid (3)
(a) Multi-pile (upper) part				
Maximum	578.54 (1.00)	132.57 (0.23)	127.29 (0.22)	120.82 (0.21)
Extreme	324.26 (1.00)	62.68 (0.19)	54.31 (0.17)	45.81 (0.14)
Normal	571.25 (1.00)	123.42 (0.22)	113.64 (0.20)	102.31 (0.18)
(b) Concrete base (bottom) part				
Maximum	-	644.25	873.13	1115.37
Extreme	-	506.86	679.04	854.01
Normal	-	427.51	600.15	800.37
(c) Substructure System (Total)				
Maximum	578.54 (1.00)	740.99 (1.28)	959.43 (1.66)	1190.97 (2.06)
Extreme	324.26 (1.00)	569.54 (1.76)	733.35 (2.26)	899.82 (2.77)
Normal	571.25 (1.00)	550.93 (0.96)	713.79 (1.25)	902.68 (1.58)

As the results of diffraction analysis for the multi-piles (upper) part, maximum wave forces of a mono-pile and three hybrid cases were about 578.54, 132.57, 127.29, and 120.82kN/m, respectively, as presented in Fig. 6(a) and Table 6(a). Although the wave force projection area (6.8 m/m) of hybrid cases was about 13.3% larger than the mono-pile (6.0 m/m), wave force of hybrid cases indicated about 21~23 % level than that of mono-pile case. It was caused by wave-structure interaction between the multi-piles of three hybrid cases [1, 2]. Wave forces of three hybrid cases according to the concrete base height indicated similar level with each other because the wave force projection widths were the same and the projection lengths were little different with each other. The maximum wave forces occurred at the short wave period of near 5.0 sec and, as the wave periods increased, wave forces reduced gradually for a mono-pile and three hybrid cases. Considering the extreme and normal wave periods of this study were about 15.0 and 6.2 sec, the wave forces of three hybrid cases indicated even lower wave force about 14~19 % at the extreme wave condition and about 18~22 % at the normal wave condition than the mono-pile case, as presented in Fig. 7 and Table 6(a).

As the results of diffraction analysis for the concrete base (bottom) part, maximum wave forces of three hybrid cases were about 644.25, 873.19,and 1115.37kN/m, respectively, as presented in Fig.6(b) and Table 6(b). Wave forces of three hybrid cases indicated even larger level than the mono-pile. It was caused by wave diffraction effect due to the large projection area of the concrete base (bottom) part of three hybrid cases. Wave forces of three hybrid cases indicated significantly different level according to the concrete base height because the wave force projection lengths were different with each other. The maximum wave forces occurred at the wave periods of9.0, 8.9, and 8.7 sec for the three hybrid cases, respectively.

As the results of diffraction analysis for the substructure system, total maximum wave forces of a mono-pile and three hybrid cases were about 578.54, 740.99,959.43, and 1190.97kN/m, respectively, as presented in Fig. 8 and Table 6(c). Total wave forces of three hybrid cases indicated larger level than mono-pile case although wave forces of the multi-piles (upper) part were even smaller than the mono-pile case. It was caused that the targeted water depth of this study was just 20.0 m and, considering wave length at the extreme wave condition, wave force at the concrete base (bottom) part did not decreased and maintained the similar level with the sea surface level [12, 13], as illustrated in Fig. 7. Therefore, increasing of the wave force due to the larger projection area of the concrete base (bottom) part was much larger than the decreasing of the wave force due to the wave-structure interaction at the multi-piles (upper) part.

The maximum wave forces occurred at the wave period 5.5 sec for the mono-pile case and at the wave period of8.6 ~ 8.7 sec for the three hybrid cases. Considering the extreme and normal wave periods of this study were about 15.0 and 6.2 sec, total wave force of hybrid cases indicated larger wave force about 176 ~ 277 % at the extreme wave condition and about 96 ~ 158 % at the normal wave condition than the mono-pile case, as presented in Fig.8 and Table 6(c).

