Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

Comparative study of the influence of kinematic interaction on the seismic response of monopile and jacket supported offshore wind turbines

To cite this article: Carlos Romero-Sánchez *et al* 2024 *J. Phys.: Conf. Ser.* **2647** 112002

View the article online for updates and enhancements.

Journal of Physics: Conference Series **2647** (2024) 112002 doi:10.1088/1742-6596/2647/11/112002

Comparative study of the influence of kinematic interaction on the seismic response of monopile and jacket supported offshore wind turbines

Carlos Romero-Sánchez, Luis A. Padrón, Guillermo M. Álamo, Cristina Medina, Juan J. Aznárez and Orlando Maeso

Instituto Universitario de Sistemas Inteligentes y Aplicaciones Numéricas en Ingeniería, Universidad de Las Palmas de Gran Canaria, Las Palmas de Gran Canaria 35017, Spain

E-mail: {carlos.romero, luis.padron, guillermo.alamo, cristina.medina, juanjose.aznarez, orlando.maeso}@ulpgc.es

Abstract. In the last few years, offshore wind energy has been increasing significantly, being the energetic potential of this technology much higher than that of other renewables energies. Most of Offshore Wind Turbines (OWTs) installed in Europe are founded to the sea floor but, due to the increase in offshore wind turbine installations and the visual impact problem, new locations are being considered with greater depths and increasing seismic risk. In this field, jackets substructures are one of the most attractive options. Despite the low natural frequencies that characterise these systems, the effect of the kinematic interaction can be highly relevant in OWTs on monopiles. For this reason, the need arises to analyse the importance of the influence of kinematic interaction on the seismic responses of multi-supported substructures, such as jackets with deep foundations. This paper presents a comparison of the kinematic interaction effects on the seismic response of two types of substructures for OWTs. OpenFAST is used to analyse the dynamic behaviour of OWTs founded either on monopiles or through jacket substructures on deep foundations, taking soil-structure interaction into account. The comparative study shows that the influence of kinematic interaction in both cases is notably different. As expected, in the case of the monopile, the rotational motion has a strong effect on the accelerations and the internal forces in the structure, although the impact of the translational filtered signal is small. However, in the jacket, the influence of the rotational motion is less pronounced.

1. Introduction

Nowadays offshore wind energy has been increasing significantly, being the energetic potential of this technology much higher than that of other renewables energies. Most of Offshore Wind Turbines (OWTs) installed in Europe are founded to the sea floor but, due to the increase in offshore wind turbine installations and the visual impact problem, new locations are being considered with greater depths and increasing seismic risk. In this field, jackets substructures are one of the most attractive options. Despite the low natural frequencies that characterise these systems, the effect of the kinematic interaction (rotational and horizontal) can be highly relevant in OWTs on monopiles, as pointed out by Kaynia [1]. For this reason, the need arises to analyse the importance of the influence of kinematic interaction on the seismic responses of multi-supported substructures, such as jackets with deep foundations.

Journal of Physics: Conference Series **2647** (2024) 112002 doi:10.1088/1742-6596/2647/11/112002

This paper presents a comparison of the kinematic interaction effects on the seismic response of two types of substructures for OWTs. OpenFAST [2] is used to analyse the dynamic behaviour of OWTs founded either on monopiles or through jacket substructures on deep foundations, taking soil-structure interaction into account.

2. Problem definition

2.1. Reference wind turbines and substructures

The reference wind turbine is the NREL 5 MW three-bladed turbine [3]. Two different substructures are considered in this study to compare the influence of kinematic interaction. The monopile described in the OC3 project [5] and the jacket used in the OC4 project [6] are selected for this study. Table 1 and Figure 1 show the main properties of each substructure.

In addition, steel material properties are considered for the substructures: Young's modulus, 210 GPa, shear modulus, 80.8 GPa, mass density, 8500 kg/m^3 in the monopile, 7850 kg/m^3 in the jacket and damping ratio, 2%. The fundamental frecuencies in the fore-aft direction for parked conditions are 0.300 Hz for the OWT on jacket substructure and 0.259 Hz for the OWT on monopile substructure.

Table 1. Key parameters of the considered substructures.

