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Comparison of Coupled and Uncoupled Simulation on a Gravity substructure for 5MW Offshore Wind Turbine

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***Abstract*— The offshore wind energy has gained attention from many countries to find alternative and reliable energy sources. Therefore, many offshore wind farms are in the planning phase. In order to construct the offshore wind farms, the substructures supporting offshore wind turbines have to resist loads from wind and wave. In the present study the gravity substructure with suction bucket foundation system for 5MW offshore wind turbine is suggested. The Abaqus software is used to calculate the foundation stiffness of suction bucket system on the structure-soil interaction conditions. The computation of the loads on the substructure requires fully coupled aero-hydro-elastic simulations. However on many occasions, the turbine design is made by a manufacturer and the substructure design is made at another company and it is often not possible to a have a fully integrated model in a numerical simulation. It is then imperative to understand the difference in substructure internal forces and moments from those obtained in fully coupled load simulations against those determined using uncoupled load simulation. To evaluate the difference between the fully coupled analysis and the uncoupled analysis, the comparison of fully coupled and uncoupled simulation method is made.**

***Keywords*— offshore wind turbine, gravity substructure, fully coupled simulation, uncoupled simulation, suction bucket foundation system**

I. INTRODUCTION

Nowadays, the main source of energy in the world is fossil fuel. But the amount of fossil fuel is limited and the use of it causes environmental pollution and global warming. Thus, the studies of renewable energy such as hydro energy, wind energy, solar energy and geothermal energy are being carried out actively all over the world. The offshore wind energy has gained attention from many countries to find alternative and reliable energy sources since the potential of offshore wind energy has been recognized for long and mostly associated with a non-destructive renewable energy. Therefore, many offshore wind farms are in the planning phase. Various studies have been conducted on wind energy [1-5]. In order to construct the offshore wind farms, the substructures supporting offshore wind turbines have to resist loads from wind and wave.

The wind loads from the rotor can cause design challenges on the support structure such as fatigue damage especially within a wind farm due to the wake from surrounding turbines or when the wind and wave directions are not coincident [6]. In addition, since a large offshore wind turbine has a heavy dead load, the reaction forces on the substructure become severe, thus very firm foundations should be required. Therefore, soil-structure interaction model should be cleverly chosen according to analysis type with performing a sensitivity analysis. Some guidelines such as DNV, API and GL are recommended that the full nonlinear model must be used for extreme load cases and foundation design.

In the present study the gravity substructure with suction bucket foundation system for 5MW offshore wind turbine is suggested. The Abaqus software is used to calculate the foundation stiffness of suction bucket system on the structure-soil interaction conditions. The design of offshore wind turbine structures is based on computer simulations of various load cases that the turbine is expected to experience in its life time as stipulated in the IEC 61400-3 standard [7]. The computation of the loads on the substructure based on these design load cases requires fully coupled aero-hydro-elastic simulations. Using the foundation stiffness obtained from Abaqus software, the design of gravity substructure is carried out through the Flex 5 based on the fully coupled aero-hydro-elastic simulations. However on many occasions, the turbine design is made by a manufacturer and the substructure design is made at another company and it is often not possible to a have a fully integrated model in a numerical simulation. It is then imperative to understand the difference in substructure internal forces and moments from those obtained in fully coupled load simulations against those determined using uncoupled load simulations where the tower top loads from the rotor are captured using an aero-elastic software and then used in a different software in which the tower, transition piece and substructure are represented [6]. To evaluate the difference between the fully coupled analysis and the uncoupled analysis, the comparison of fully coupled and uncoupled simulation method is made.

For the uncoupled simulation the tower, transition piece and gravity substructure of the 5MW offshore wind turbine are modelled in the ANSYS Asas software. The hydrodynamic loads are input to the Asas using the Morison equation with linear regular wave model. The forces and bending moments at transition piece are input to the Asas model based on normal turbulent wind simulations conducted in the Flex 5 aero-elastic software.

