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Dynamic lateral response of suction caissons

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ABSTRACT

Deeper water installations of offshore wind turbines may be supported by jacket structures. This study investigates the dynamic response of suction caissons for jackets by analysing 3D finite element models in the frequency domain. The numerical modelling was firstly validated by analytical solutions for pile foundations. Groups of crucial dimensionless parameters related to the soil profile and the foundation geometry are identified and their effects on the response of suction caissons are studied. Static stiffness coefficients are presented in a form of mathematical formulas obtained by fitting the numerical results, pertaining foundations with different slenderness ratios and embedded in different soil profiles.

Sensitivity of the dynamic impedances of suction caissons on the skirt length was showed in this study. Moreover, the results for the suction caissons indicated that the overall dynamic response is profoundly affected by the relative thickness of the soil layer and by the variation of soil stiffness with depth.

1. Introduction

The offshore wind market is developing towards wind farms with higher capacity generators and in deeper waters, which places new demands on current offshore design procedures. So far the selection of the type of support structures for offshore wind turbines are determined by the water depth. In shallow waters, monopiles and monopod suction buckets are mostly utilized, while jacket structures with piles or with suction caissons would be the design configuration for deeper waters following the designs traditionally used by the oil and gas industry [1]. In the work of Houlsby et al. [2] the applicability of suction caissons as offshore wind turbine foundations is suggested for suitable soil conditions and particularly for deeper waters, with a water depth of up to about 40 m. Suction caissons are skirted shallow foundations (with a slenderness ratio H_p/d lower than 4, where H_p and d are the foundation height and diameter, respectively) that are first installed using self-weight and then by pumping out the water trapped within the skirts [3]. In contrast to driven piles, heavy duty equipment is not required for suction caisson installation. Moreover the noise disturbance of the marine life is diminished, making this type of foundation an attractive alternative for deep water installations.

In the design of offshore wind support structures one of the critical issues is the fatigue that occurs due to the combination of wind, wave and earthquake loading. In addition, the potential of structural resonance with the dynamic forces of wind loading would result in large amplitude stresses and accelerated fatigue. Therefore, it is fundamental to accurately assess the resonance frequencies of the wind turbine structure in order to ensure that the first resonance frequency of the wind turbines does not coincide with the excitation frequencies of the rotor system [4]. Furthermore, the overall damping of the structure reduces greatly fatigue damage, since the amplitude of vibrations at resonance is inversely proportional to the damping ratios [5]. Wolf [6] showed that both the eigenfrequency and the damping of any structure subjected to dynamic load are modified due to the soil-foundation interaction. Hence the dynamic stiffness and damping of the soil-foundation system should be included in the estimation of the natural vibration characteristics of any offshore wind turbine as indicated by several studies [7–9].

In the literature the problem of the dynamic soil-pile interaction has been extensively investigated. Indeed, there are several analytical and numerical studies on the estimation of the dynamic impedances of the horizontal vibration of single piles. Considering only those for a linear elastic soil layer they can be classified as follows:

a) analytical continuum solutions for end bearing piles [10–12], where the soil was modelled as a homogeneous layer with hysteretic material damping;
b) Winkler type analytical solutions [13–15], where the supporting soil was substituted by a bed of independent elastic springs overlying a rigid bedrock. For dynamic problems Novak [13] recommended the use of Winkler foundation coefficients based on Baranov's equation for the in-plane and out-plane vibration of a disk. An improved model incorporating in the analysis the normal and shear stresses acting on the upper and lower faces of a horizontal soil element by

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Nomenclature

Latin upper case

E_s	soil modulus of elasticity
E_p	Young modulus of foundation
G	soil shear modulus
H_s	thickness of soil layer
H_p	height of foundation
I	moment of inertia of pile
L_{inf}	length of the infinite soil domain
L_{fin}	length of the finite soil domain
K_r	foundation flexibility factor
K_{su}	dynamic stiffness coefficient - force for unit displacement
K_{mu}	dynamic stiffness coefficient - moment for unit displacement
$K_{s\vartheta}$	dynamic stiffness coefficient - force per unit rotation
$K_{m\vartheta}$	dynamic stiffness coefficient - moment for unit rotation
$K^0{}_{su}$	static stiffness coefficient - force for unit displacement
$K^0{}_{mu}$	static stiffness coefficient - moment for unit displacement
$K^0{}_{s\vartheta}$	static stiffness coefficient - force for unit rotation
$K^0{}_{m\vartheta}$	static stiffness coefficient - moment for unit rotation
M	reaction moment at the foundation head
S	horizontal reaction force at the foundation head
V_s	soil shear wave velocity
V_0	surface soil shear wave velocity
V_H	reference base soil shear wave velocity