	Monopile	Jacket
Tower top (H_{top}) [m]	87.6	88.15
Tower base [m]	10	20.15
Water depth (W)[m]	20	50
Substructure height (H_{sub}) [m]	30	70.15
Pile diameter [m]	6.0	2.082
Pile thickness [mm]	60	60
Pile depth [m]	36.0	34.0

2.2. Soil profile

In this study, monopile and piles are assumed to be embedded in a three-layer sandy soil deposit, as described in [5] and in Table 2.

Table 2. Properties of the soil deposit.

	Stratified Soil
Soil profile	layered, sand
Poisson's ratio, ν_s [-]	0.35
Density, ρ_s [kg/m^3]	2000
Shear wave velocity, v_s [m/s]	145.9 ($0 < z < 5$ m)
	175.9 ($5 < z < 9$ m)
	209.0 ($9 < z < \infty$ m)
Damping, $\zeta_s[-]$	0.05

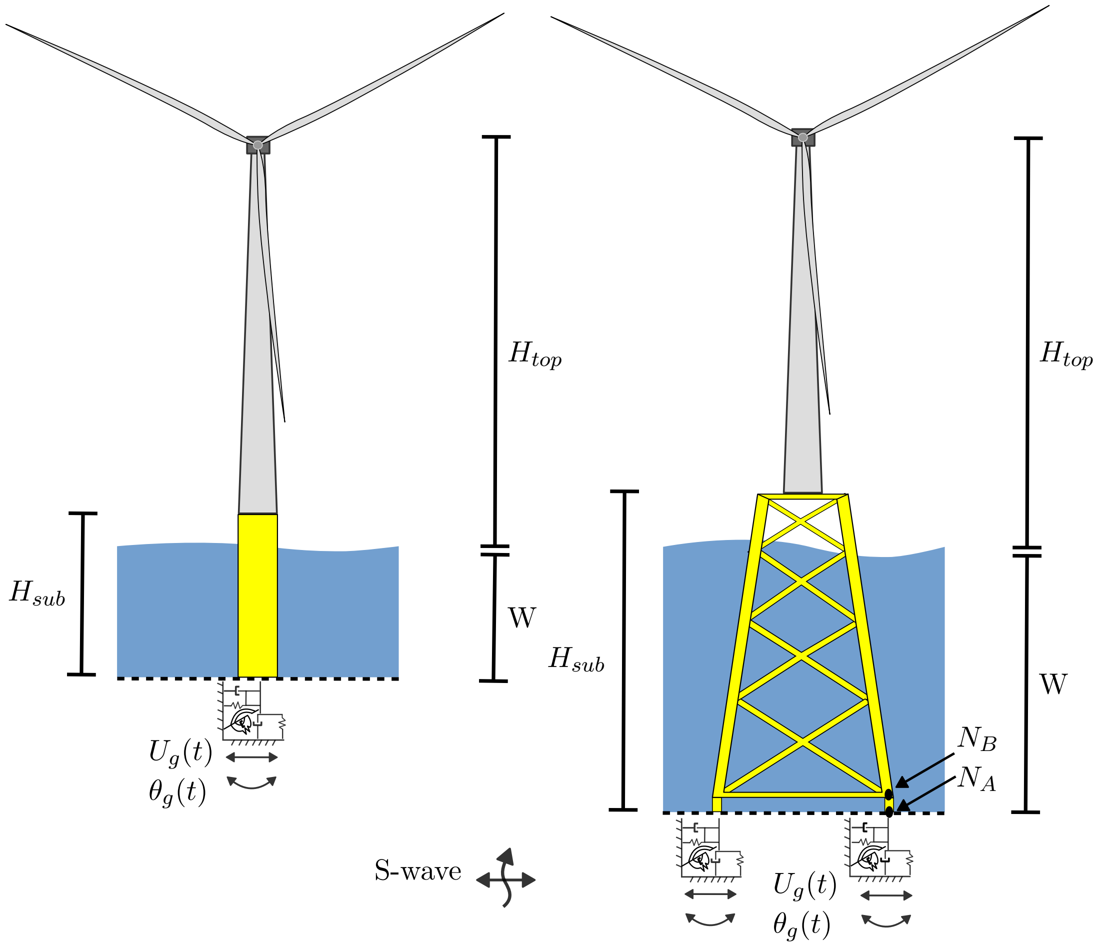

Figure 1. Offshore wind turbine on monopile and jacket support.

