Seismic response of monopile-supported offshore wind turbines embedded in different seabed profiles including dynamic soil-structure interaction

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ABSTRACT

Due to offshore wind power energy expansion in recent years, seismic analysis of offshore wind turbines (OWTs) has become a relevant factor to consider. Recent recommended practices (such as DNV-RP-0585 "Seismic design of wind power plants" [1]) and many earthquake studies have been published recently. Although most of these works are focused on analysing the effects of soil-structure interaction (SSI, e.g. [2, 3]), other aspects such as the seabed profile typology on which they are founded, or the influence of kinematic interaction (KI) within SSI on the seismic response of this type of structures, have not yet been addressed in detail. For this reason, this work aims to study the seismic structural response of four monopile-supported OWTs embedded in different seabed profiles, including SSI effects and analysing KI contribution on it. The effects of the soil profile on the seismic response are studied by considering one homogeneous and two non-homogeneous soil profiles with equivalent shear-wave velocities. The system response is quantified in terms of maximum bending moments and acceleration amplification factors, which are computed by using a finite element substructuring model in frequency domain, the foundation behaviour is obtained by a continuum model including kinematic and inertial interaction. The results show that the differences between homogenous and variable-with-depth soils arise mainly from the rotational KI factor. However, the largest responses are obtained when SSI effects and the equivalent homogeneous soil profile are considered, justifying the use of homogeneous soils in the initial design stages of this type of structures.

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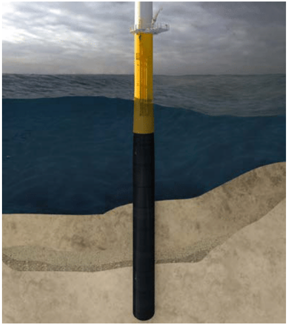
Introduction

- Broad growth of offshore wind technology in recent years, developing:
  - Larger offshore wind turbines (OWT).
  - More competent bottom-fixed foundations. (Predominance of monopiles).
- Seismic analysis of OWTs has become a relevant factor to consider, emerging:
  - New recommended practices (DNV-RP-0585).
  - Earthquake studies



Objectives

Objectives

To study the seismic response of monopile-supported OWTs embedded in different seabed profiles, including soil-structure interaction (SSI) effects and analysing kinematic interaction (KI) contribution on it.

Methodology

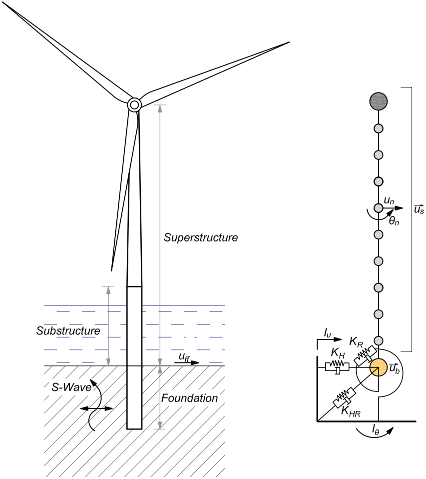
Finite element substructuring model

Finite element substructure model

- **1 - Superstructure model**
  - Finite element method (FEM)
- **2 - Foundation model**
  - Impedance functions
  - Kinematic Interaction (KI) factors
- **3 - Frequency Domain Method**

Seismic excitation

Planar S vertical wave

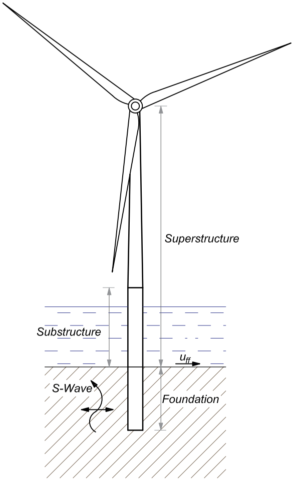


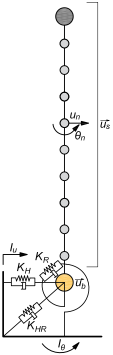
Methodology

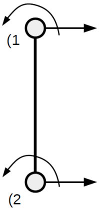
Finite element substructuring model

Superstructure modelling

- Bernoulli's beam finite elements with distributed inertial properties
- Lateral behaviour
- Mass of the rotor-nacelle assembly as a punctual mass at the top node
- Hysteretic damping