II. FULLY COUPLED SIMULATION OF GRAVITY SUBSTRUCTURE

A. *5MW offshore wind turbine and gravity substructure*

The H heavy industries 5.0MW wind turbine model is selected for the structural safety analysis of gravity substructure with suction bucket foundation system. The details of H heavy industries 5.0MW wind turbine are provided in Table 1.

TABLE I
DETAIL OF 5MW WIND TURBINE MODEL

Turbine parameter	Unit	Value
Rating	MW	5.0
Configuration	-	3 blades
Rotor diameter	m	139
Cut-in, Rated wind speed	m/s	3.4, 11.3
Cut-out wind speed	m/s	25
Erection and transport wind speed	m/s	12.5
Hub, Nacelle mass	ton	57, 290
Blade mass (per blade, without bolts)	ton	26.5
Weight of bolts (per blade)	ton	0.575

The gravity substructure with suction bucket foundation system for 5.0MW offshore wind turbine composes of a pre-stressed concrete (compressive strength 45MPa) with 0.5m thickness and the height of gravity substructure is 39.0m from seabed as shown in Fig. 1.

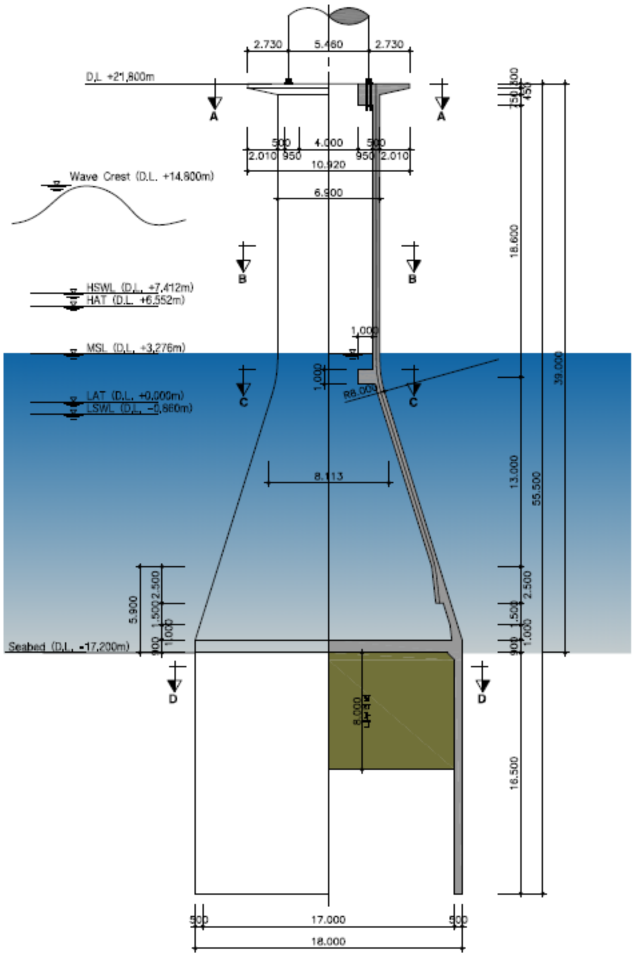


Figure 1: Geometrical definition of gravity substructure.

B. *Environmental conditions and design load cases*

Environmental conditions of wind and wave for the southern-western sea of South Korea are presented in Table 2. Extreme wind and wave conditions subjected to the gravity substructure are calculated based on the wind speed and the wave period of return period 50 years.

TABLE II
ENVIRONMENTAL CONDITIONS

	Wind	Wave	Limit state
Normal	6.90 m/s	H_s=1.48m T_p=6.25sec	FLS
Extreme	42.99 m/s	H_s=6.87m T_p=13.70sec	ULS
Extreme Design	42.99 m/s	H_d=12.78m T_P=13.70sec	ULS

Design code of GL Wind Guideline [8] is adopted and structural analysis is carried out according to the ultimate design load conditions presented in Table 3.