2.3. Seismic signals

Different accelerograms have been considered to compare the influence of kinematic interaction on the seismic response of the two proposed systems. In particular, two different acceleration signals extracted from PEER Ground Motion Database [7] are selected. The choice has been made on the basis of stations located over soils with average shear wave velocities in a range close to that of the proposed soil deposit ($V_{s,30}$ = 190-200 m/s). Table 3 shows the selected accelerograms.

Table 3. Main information about the accelerograms [7].

RSN	Dir.(^{o})	Event name	Year	Situation name	$V_{s,30}$(m/s)	a_g(g)
192	180	Imperial Valley-06	1979	Westmorland Fire Station	194	0.11
777	180	Loma Prieta	1989	Hollister City Hall	199	0.22

Figure 2 presents the pseudo-spectral accelerations (PSA) and the accelerograms. This study assumes that these seismic signals, defined at free-field ground surface, are generated by vertically–incident far-field S-waves that produce the seismic shaking in a particular direction. Specifically in this paper, the shaking direction is considered to be aligned with the environmental loads in the fore-aft direction.

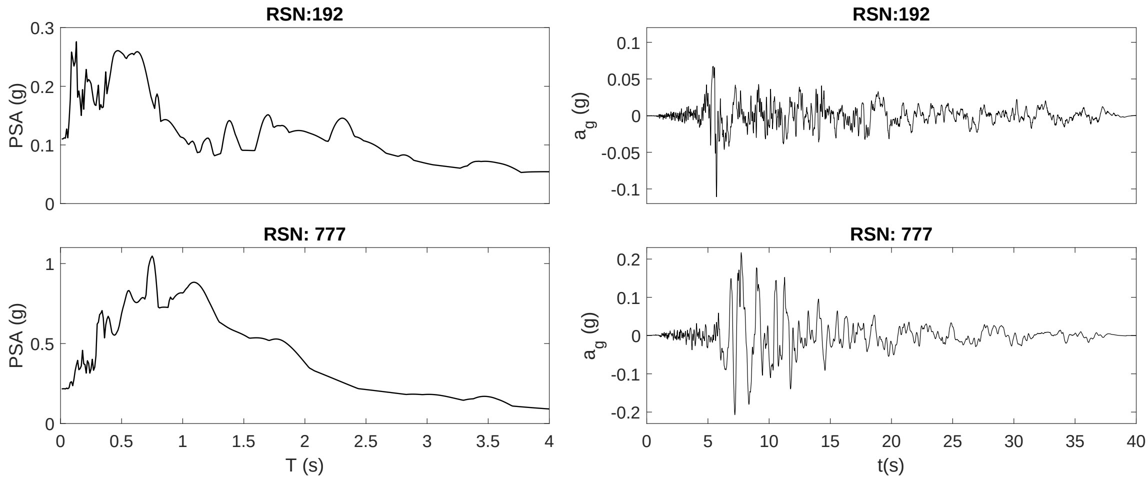

Figure 2. Pseudo-spectral accelerations (PSA) and ground acceleration (a_g) of the seismic signal used.

3. Methodology

Firstly, the numerical model is described in section 3.1. The dynamic response of the offshore wind turbines is modeled using OpenFAST [2], including the impedance of the soil-foundation subsystem and the ground input motion. Section 3.2 describes the model used to compute the impedance and the kinematics factors.

3.1. OpenFAST

The numerical tool used in this paper is based on OpenFAST [2], which is a multi-physics and multi-fidelity tool for simulating the coupled dynamic response of wind turbines, in time domain. It is open-source, programmed in Fortran 95, it is managed by National Renewable Energy Lab and it might be considered not as a single program, but as a framework that couples computational modules. The different modules interact in a loosely coupled time-integration scheme, where a glue-code transfers data among modules at each time step.