Methodology

Finite element substructuring model

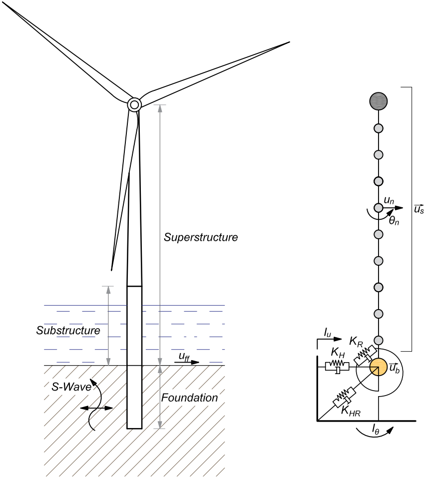
Foundation modelling

- Impedance functions to model the foundation-soil stiffness and damping:

$$K_{SSI}(\omega) = \begin{bmatrix} K_H(\omega) & K_{HR}(\omega) \\ K_{RH}(\omega) & K_R(\omega) \end{bmatrix}$$

- Kinematic Interaction (KI) factors to model the filtering of the ground motion produced by the foundation:

$$\vec{I}_{SSI}(\omega) = \begin{Bmatrix} I_u(\omega) \\ I_\theta(\omega) \end{Bmatrix} = \begin{Bmatrix} \frac{u_p(\omega)}{u_{ff}} \\ \frac{\theta_p(\omega)}{u_{ff}} \end{Bmatrix}$$



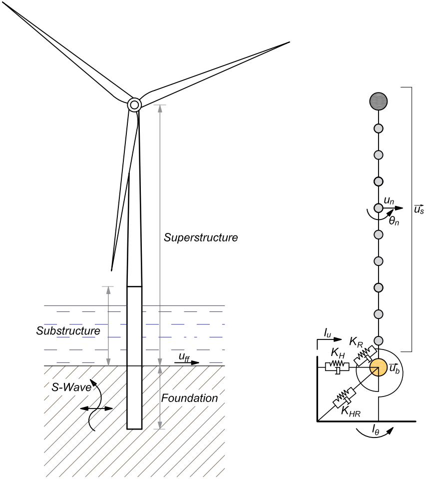
Methodology

Finite element substructuring model

Foundation modelling

Five different foundation models:

- **Rigid base** assumption
- Four flexible base models:
    - **With KI**: $\vec{I}_{SSI}(\omega) = \begin{Bmatrix} I_u(\omega) \\ I_\theta(\omega) \end{Bmatrix}$
    - **Without KI**: $\vec{I}_{SSI}(\omega) = \begin{Bmatrix} 1 \\ 0 \end{Bmatrix}$
    - I_u **contribution**: $\vec{I}_{SSI}(\omega) = \begin{Bmatrix} I_u(\omega) \\ 0 \end{Bmatrix}$
    - I_θ **contribution**: $\vec{I}_{SSI}(\omega) = \begin{Bmatrix} 0 \\ I_\theta(\omega) \end{Bmatrix}$



Methodology

Finite element substructuring model

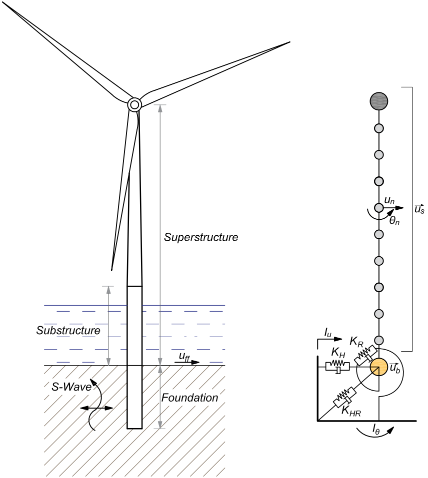
Coupled system response

$$(K_s(\omega) - \omega^2 M_s)\vec{u}_s(\omega) = \vec{F}_s(\omega)$$

$$\vec{f}_e(\omega) = (K_e^* - \omega^2 M_e)\vec{u}_e(\omega)$$

Frequency domain method ⟶ Time domain response

- Maximum bending moments and shear forces (mudline level)
- Maximum relevant accelerations (hub height)