TABLE III
DESIGN LOAD CASES (DLC) FOR ULTIMATE LIMIT STATE

DLC	Condition	Wave	Wind
1.1	Power production	Normal	Normal
1.3	Power production	Normal	Extreme
1.4	Power production	Normal	Normal
1.5	Power production	Normal	Extreme
1.6	Power production	Normal	Extreme
2.1	Power production plus control system fault	Normal	Normal
2.2	Power production plus preceding internal electrical fault	Normal	Normal
2.3	Power production plus safety system fault	Normal	Extreme
4.2	Normal shut-down	Normal	Extreme
5.1	Emergency shut-down	Normal	Normal
6.1a	Idling	Extreme	Extreme
6.2a	Idling with grid loss	Extreme	Extreme
6.3a	Idling with extreme oblique inflow	Extreme	Extreme
7.1a	Parked plus fault conditions	Extreme	Extreme
8.1	Transport, erection, maintenance and repair	Normal	Normal

C. *Stiffness of suction bucket foundation system*

TABLE IV
STIFFNESS OF SUCTION BUCKET FOUNDATION SYSTEM

	Ux (1/m)	Uy (1/m)	Uz (1/m)	Θx (1/rad)	Θy (1/rad)	Θz (1/rad)
Fx (N)	3.24E+09					
Fy (N)	0	3.24E+09				
Fz (N)	0	0	3.26E+09			
Mx (Nm)	0	3.34E+10	0	5.47E+11		
My (Nm)	3.34E+10	0	0	0	5.47E+11	
Nz (Nm)	0	0	0	0	0	1.47E+11

As the substructure mass increases, the interaction between the superstructure and foundation system intensifies, thus the contribution to the structural response of the total system increases. In the present study the Abaqus software is used to calculate the stiffness matrices of suction bucket foundation system on the structure-soil interaction conditions. The stiffness of suction bucket foundation system is provided in Table 4.

D. *Natural frequency and resonance*

The first few natural frequencies of substructure are heavily influenced by the wind turbine. Therefore, the first natural frequency of substructure is to be within the soft-stiff range between the 1P and 3P frequency ranges. In order to evaluate the resonance between the wind turbine and the gravity substructure, the modal analysis is carried out through Flex 5 with the foundation stiffness obtained from Abaqus software. The natural frequencies and Campbell diagram of gravity substructure present in Table 5, and Fig 2, respectively. It is found that the natural frequency of gravity substructure system is located between the rotor frequency range (1P) and the blade passing frequency range (3P). Therefore, the resonance between the wind turbine and the gravity substructure is not occurred.

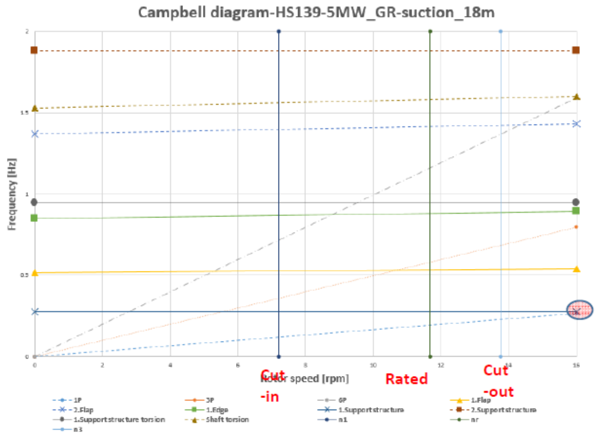


Figure 2: Campbell diagram of gravity substructure.

TABLE V
NATURAL FREQUENCY OF GRAVITY SUBSTRUCTURE

Mode	1	2	3
Frequency (Hz)	0.273	0.946	1.879

E. Structural results

The maximum loads at TP (39m from sea bed), middle part (18.9m from seabed) and seabed part (0m from seabed) obtained from Flex 5 are presented in Table 6, 7 and 8, respectively. The combined stress is concentrated at the connection part. Therefore, this connection part should be examined explicitly for the reliable substructure design. It is found that the ultimate strength of gravity substructure system satisfies ULS design condition for various design load conditions.