The SubDyn module [4] was modified in order to be able to take into account dynamic soil–structure interaction and ground input motion. The module integrates its equations through its own solver. The equation of motion of the substructure is written as:

$$\mathbf{M}\,\ddot{\mathbf{u}}(t) + \mathbf{C}\,\dot{\mathbf{u}}(t) + \mathbf{K}\,\mathbf{u}(t) = \mathbf{F}(t) - \mathbf{M_g}\,\ddot{\mathbf{u}}_\mathbf{g}(t) - \mathbf{C_g}\,\dot{\mathbf{u}}_\mathbf{g}(t) - \mathbf{K_g}\,\mathbf{u_g}(t) \tag{1}$$

where the motion vectors have been partitioned to separate the response quantities from the input. The motions vectors contain two parts: $u(t)$ includes the degrees of freedom of the structure and $u_g(t)$ contains the components of the foundation input motions at each support. The dots represent differentiation with respect to time. The global mass, damping and stiffness matrices have been partitioned accordingly. The expression for the effective seismic loading is obtained by separating the support motion effects from the response quantities and transferring these input terms to right hand side [8]. For more information, the implementation is described in Romero-Sánchez and Padrón [9].

3.2. Computation of impedances and kinematic interaction factors

The soil-foundation system response is modelled through impedance functions and kinematic interaction factors computed with a continuum model [10] for the dynamic analysis of pile foundations. Thus, linear-elastic behavior is assumed for the whole soil-foundation-structure system. OpenFAST is a nonlinear aero-hydro-servo code for the simulation of wind turbines in the time domain. In order to be able to introduce the soil-foundation impedance functions in the OpenFAST model, Lumped Parameter Models [11] are fitted and implemented. More information related to the introduction of this model into SubDyn can be found in [12]. The resulting LPM is introduced in the finite elements model of the substructure as an additional element at mudline level. The LPM configuration allows to model and fit simultaneously the traslational, rotational and horizontal-rocking coupled impedance functions, while the spring-damper model is adopted for vertical and torsional vibrations.

The lateral I_u and rotational I_θ kinematic interaction factors quantify the filtering effect due to the presence of the pile in the soil in terms of the ratio between the pile head displacement or rotation with respect to the free-field motion. To obtain these parameters, a single pile (without superstructure) subjected to an incident S-wave is considered. Once the kinematic interaction factors are obtained, in the frequency domain, the seismic signal is filtered.

4. Results

In order to understand the influence of kinematic interaction on the seismic response of monopile and jacket supported offshore wind turbines, the response of the turbines is simulated as operating in power production. The environmental loads are described in the reference projects [5, 6]. The arrival time of the earthquake ocurrs at t=200 s, and each case is simulated during 300 s. The results are analysed since the arrival of the earthquake until the end of the simulation. The time duration of the earthquakes is described in Figure 3. In all cases, all the forces (wind, waves and seismic loading) are aligned in the fore-aft direction.

Three different cases are considered, as described in the results: a) taking into account both translational and rotational foundation input motions (With KI); b) taking into account only translational foundation input motions (Only I_u); and c) considering the original seismic input motion as translational input motion (Without KI).

4.1. Tower top accelerations

Figure 3 shows the time histories of the tower top acceleration for the 5MW OWT founded on soil profile and subjected to the environmental conditions and the seismic input signals considered in this study. The figure presents the acceleration of the top tower (a_{top}) versus time (t). Each line in the figure represents the acceleration of the tower top in the three different cases considered in the study, also the accelerogram is shown.

In both systems, in this specific case, when only lateral kinematic interaction factor is considered, no significant increases are observed in the acceleration of the top tower. The relevant role of the rotational kinematic interaction factors is appreciated in the monopiled system. In the OWT on the jacket substructure, rotational KIF is noticiable, but not very relevant in terms of accelerations. On the other hand, the rotational kinematic interaction factor is clearly more relevant in the RSN:192 earthquake compared to the RSN:777.