Problem definition

OWT properties

Table: *Main characteristics of the OWTs and its monopiles*

OWT	5 MW	8 MW	10 MW	15 MW
Rotor-Nacelle-Assembly mass (t)	350	480	674	1017
Tower height (m)	90	110	119	135
Rotor diameter (m)	126	164	178.3	240
Rated wind speed (m/s)	11.4	12.5	11.4	10.59
Cut-out wind speed (m/s)	25	25	25	25
Rotor operational speed range (rpm)	6.9-12.1	6.3-10.5	6-9.6	5-7.56
Tower top diameter (m)	3.87	5	5.5	6.5
Tower bottom diameter (m)	6	7.7	8.3	10
Tower top thickness (m)	0.019	0.022	0.020	0.024
Tower bottom thickness (m)	0.027	0.036	0.038	0.041
Pile diameter (m)	6.04	7.70	8.30	10.00
Pile thickness (m)	0.067	0.084	0.090	0.107
Pile length over mudline (m)	32.6	32.6	32.6	32.6
Pile embedded length (m)	49.7	60.1	63.8	73.8

- Material: S355 Structural Steel.

Problem definition

Soil properties

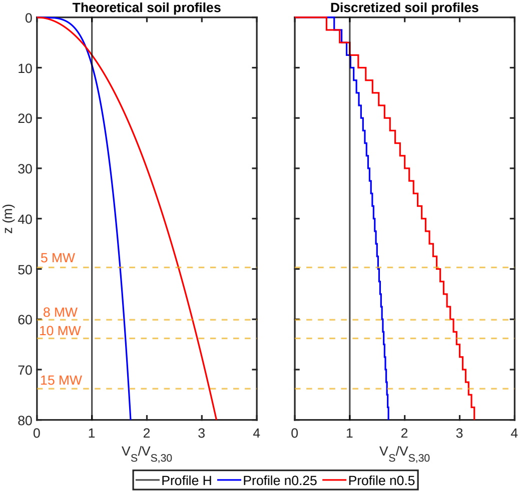
Table: *Soil profiles*

Profiles	n
Homogeneous	
Non-homogeneous ($n = 0.25$)	0.25
Non-homogeneous ($n = 0.5$)	0.5

Table: *Soil properties*

Properties	**Value**
Density $[\rho_s](\mathrm{kg/m^3})$	2000
Poisson's ratio $[\nu_s]$	0.49
Hysteretic damping (%)	2.5
Shear wave velocity $[V_{S,30}]$ (m/s)	**100:25:300**

$$V_S(z) = \frac{V_{S,30}}{30^n(1-n)} z^n$$



Problem definition

Seismic excitations

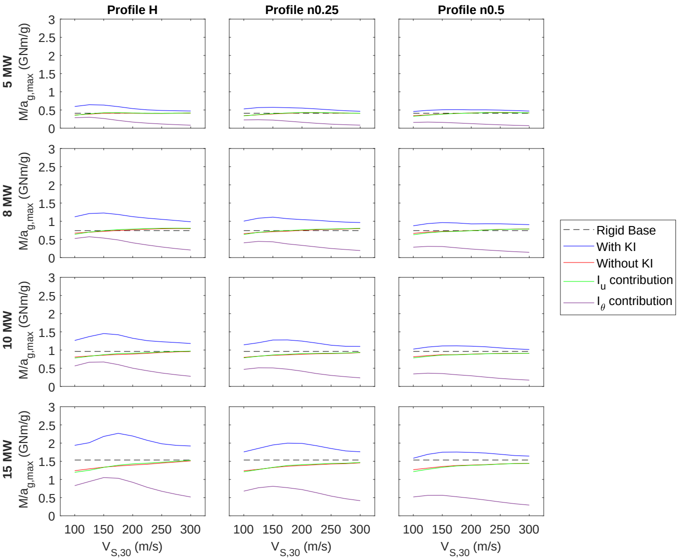
Table: *Information about the seismic signals (accelerograms) used in this work.*