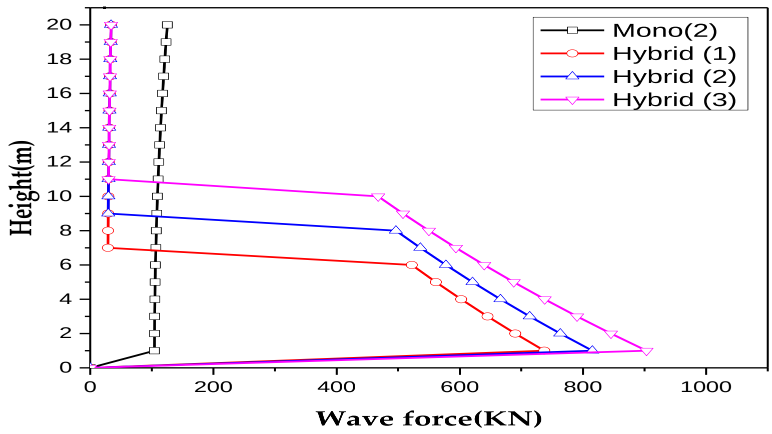


Fig7. *Wave force diagram at extreme wave period (15.0 sec)*

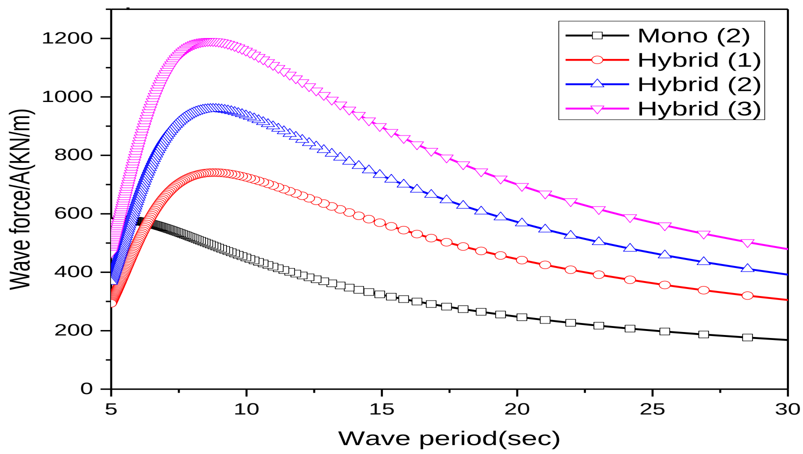


Fig8. *Total wave forces of substructure to wave periods*

5. Substructure Shape dependent Bending Moment

5.1 Substructure

In order to design substructure for the ultimate limit state (ULS) condition, based on the wave force subjected to the substructure, design bending moments of substructure were calculated at thecritical bending points. In case of the mono-pile, the critical bending point is clearly seabed point. However, in cases of threehybrid cases, the critical bending point is not seabed point but multi-piles to concrete base connection points, since design of the concrete base is governed by not bending moment but axial or shear force. Therefore, critical bending points were selected as seabed for a mono-pile and multi-piles to concrete base connection points, namely B-B line at the Fig.5, for the three hybrid cases, respectively.

As the results of bending moment calculation at the critical bending points, wave-induced bending momentswere plotted at Fig.9 according to the wave periods. At the extreme wave condition of wave period of 15.0 sec, wave-induced bending moment of a mono-pile and three hybrid caseswere about 23040, 4765, 5292, and 5695kN·m, respectively, as presented in Fig.10 and Table 7.Wave-induced bending moment of three hybrid cases indicated about 20.6 ~ 24.7 % level than that of mono-pile case for the extreme wave loading. It was caused by wave-structure interaction between the multi-piles (upper) part of three hybrid cases. Wave-induced bending moments of three hybrid cases indicated similar level because the wave force projection areas were the similar with each other.