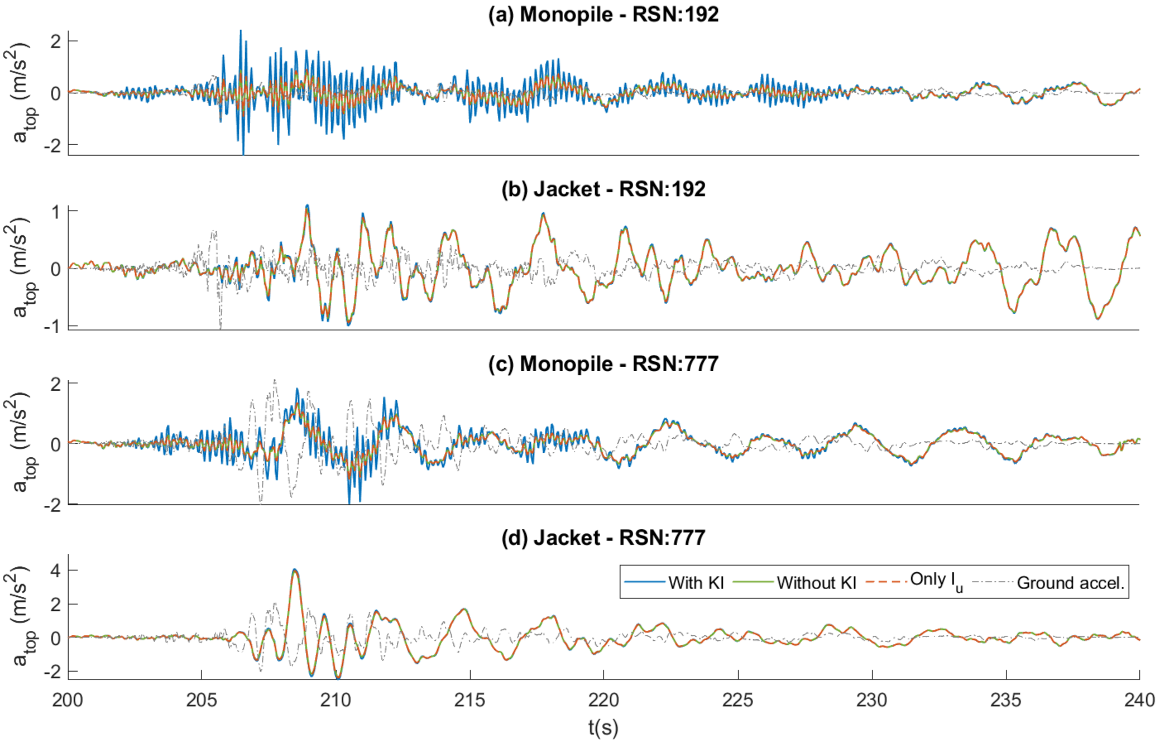

Figure 3. Time histories of the tower top acceleration for the two substructures, monopile and jacket, subjected to the two seismic signals and environmental conditions.

4.2. Internal forces in the substructures

The bending moments obtained in the substructure of the two systems considered in this study reach their maximum value at the mudline level, for both the monopile and the jacket. Furthermore, shear forces are also analised. In the case of the monopile substructure the node studied is at the mudline level and in the jacket, the internal forces in two different nodes are obtained. N_A and N_B, at the mudline level and the node immediately above it, respectively. These nodes are marked in Figure 1.

Figures 4 and 5 present the response of the systems in terms of shear forces and bending moments, respectively. In both figures, the time history presented for the jacket is at the point N_A.

An important role of the rotational kinematic interaction factors is appreciated in the monopile substructure in terms of shear forces. In the OWT on jacket substructure, the influence of the rotational KIF is appreciable in the peak values of shear forces, although considerably less than in the monopile. When considering only lateral KIF, the influence on the seismic response is not very relevant, the behaviour is similar to that obtained for accelerations.

In the case of bending moments, the increase produced in the peak value when comparing the response between taking into account, or disregarding, kinematic interaction, is lower than the values obtained for the accelerations and shear forces. In spite of this, a greater influence of KIFs in terms of internal forces is observed in the monopile compared to the jacket.