RSN	**Dir.(º)**	**Event Name**	**Year**	**Station Name**	$V_{S,30}$**(m/s)**	$a_{g,max}$ **(g)**
186	90	Imperial Valley-06	1979	Niland Fire Station	212	0.11
266	102	Victoria Mexico	1980	Chihuahua	242	0.15
729	0	Superstition Hills-02	1987	Imperial Valley W.L.A	179	0.21
1176	60	Kocaeli Turkey	1999	Yarimca	297	0.23
1498	59	Chi-Chi Taiwan	1999	TCU059	273	0.16
1792	90	Hector Mine	1999	Indio-Riverside C.F.G	282	0.12
2715	47	Chi-Chi Taiwan-04	1999	CHY047	170	0.13
3683	11	Taiwan SMART1(45)	1986	SMART1 O11	295	0.13
3965	8	Tottori Japan	2000	TTR008	139	0.32
5666	7	Iwate Japan	2008	MYG007	167	0.13

- Scaled response with respect to the $a_{g,max}$.
- Average of the maximum responses of the ten seismic signals.

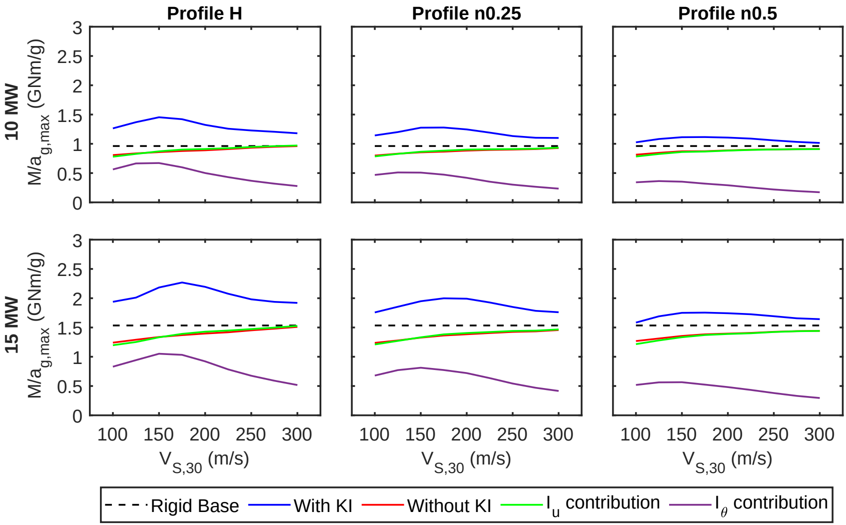
Results

Maximum seismic response - Bending moments



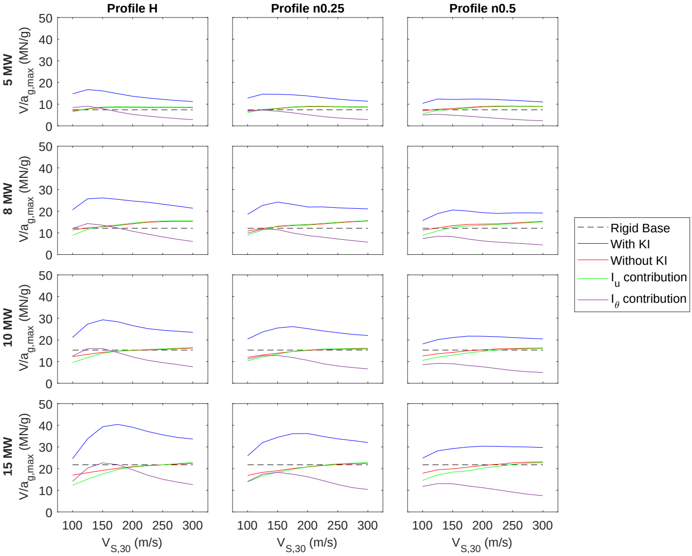
Results

Maximum seismic response - Bending moments



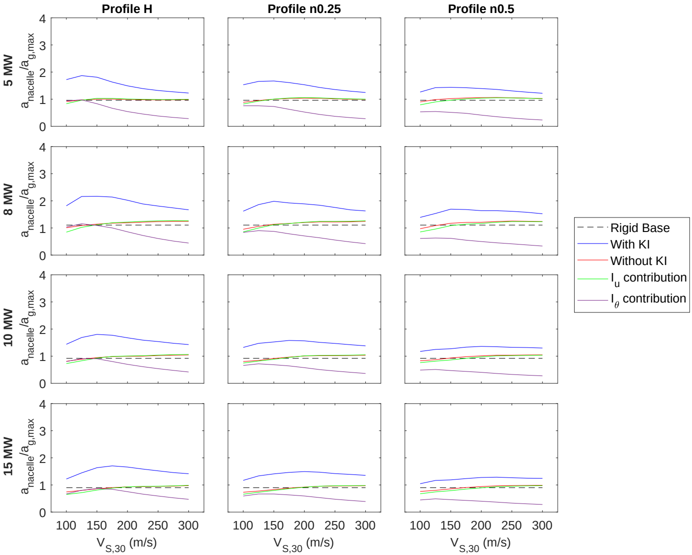
Results

Maximum seismic response - Shear Forces



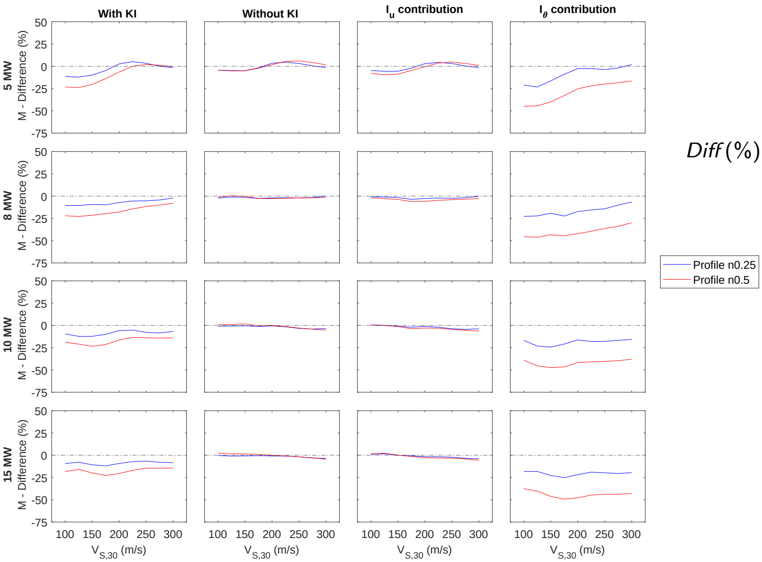
Results

Maximum seismic response - Accelerations



Results

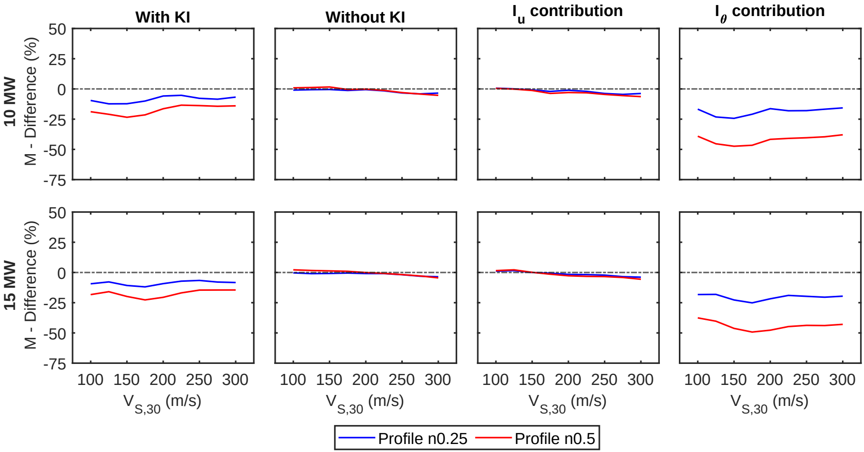
Relative differences between soil profiles - Bending Moments