TABLE VI
EXTREME MAXIMUM VALUES AT TP

	Fx (MN)	Fy (MN)	Fz (MN)	Mx (MNm)	My (MNm)	Mz (MNm)
Fx (MN)	-1.127	0.318	0.018	0.318	-1.127	-0.2278
Fy (MN)	0.200	1.81	0.0585	1.81	0.2	0.0099
Fz (MN)	-9.879	-8.181	-11.1	-8.181	-9.879	-7.923
Mx (MNm)	0.786	-142.2	1.52	-142.2	0.786	7.0
My (MNm)	-88.1	31.8	11.5	31.8	-88.1	-14.89
Mz (MNm)	-3.602	2.09	1.89	2.09	-3.602	-20.02
Safety factor	1.35	1.1	1.5	1.1	1.35	1.1
Load case	DLC 6.3a	DLC 2.22	DLC 8.1	DLC 2.22	DLC 6.3a	DLC 2.22

TABLE VII
EXTREME MAXIMUM VALUES AT MIDDLE PART

	Fx (MN)	Fy (MN)	Fz (MN)	Mx (MNm)	My (MNm)	Mz (MNm)
Fx (MN)	4.02	-0.0104	0.018	0.318	-0.8875	-0.2254
Fy (MN)	0.263	6.49	-0.066	1.81	0.0222	0.0279
Fz (MN)	-25.19	-27.52	-34.47	-25.31	-30.91	-25.06
Mx (MNm)	-4.828	-72.29	0.579	-178.6	-2.763	6.80
My (MNm)	96.9	2.1	11.8	38.2	-110.1	-19.47
Mz (MNm)	2.55	-1.593	1.89	2.09	-3.605	-20.02
Safety factor	1.1	1.2	1.5	1.1	1.35	1.1
Load case	DLC 6.2a	DLC 1.2	DLC 8.1	DLC 2.22	DLC 6.3a	DLC 2.22

TABLE VIII
EXTREME MAXIMUM VALUES AT SEABED PART

	Fx (MN)	Fy (MN)	Fz (MN)	Mx (MNm)	My (MNm)	Mz (MNm)
Fx (MN)	9.46	-0.0497	0.018	0.128	9.42	0.0228
Fy (MN)	0.473	0.019	-0.8652	18.5	0.467	1.81
Fz (MN)	-66.76	-72.83	-91.14	-72.87	-66.76	-66.62
Mx (MNm)	-11.11	-265.1	-6.36	-285.8	-11.4	-2.769
My (MNm)	202.0	0.939	12.1	19.3	203.0	-22.27
Mz (MNm)	2.58	-3.204	1.95	0.298	2.6	-19.97
Safety factor	1.1	1.2	1.5	1.2	1.1	1.1
Load case	DLC 6.2a	DLC 1.2	DLC 8.1	DLC 1.2	DLC 6.2a	DLC 2.22

III. UNCOUPLED SIMULATION OF GRAVITY SUBSTRUCTURE

A. RNA modelling in uncoupled simulation

In an uncoupled analysis, the RNA is modelled as a point mass at the top of tower as shown in Fig. 3 and Table 9.

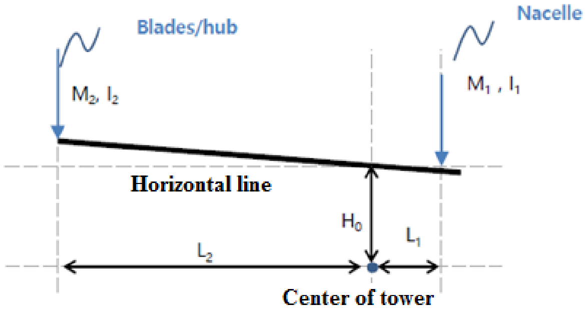


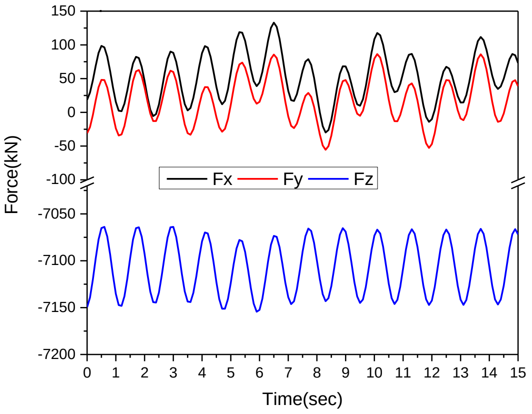
Figure 3: RNA modeling as a point mass at the top of tower.