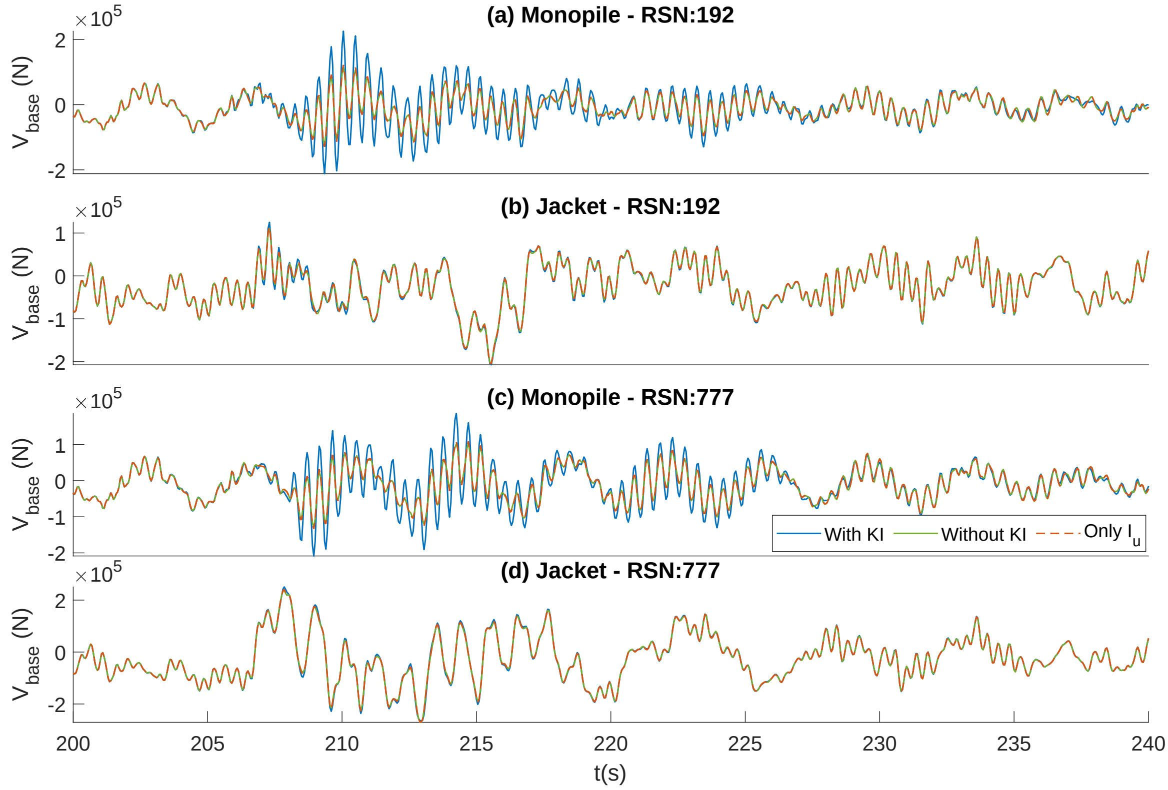

Figure 4. Time histories of the shear forces at mudline level for the two substructures, monopile and jacket, subjected to the two seismic signal and environmental conditions.

4.3. Discussion

Table 4 and 5 present the peak values of the accelerations at the tower top, and the peak values of shear forces and bending moments at selected sections, respectively, when both traslational and rotational kinematic interaction factors are considered. In the case of the monopile, the internal forces at mudline level are obtained while nodes N_A and N_B are considered for the jacket substructure. The differences between the responses computed taking into account (R_{KI}), or disregarding (R_{NOKI}), kinematic interaction, are also presented in both tables for accelerations (Δa_{KI}), shear forces (ΔV_{KI}) and bending moments (ΔM_{KI}). The equation (2) is used to compute these porcentages, where R represents the peak values.

Table 4. Peak accelerations at tower top obtained in the cases considered with the kinematic interaction.

Case	a_{top} [m/s^2]	Δa_{KI} [%]
M - RSN: 192	2.43	176.67
M - RSN: 777	2.01	52.46
J - RSN: 192	1.12	5.70
J - RSN: 777	4.09	3.91