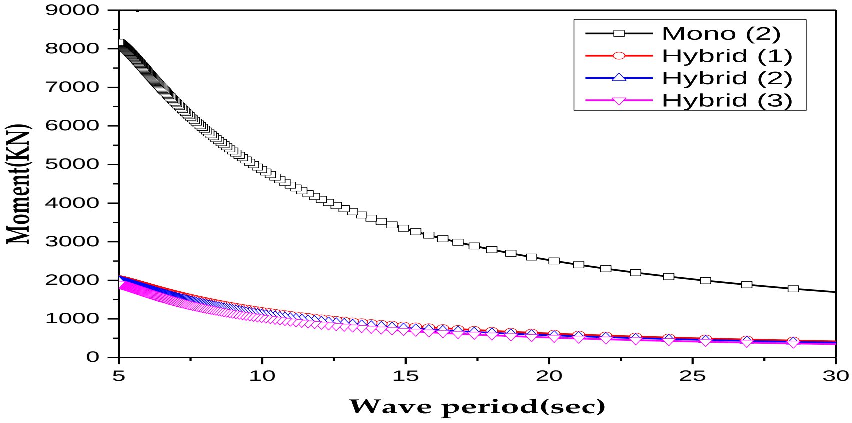


Fig9. *Bending moment at the critical bending points (B-B line at Fig. 3)*

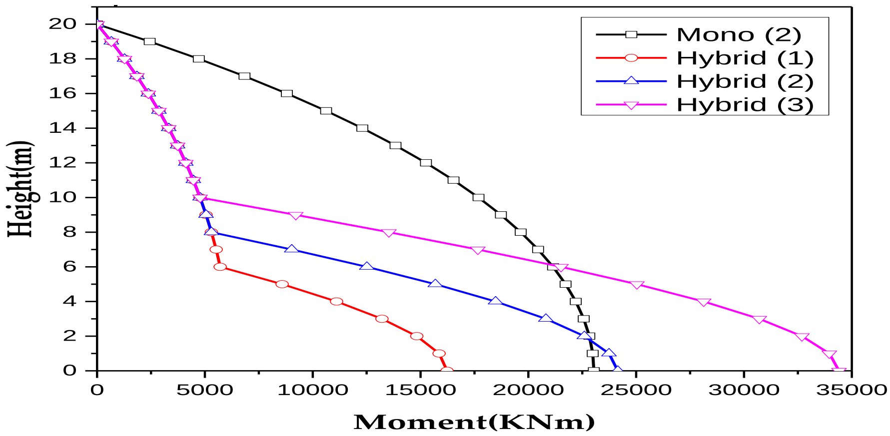


Fig10. *Bending moment diagram at extreme wave period (15.0 sec)*

Table7. *Bending moment at critical bending points of substructure (kN·m)*

	Mono (2)	Hybrid (1)	Hybrid (2)	Hybrid (3)
Wind	135,162 (1.000)	114,535 (0.847)	118,661 (0.877)	122,786 (0.908)
Wave	23,040 (1.000)	4,765 (0.206)	5,292 (0.229)	5,695 (0.247)
Total	158,203 (1.000)	119,301 (0.754)	123,953 (0.783)	128,482 (0.812)

Considering wind-induced bending moment resulting from bladed, turbine, and tower, integrated bending moment of three hybrid cases indicated about 75.4 ~ 81.2 % level of the mono-pile case, namely integrated bending moment decreased about 18.8 ~ 24.6 % comparing with the mono-pile case.

5.2 Foundation Pile Head

In order to design foundation piles for the ultimate limit state (ULS) condition, based on the wave force subjected to the substructure, design bending moments of foundation pile were calculated at the foundation pile head.Foundation pile head were the same position for a mono-pile and three hybrid cases, namely C-C line at the Fig.5. Therefore, in case of the mono-pile, bending moment at the foundation pile point is the same with the critical bending point of the seabed. However, in cases of the three hybrid cases, bending moment at the foundation pile head were calculated by combining bending moment at the critical bending point of 5.1 section with the bending moment resulting from wave force subjected to the concrete base (bottom) part, as presented in Fig.11.

As the results of bending moment calculation at the foundation piles head, wave-induced bending moment was plotted at Fig.12 according to the wave periods. At the extreme wave condition of wave period 15.0 sec, wave-induced bending moment of a mono-pile and three hybrid cases were about 23040, 34388, 24077, and 16186kN·m, respectively, as presented in Fig. 10,Fig.12, and Table 8.

Wave-induced bending moment of three hybrid cases indicated about 70.2 ~ 149.2 % level than that of mono-pile case for the extreme wave loading. It was caused by wave diffraction effect due to the large projection area of the concrete base (bottom) part of three hybrid cases.