TABLE IX
DETAIL OF RNA MODELLING

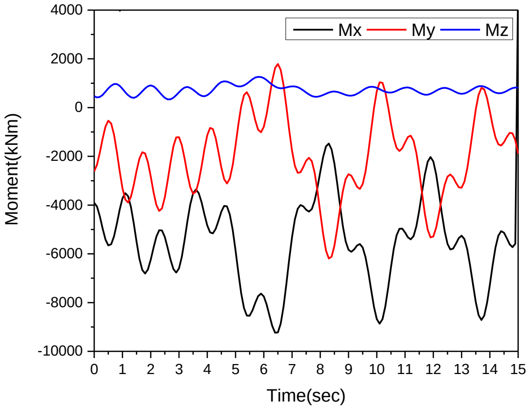
<table>
<tr><th colspan="2">Nacelle mass (M1)</th><th colspan="2">Nacelle inertia (I1: Ix, Iy, Iz)</th><th colspan="2">Blades/Hub mass (M2)</th></tr>
<tr><td colspan="2">290 ton</td><td colspan="2">510/510/253 ton·m^2</td><td colspan="2">138 ton</td></tr>
<tr><th colspan="3">Bladed/Hub inertia (I2: Ix, Iy, Iz)</th><th colspan="3">Distance (H0, L1, L2)</th></tr>
<tr><td colspan="3">13,165/131,365/154 ton·m^2</td><td colspan="3">2.63/0.6/4.76 m</td></tr>
</table>

B. Semi uncoupled and uncoupled simulation

In a semi-uncoupled analysis, the RNA is also modelled as a point mass at the top of tower as shown in Fig.3 and Table 9. The time domain forces and bending moments at transition piece as shown in Fig. 4 are input to the Asas model based on normal turbulent wind simulations conducted in the Flex 5 aero-elastic software with DLC8.1.



(a) Wind forces at TP



(b) Wind moments at TP

Figure 4: Time domain wind loads at TP for DLC8.1.

In an uncoupled analysis, the maximum, minimum and absolute forces and bending moments at transition piece as shown in Table 10 are input to the Asas model as constant values.

TABLE X
EXTREME VALUES AT TP FOR DLC8.1

	Fx	Fy	Fz	Mx	My	Mz
Max	132.8	86.39	-7,063.8	-1,472.9	1,792.12	1,261.4
Min	-29.7	-55.4	-7,154.3	-9,237.3	-6,192.3	337.89
Abs	132.8	86.39	-7154.3	-9,237.3	-6,192.3	1,261.4

The hydrodynamic loads are input to the Asas using the Morison equation with linear regular wave model for all cases. The wave condition is presented in Table 11.

TABLE XI
WAVE CONDITIONS FOR DLC8.1

Wave theory	Wave period	Wave height	Water depth	Cd
Airy	9 sec	2.32 m	21.3 m	0.7
Cm	**Surface current**	**Bottom current**	**Wind direction**	**Wave direction**
1.6	1.07 m/s	0.0 m/s	-30 deg	0 deg