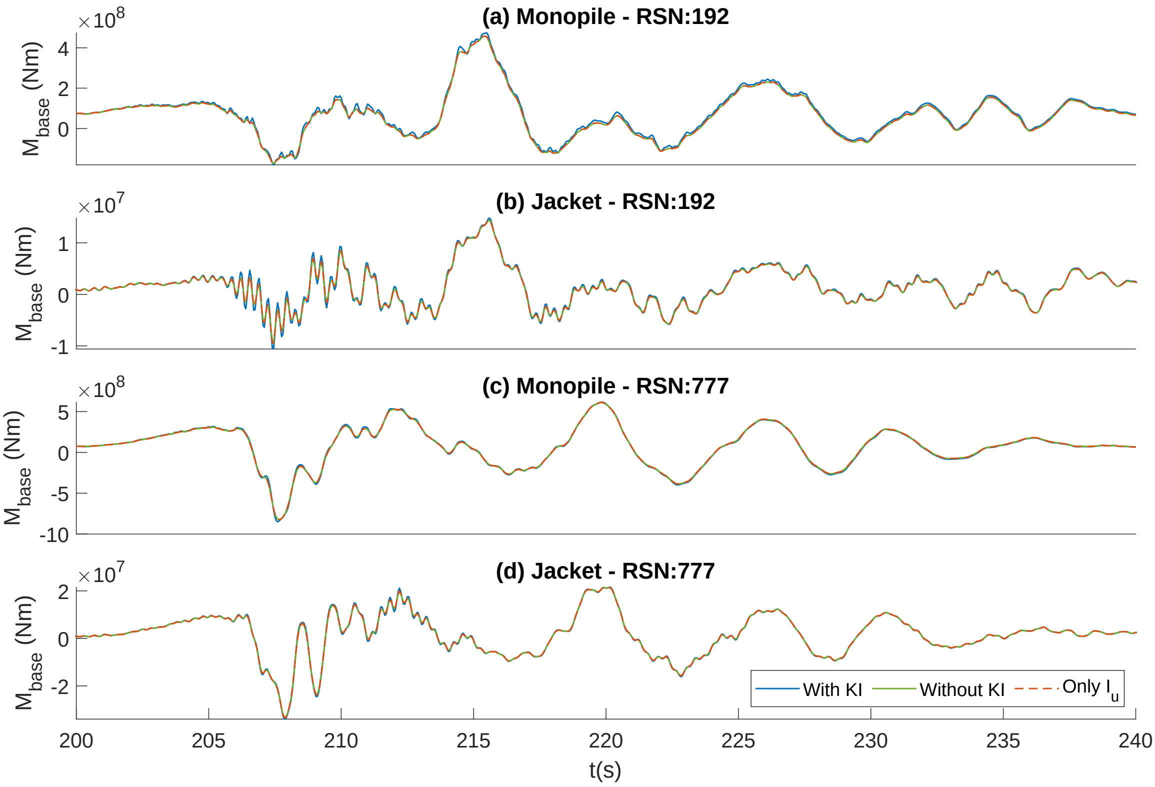

Figure 5. Time histores of the bending moments at mudline level for the two substructures, monopile and jacket, subjected to the two seismic signal and environmental conditions.

Table 5. Peaks shear forces and bending moments obtained in the cases considered with the kinematic interaction.

Case	V_{max}[MN]	M_{max}[MNm]	ΔV_{KI} [%]	ΔM_{KI} [%]
M - RSN: 192	0.225	473.93	81.32	6.22
M - RSN: 777	0.209	849.44	63.2	4.48
J - RSN: 192 (N_A)	0.303	14.82	3.88	2.46
J - RSN: 777 (N_A)	0.206	34.37	2.39	2.65
J - RSN: 192 (N_B)	0.299	13.64	6.81	2.39
J - RSN: 777 (N_B)	0.202	31.60	2.59	2.19

$$\Delta R_{KI} = \frac{R_{KI} - R_{NOKI}}{R_{KI}} \times 100 \quad (2)$$

When taking kinematic interaction factors into account, significantly higher values are obtained in terms of accelerations and shear forces, in the case of the monopile. In addition, the increase in peak values of the bending moment is higher than in the jacket. This indicates that the influence of kinematic factors in the case of an OWT on a monopile is very relevant.

On the other hand, the influence of KIFs in the peak values obtained in the jacket is much lower than those obtained in the monopile, being less than 10% in the accelerations and the internal forces considered.