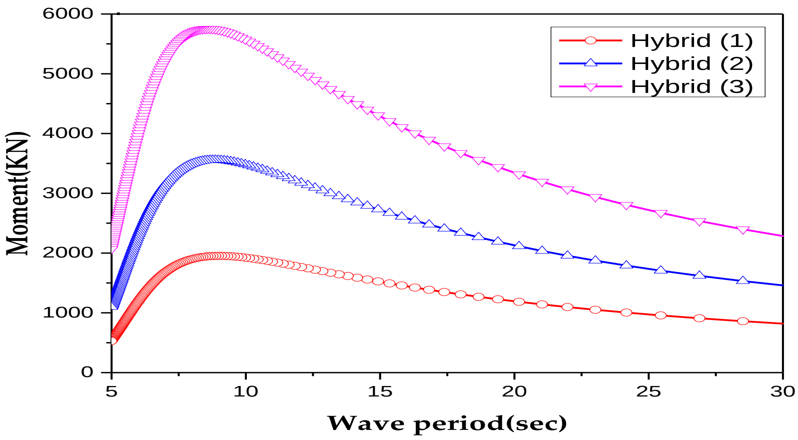


Fig11. *Bending moment at concrete base (bottom) part*

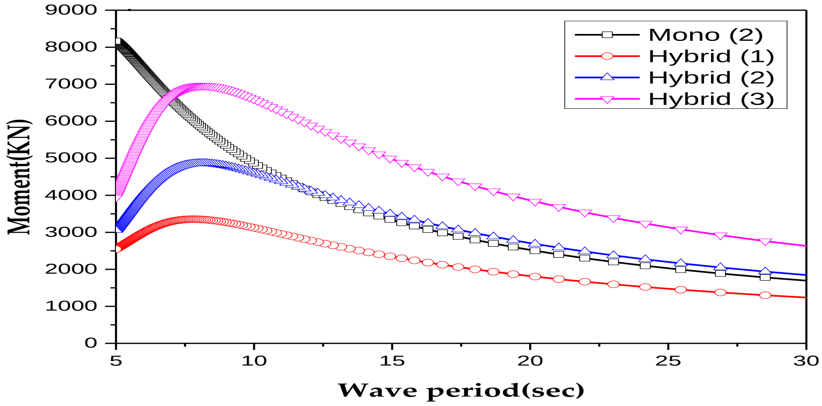


Fig12. *Bending moment at the foundation pile's head(C-C line at Fig. 3)*

Table8. *Bending moment at foundation pile head*

	Mono (2)	Hybrid (1)	Hybrid (2)	Hybrid (3)
Wind	135,162 (1.000)	135,162 (1.000)	135,162 (1.000)	135,162 (1.000)
Wave	23,040 (1.000)	34,388 (1.492)	24,077 (1.045)	16,186 (0.702)
Total	158,203 (1.000)	169,551 (1.071)	159,240 (1.006)	151,349 (0.956)

Considering wind-induced bending moment resulting from bladed, turbine, and tower, integrated bending moment of three hybrid cases indicated about 95.6 ~ 107.1 % level of the mono-pile case, namely integrated bending moment increased about 7.1 % for the Hybrid (1), similar for the Hybrid (2), and decreased about 4.4 % for the Hybrid (3) comparing with the mono-pile case, respectively.

6. Conclusions

In this study, analytical study to improve structural safety of the CFMP (Concrete Filled Multi-Piles) based offshore wind hybrid substructure system was carried out. Firstly, in order to optimally arrange the multi-piles at the upper part, diffraction analyses were carried out for the three multi-piles arrangement cases and wave forces subjected to the upper part of the substructure were analyzed. Then, in order to minimize wave-induced bending moment at the substructure, diffraction analysis and structural analysis were carried out for the four cases substructure system of a mono-pile and three hybrid cases.

As the results of diffraction analysis for the three multi-piles arrangement cases, maximum wave force of five multi-piles case indicated about 70 ~ 72 % level than that of mono-pile case. Therefore, multi-piles arrangement of hybrid substructure was decided as five multi-pile case. As the results of diffraction analysis for the four substructure system, total wave forces of the hybrid cases indicated larger level than mono-pile although wave forces of the multi-piles (upper) part were even smaller than the mono-pile case. It was caused that the targeted water depth was just 20.0 m and, considering wave length at the extreme wave condition, wave force at the concrete base (bottom) part maintained the similar level with the sea surface level.

As the results of bending moment calculation at the critical bending points, wave-induced bending moment of hybrid cases decreased about 75.3 ~ 79.4 % for the extreme wave loading. Integrated bending moment of three hybrid cases including wind-induced bending moment decreased about 18.8 ~ 24.6 % comparing with the mono-pile case. As the results of bending moment calculation at the foundation pile head, integrated bending moment of the concrete base height 8.0 m was similar with the mono-pile and of the concrete base height 6.0 m decreased about 4.4 %, respectively.

Therefore, in order to certify the same level of the structural safety for the hybrid substructure of this study with the typical mono-pile system, it was found that the critical height of the concrete base was the 8.0m. In this case, structural safety at the foundation pile has the same level with the mono-pile case. However, structural safety at the multi-pile (upper) part has the enhanced safety level comparing with the mono-pile.

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