IV. COMPARISON OF FULLY COUPLED AND UNCOUPLED SIMULATION

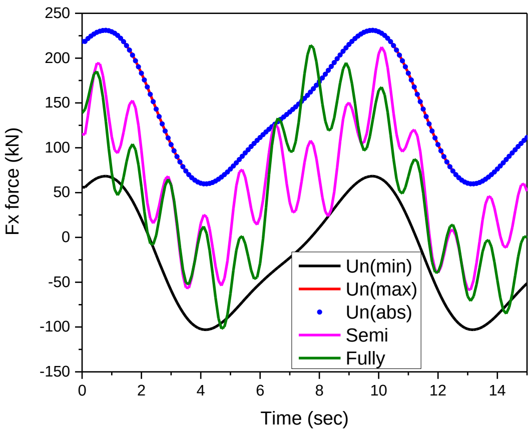
A. Comparison of natural frequency

The comparison of natural frequency between fully coupled and uncoupled model is made in Table 12 to check the uncoupled model. The modal analysis of uncoupled model is carried out through ANSYS Asas with the foundation stiffness obtained from Abaqus software. The difference of the first mode between fully coupled and uncoupled model is about 1.5%. It means that the first natural frequency of uncoupled model is to be within the soft-stiff range between the 1P and 3P frequency ranges, and the resonance between the wind turbine and the uncoupled model is not occurred.

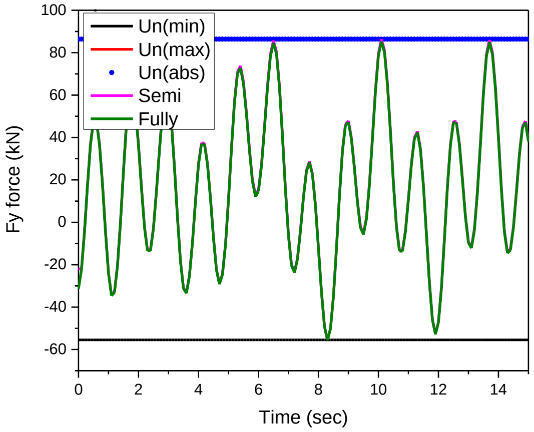
TABLE XII
NATURAL FREQUENCY OF GRAVITY SUBSTRUCTURE

Mode	Flex 5 (Hz)	Asas (Hz)	Difference (%)
1	0.273	0.277	1.50
2	0.946	0.283	-70.06
3	1.876	1.510	-19.59

B. Comparison of structural results



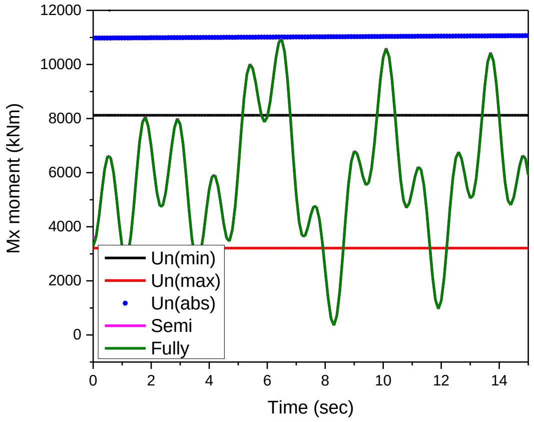
(a) Fx forces



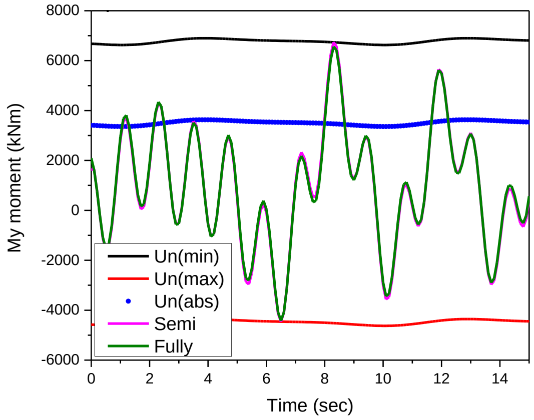
(b) Fy forces

Figure 5: Comparison of forces at the middle part.