5. Conclusions

The comparison of the influence of kinematic interaction on the seismic response of the two systems studied presents a notable difference. Results are presented in terms of peak response values of the tower top accelerations, shear forces and bending moments at the mudline level. In addition, another node of the legs is analysed in the jacket substructure. Each seismic signal is filtered to obtain three different scenarios: taking both traslational and rotational kinematic interaction factors into account; taking only the traslational kinematic interaction factor into account; or disregarding kinematic interaction completely. Environmental loads under normal operation conditions are considered to be aligned with the seismic excitation.

As expected, in the case of the monopile, the rotational motion has a strong effect on the accelerations and the shear forces, although the impact of the translational filtered signal is small. In the case of bending moments, the differences between the responses computed taking into account, or disregarding, kinematic interaction is significantly lower than for accelerations and shear forces.

However, in the jacket, the influence of the rotational motion is less pronounced. Considering the kinematic interaction factors in this type of substructure produces a light increase in the accelerations and the internal forces considered, but with a considerably smaller importance than in an OWT on a monopile.

Acknowledgments

This research was funded by Consejería de Economía, Conocimiento y Empleo (Agencia Canaria de la Investigación, Innovación y Sociedad de la Información) of the Gobierno de Canarias and FEDER through research project ProID2020010025 and by the Ministerio de Ciencia, Innovación y Universidades and the Agencia Estatal de Investigación of Spain, and FEDER, through research project PID2020-120102RB-I00. In addition, C. Romero-Sánchez is a recipient of the research fellowship (TESIS2022010011), from the Program of predoctoral fellowships from the Consejería de Economía, Conocimiento y Empleo (Agencia Canaria de la Investigación, Innovación y Sociedad de la Información) of the Gobierno de Canarias and Fondo Social Europeo. The authors are grateful for this support.

References

[1] Kaynia AM 2020 Effect of kinematic interaction on seismic response of offshore wind turbines on monopiles *Earthquake Engineering* & *Structural Dynamics* **50** 777-790.

[2] OpenFAST Documentation, National Renewable Energy Laboratory (version 3.4.0, February 12, 2023). Updates and new releases of OpenFAST can be found on `https://github.com/OpenFAST/openfast` and `https://openfast.readthedocs.io/en/main/`.

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

[4] Damiani R, Jonkman J, and Hayman G 2015 SubDyn user's guide and theory manual *Technical Report NREL/TP-5000-63062 National Renewable Energy Laboratory.*

[5] Jonkman J and Musial W 2010 Offshore Code Comparison Collaboration (OC3) for IEA Task 23 Offshore Wind Technology and Deployment *Technical Report NREL/TP-5000-48191 National Renewable Energy Laboratory.*

[6] Popko W et al. 2014 Offshore Code Comparison Collaboration Continuation (OC4), Phase I-Results of Coupled Simulations of an Offshore Wind Turbine with Jacket Support Structure *Journal of Ocean and Wind Energy* **1** 1-11.

[7] Pacific Earthquake Engineering Research Center (PEER, February 20, 2023). NGA-West2 Ground Motion Database can be found on `http://ngawest2.berkeley.edu/`.

Journal of Physics: Conference Series **2647** (2024) 112002 doi:10.1088/1742-6596/2647/11/112002

[8] Clough RM and Penzien J 1995 Dynamics of Structures *3th edition Computers & Structures, Inc.*

[9] Romero-Sánchez C and Padrón LA 2023 An implementation of multi-support input motion into openfast for the earthquake analysis of offshore wind turbines. *9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering* (Athens: COMPDYN 2023).

[10] Álamo GM, Bordón JDR and Aznárez JJ 2021 On the application of the beam model for linear dynamic analysis of pile and suction caisson foundations for offshore wind turbines *Comp. Geotech* **134** 104107.

[11] Carbonari S, Morici M, Dezi F and Leoni G 2018 A lumped parameter model for time-domain inertial soil-structure interaction analysis of structures on pile foundations *Earthquake Engineering* & *Structural Dynamics* **47** 2147-2171.

[12] Romero-Sánchez C and Padrón LA 2022 Implementation of Ground Input Motion and Dynamic Soil-Structure Interaction into Openfast for the Seismic Analysis of Offshore Wind Turbines *Congress on Numerical Methods in Engineering* (Las Palmas de Gran Canaria: CMN 2022) 337-356.