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ABSTRACTS
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Simplified model to calculate the envelopes of bending moments along offshore wind turbines on monopiles

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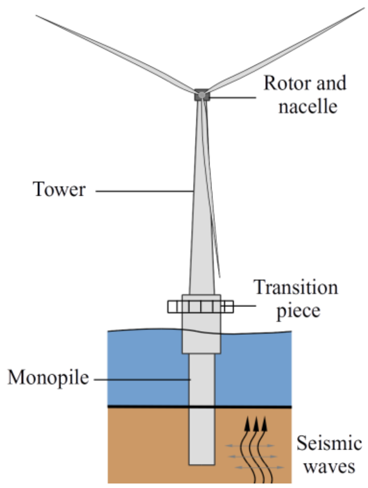
1. Introduction – Against the high computational costs necessary to solve the soil-structure interaction problems rigorously, a simplified model applied to offshore wind turbines on monopiles is proposed. The Bernoulli beam is used in this model and the interaction with the soil is represented by the Winkler model. The proposed model is used to calculate the envelopes of bending moments on commercial wind turbines with known properties against seismic forces, being the results contrasted with rigorous methods. The obtained results allow analysing three different terms:

a) From the structure (which is above the soil), the effects of the foundation on the response (soil-structure interaction effects).
b) From the foundation, the effects of the structure on the response.
c) From the soil, the effects of the variable profile on the response.



2. Methodology - To define the structure and pile foundation, the model uses the analytic solution of the Bernoulli beam, obtained by the equation:

$$\frac{d}{dx^2}\left(EI(x)\,\frac{d^2u(x)}{dx^2}\right) - \rho\, A(x)\, w^2\, u(x) = p(x) \qquad (1)$$

Where $EI(x)$ represents the product of the Young's modulus and the moment of inertia of the section, ρ the density of the material, $A(x)$ the area of the section, w the angular frecuency, $p(x)$ the external force on the section and x the longitudinal coordinates along the whole structure.

In this problem, there are three different parts that must satisfy this equation, but each one has some particularities that simplify it:

a) For the tower, with variable section and no external forces, the equation (1) must be transformed in order to be solved (see e.g. M.H. Taha and S. Abohadima [1]):

$$EI_{bot}\,\frac{d}{dx^2}\left(\left(1-\alpha\frac{x}{L}\right)^{n+2}\frac{d^2u(x)}{dx^2}\right) - \rho\, A_{bot}\left(1-\alpha\frac{x}{L}\right)^{n} w^2\, u(x) = 0 \qquad (2)$$

Where α represents the relation between the properties of the top and the bottom of the beam and n represents the degree of the polynomial function which describes the variation of the area along the beam. In this problem, the variation of the moment of inertia along the beam is described as a polynomial function with a degree two orders higher than the area variation.

b) For the part of pile which is above the soil, with constant section and no external forces, the equation (1) is reduced to:

$$EI\,\frac{d^4u(x)}{dx^4} - \rho\, A\, w^2\, u(x) = 0 \tag{3}$$

c) For the part of pile which is embedded in the soil, with constant section and external forces related to the interaction with the soil, the equation (1) is reduced to:

$$EI\,\frac{d^4u(x)}{dx^4} + (k - \rho\, A\, w^2)\, u(x) = k\, u_i(x) \tag{4}$$

Where, k represents the impedance provided by the soil, whose value is obtained by the impedance functions from Novak et al.[2]; and $u_i(x)$ are the displacements of the incident field.

To consider the interaction of the structure with the water, its effect is simplified as an additional mass applied in the section submerged.

To completely define the problem, it's necessary to determine the boundary conditions of each beam. On the top of the tower it is necessary to consider the effect of the mass of the rotor and nacelle:

$$Q(H) + w^2\, M_{RNA}\, u(H) = 0 \tag{5a}$$

$$M(H) = 0 \tag{5b}$$

Between each part, the conditions of continuity are:

$$u^i(H_i) = u^j(0) \tag{6a}$$

$$\theta^i(H_i) = \theta^j(0) \tag{6b}$$

$$Q^i(H_i) = Q^j(0) \tag{6c}$$

$$M^i(H_i) = M^j(0) \tag{6d}$$

At the bottom of the pile, the free tip conditions are considered:

$$Q\left(-H_p\right) = 0 \tag{7a}$$

$$M\left(-H_p\right) = 0 \tag{7b}$$

To analyse the effects that the structure and the embedded pile induce on the other one, it is necessary to study the problem of each part separately. In case of the structure, the base is assumed to be rigidly attached to soil.

$$u(0) = u_i(0) \tag{8a}$$

$$\theta(0) = 0 \tag{8b}$$

In case of the pile, free displacement and fixed rotation are considered.

$$Q(0) = 0 \tag{9a}$$

$$\theta(0) = 0 \tag{9b}$$

As linear behaviour is assumed for soil and structure, the problem is solved in the frequency domain, using the Fourier Transform to know the frequency properties of the seismic excitation and the Inverse Fourier Transform to compute the real bending moments on the structure.

3. Results and Discussion – By this model, two different length OWTs founded on a homogeneous soil and a two-layered soil are calculated. The properties are extracted from the work of Lombardi [3] and correspond to data from different wind farms in the UK.

Table 3 Properties of Offshore Wind Turbines

OWT Id.		1	2
$M_{RNA\ (t)}$		80	80
Tower length (m)		60	78
Pile length (m)	Submerged	11	11
	Embedded	15	15
D_{top} (m)		2.3	2.3
D_{bot} (m)		4.2	4.2
δ_t (%)		98	98
D_p (m)		3.5	3.5
δ_p (%)		97.4	97.4

Related with Table 1, M_{RNA} represents the punctual mass of the rotor and nacelle, while δ is the relation between the external and internal diameter of the tubular structure.