$$Diff\,(\%) = \frac{X_n - X_H}{X_H}$$

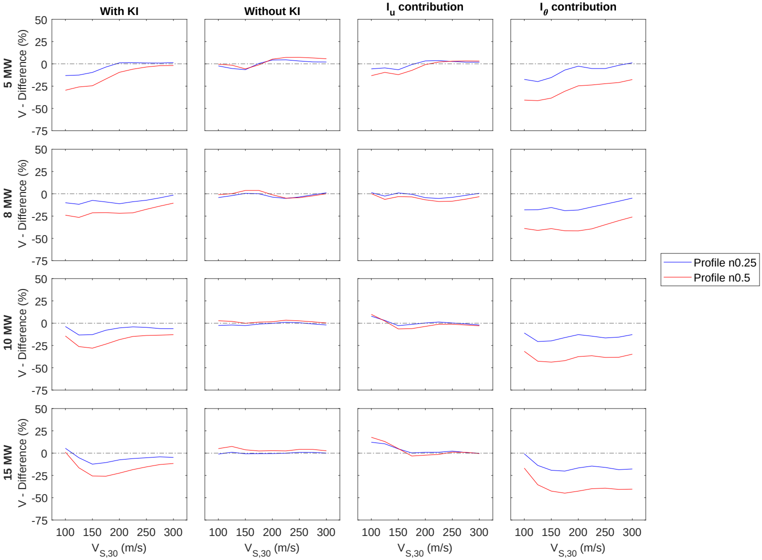
Results

Relative differences between soil profiles - Bending Moments



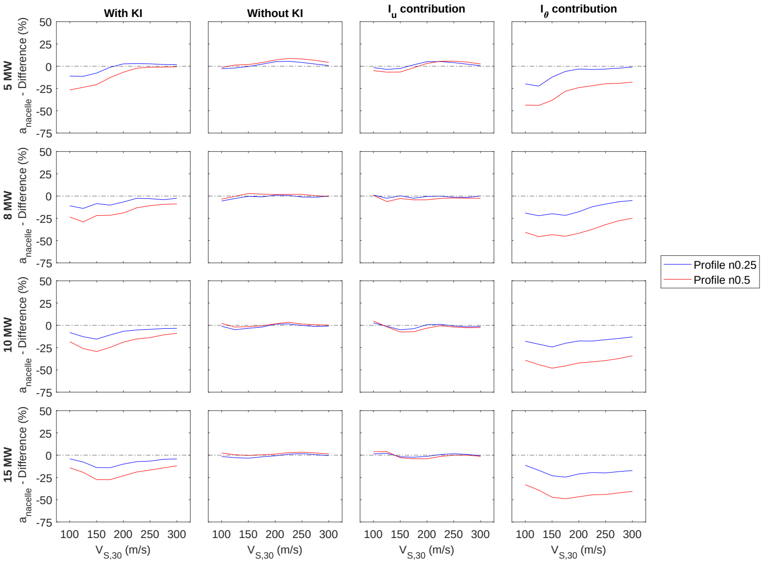
Results

Relative differences between soil profiles - Shear Forces



Results

Relative differences between soil profiles - Accelerations



Conclusions

This work studies the seismic response of different monopile-supported OWTs embedded in different seabed profiles, analysing the SSI effects and the contribution of each KI factor on it.

- Highest seismic responses are obtained when both the inertial and kinematic soil-structure interaction are considered.
- Results show a significant dependence of the soil profile when the rotational kinematic interaction is contemplated.
- Conservative results are obtained when a homogeneous soil profile is considered.

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