Using the wind loads at transition pieces (TP) and the stiffness matrices on suction bucket foundation system, the structural analysis of semi coupled and uncoupled is carried out through ANSYS Asas. The comparisons on various analysis methods such as fully coupled, semi coupled and uncouple are plotted Fig. 5 and Fig. 6, respectively. Since the combined stress is concentrated at the connection part between a circular cylinder and a con cylinder, the comparisons is made at the middle part (18.9m from seabed). The structural results are summarized in Table 13.



(a) Mx moments



(b) My moments

Figure 6: Comparison of moments at the middle part.

TABLE XIII

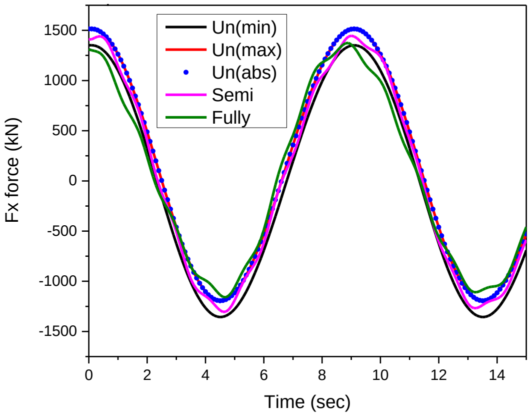
STRUCTURAL RESULTS AT THE MIDDLE PART

		Fx (kN)		Fy (kN)		Mx (kNm)		My (kNm)	
		max	**min**	**max**	**min**	**max**	**min**	**max**	**min**
Fully		214	-101	85	-55	6558	-4424	10924	357
Semi	Val	212	-58	86	-55	6736	-4457	10947	358
	Diff (%)	-0.96	-42.7	1.27	-0.13	2.71	0.75	0.21	0.28
Unco (max)	Val	231	59	86	86	-4354	-4625	3209	3209
	Diff (%)	7.72	158.5	1.27	255.6	166.3	4.54	-70.6	798
Unco (min)	Val	68	-102	-55	-55	6899	6628	8122	8122
	Diff (%)	-68.1	1.09	164	0.13	5.2	249	-25.6	2175
Unco (abs)	Val	231	59	86	86	3630	3359	11064	10974
	Diff (%)	7.72	158	1.27	255	-44.6	175.9	1.28	2973

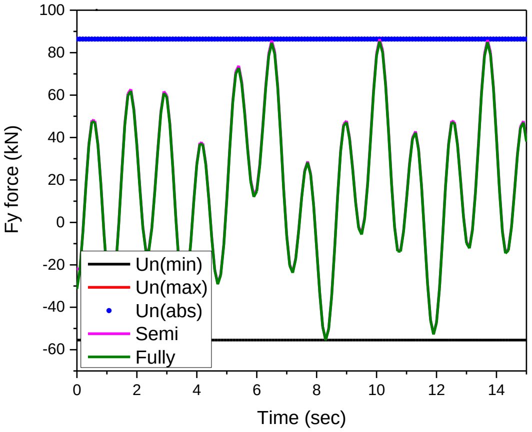
TABLE XIV

STRUCTURAL RESULTS AT THE SEABED PART

		Fx (kN)		Fy (kN)		Mx (kNm)		My (kNm)	
		max	**min**	**max**	**min**	**max**	**min**	**max**	**min**
Fully		1374	-1159	85	-55	11320	-11493	12446	-641
Semi	Val	1446	-1304	86	-55	12820	-14746	12527	-664
	Diff (%)	5.24	12.51	1.27	-0.13	13.25	28.3	0.65	3.59
Unco (max)	Val	1514	-1194	86	86	3373	-18061	4803	4803
	Diff (%)	10.19	3.02	1.27	255.6	-70.2	57.15	-61.4	849.3
Unco (min)	Val	1351	-1356	-55	-55	17627	-3806	7100	7100
	Diff (%)	-1.67	17.0	164	-0.13	55.72	-66.8	42.9	1207
Unco (abs)	Val	1514	-1194	86	86	11358	-10076	12658	12658
	Diff (%)	10.19	3.02	1.27	255	0.34	-12.3	1.7	2060