For both structures, the tower and the piles are made of steel, so the value of Young's modulus is $E = 210\ GPa$ and density $\rho = 7850\ kg/m^3$. However, the hysteretic damping coefficient is itemized for each part, assuming a value of 1% for the structure and 2% for the embedded pile. The water density is considered $\rho_w = 1000\ kg/m^3$.

The properties of the homogeneous soil used in the calculus are resumed as density $\rho = 1800\ kg/m^3$, shear wave velocity $c_s = 360\ m/s$, poisson ratio $v_s = 0.35$ and hysteretic damping coefficient $\xi_s = 5\%$. In the case of the two-layered soil, the values of the Poisson's ratio and hysteretic damping coefficient are assumed as the homogeneous soil. The top layer has a thickness of 5 m, density $\rho = 1750\ kg/m^3$ and shear wave velocity $c_s = 130\ m/s$. For the layer below, density $\rho = 2000\ kg/m^3$ and shear wave velocity $c_s = 400\ m/s$ are considered.

First of all, this model is verified with a complex procedure which use boundary element methods to model the soil and finite element methods to represent the whole structure [4]. The NS component of El Centro 1940 is considered as excitation of the problem. As the Image 2 represents, the results obtained by this model are quite similar to the ones obtained by the rigorous one, being even higher, which involve more security.
Using the same excitation, the results of both OWTs founded on the homogeneous soil and the two-layered soil are represented on Image 3, where the coupled results represent the structure founded on the embedded pile and the uncoupled results show each part separately. From the point of view of the structure, the analysis of the pile interaction effect shows that the maximum bending moments decrease, being this phenomenon more representative with a higher structure. However, analysing the bending moments on the pile, the maximum value is increased due to the mass of the tower. In a first study on the effect of including a soft layer above the stiffer soil, the distribution of bending moments along the pile decrease in a milder way until the bottom.

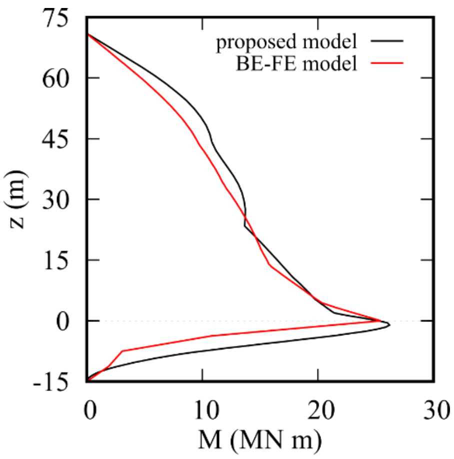


Image 2. Results verification

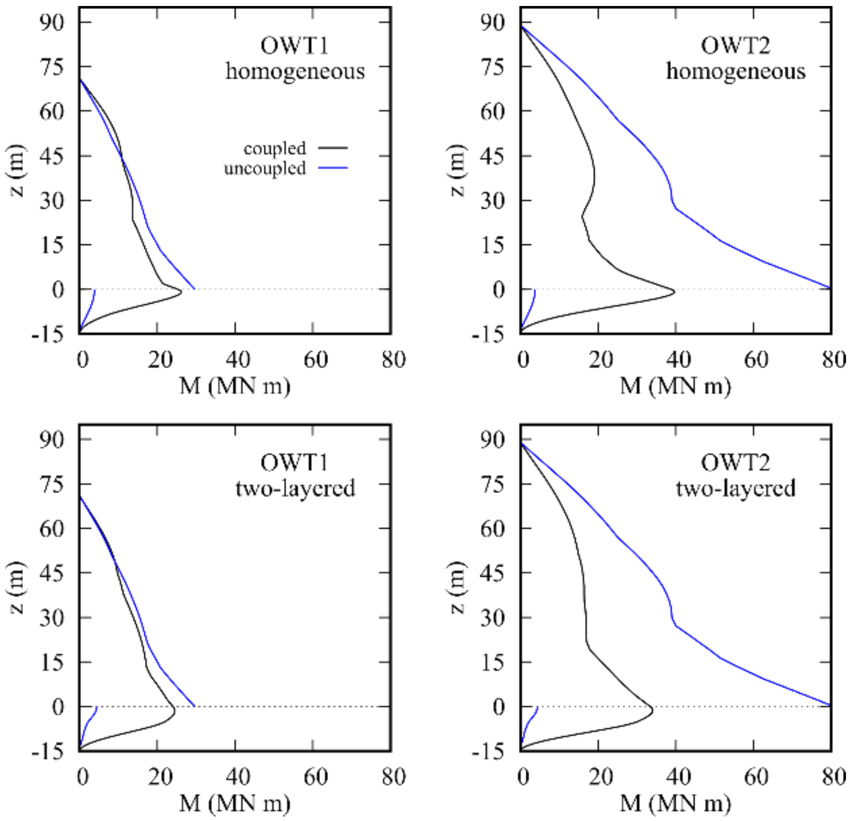


Image 3. Envelopes of maximum bending moments

4. Conclusions – The relevance of the soil-structure interaction effects and the variable character of the soil profile on the response of the structure and foundation is thoroughly analysed in terms of the obtained envelopes of maximum bending moment. Being this phenomenon especially important in the pile, where the maximum bending moment increases significantly.

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