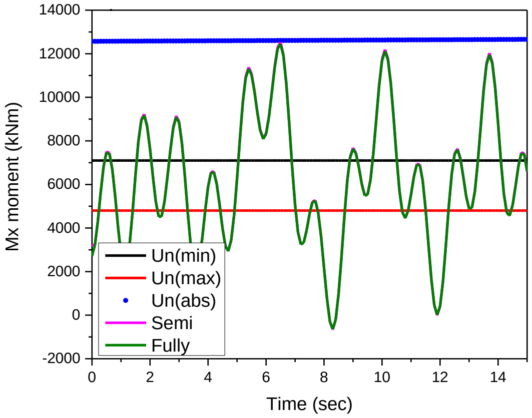
(a) Fx forces



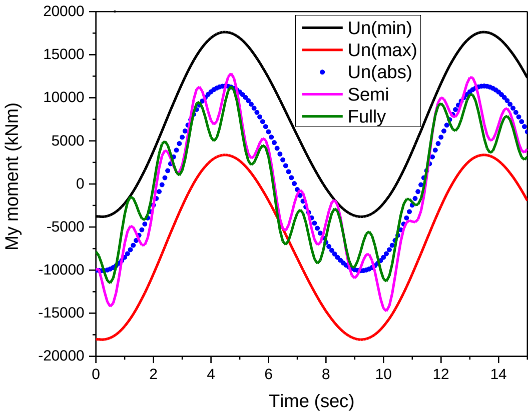
(b) Fy forces

Figure 7: Comparison of forces at the seabed part.

In a semi coupled analysis the pattern of forces and moments are very similar with fully coupled analysis and the difference between semi coupled and fully coupled is remarkably small except for x direction minimum force value (about -42.7%). In an uncoupled analysis the pattern of force and moments are significantly different from fully coupled analysis. The difference of maximum value on forces and moments is small when the three cases such as maximum, minimum and absolute are considered. It means that the three cases have to be considered when the uncoupled analysis performs.



(a) Mx moments



(b) My moments

Figure 8: Comparison of moments at the seabed part.

Since a large offshore wind turbine has a heavy dead load, the reaction forces on the substructure become severe, thus safety evaluation on foundation system should be carried out. The comparisons at the seabed are plotted Fig. 7 and Fig. 8 and the structural results are summarized in Table 14. The pattern of x direction force is very similar with the incident wave pattern and the difference among three analysis cases is small. It means that the foundation system is strongly influenced by wave forces. However, the y direction moment of uncoupled analysis has very different value from fully coupled analysis and the pattern is also different.

It is found that the moment of seabed is closely related with the incident wave force and strongly influenced by the wind moment at TP. Although the maximum difference between semi coupled and fully coupled is about 28.3%, the difference between uncoupled and fully coupled is about 57.15%. It means that the uncoupled analysis method predicts higher extreme forces and moments.

V. CONCLUSION

The computation of the loads on the substructure based on design load cases requires fully coupled aero-hydro-elastic simulations. In the present study the gravity substructure with suction bucket foundation system for 5MW offshore wind turbine is suggested. The Abaqus software is used to calculate the foundation stiffness of suction bucket system on the structure-soil interaction conditions. Using the foundation stiffness, the design of gravity substructure is carried out through the Flex 5 based on the fully coupled aero-hydro-elastic simulations. It is found that the ultimate strength of gravity substructure system satisfies ULS design condition for various design load conditions. To evaluate the difference between the fully coupled analysis and the uncoupled analysis, the comparison of fully coupled and uncoupled simulation method is carried out through the ANSYS Asas. The comparison between fully coupled and the semi coupled analysis shows reasonable match. However the extreme moments on the seabed predicts higher extreme values. The comparison shows clearly that aero-elastic and hydro-elastic coupling can account for at least 28.3% of difference in loading on the gravity substructure when compared to semi coupled analysis.

In an uncoupled analysis the difference of maximum value on forces and moments is small when the three cases such as maximum, minimum and absolute are considered. It means that the three cases have to be considered when the uncoupled analysis performs.

Acknowledgment

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