Latin lower case

d	diameter of foundation
n	dimensionless inhomogeneity factor
r_0	radius of foundation
t	thickness of foundation
t_{cap}	thickness of caisson cap
t_{skirt}	thickness of caisson skirt
u	translational degree of freedom at the foundation head

Greek

α_0	dimensionless eigenfrequency of soil layer
ζ_{su}	damping coefficient - force for unit displacement
ζ_{mu}	damping coefficient - moment for unit displacement
$\zeta_{s\vartheta}$	damping coefficient - force for unit rotation
$\zeta_{m\vartheta}$	damping coefficient - moment for unit rotation
ϑ	rotational degree of freedom at the foundation head
ν	soil's Poisson's ratio
ξ	hysteretic soil damping ratio
ρ	density of soil
η	wave velocity ratio

integrating the governing equations over the thickness of the soil layer was developed by Mylonakis [15];

c) numerical continuum finite element solutions [16–20], where the pile was modelled as series of regular beam segments with a rigid cross section and the soil was considered as an elastic continuum.

Very few studies investigating the dynamic response of floating piles either numerically [20] or analytically [21–23] are available in the literature. It was shown that the stiffness and the thickness of the soil layer play a fundamental role in the estimation of the dynamic impedances of floating piles. In addition, there is a significant number of studies analysing the dynamic lateral response of single piles or pile groups embedded in a homogeneous half space, where numerical methods (e.g. finite element [24–26], and/or boundary element methods [27,28]) or analytical elastodynamic solutions [29–31] were employed.

In the case of suction caissons the vast majority of research studies has been focused on the analysis of the load capacity under the action of combined vertical, horizontal and moment loading [32–34]. Moreover, the seismic response of suction caisson foundations was also investigated [35]. However, the dynamic response of suction caissons has received less attention [36,37]. In the work of Liingaard [36] the dynamic stiffness coefficients were determined, considering linear viscoelastic soil and modelling the suction caisson using a coupled BE/FE model in homogeneous halfspace comparing the obtained results with analytical solutions for surface foundations. In that study it was shown that the dynamic impedances pattern suggested by the analytical solution for surface foundations did not resemble the one obtained from the numerical model for $H_p/d > 0.25$, while it was in good agreement with the outcomes of the BE/FE model for the case of surface footing. Moreover, Liingaard [36] highlighted the high dependency of the horizontal and rocking component of the stiffness on Poisson's ratio and examined the influence of the skirt flexibility on the dynamic response of caisson foundations embedded in a homogeneous soil layer. It was observed that the increase of the dynamic impedances of suction caisson in the frequency domain is more pronounced when the slenderness ratio increases ($H_p/d = 0.25$–1).

The current study aims at investigating the dynamic response characteristics of suction caissons, to formulate a basis for understanding the natural vibrations characteristics of foundations for jacket structures. The literature study has shown that some aspects of the dynamic behaviour of this type of foundations has not been investigated so far (e.g. site effects). Therefore, a numerical study was performed and the dynamic impedances of suction caissons subjected to lateral loading were estimated.The vertical load response is not addressed in the present study due to space limitations, even though experimental studies [38] have shown that multi-caisson supported wind turbine structures are mainly influenced by this component. Due to the absence in the literature of analytical solutions on the dynamic response of suction caissons embedded in a soil layer on a rigid bedrock, the numerical modelling approach was validated with the analytical solution of dynamic vibration of soil-end bearing pile [10] and soil-floating pile [22]. The effect of the major parameters affecting the dynamic response of suction caissons embedded in a soil stratum on a rigid bedrock was investigated. The validated numerical methodology was adopted to perform the parametric study, while the rationale behind the selection of the parameters was to highlight the role of the nondimensional parameters of the problem such as the slenderness ratio H_p/d, the relative stiffness E_p/E_s and the relative thickness of the soil layer H_s/d. Furthermore, the dynamic response of suction caissons was analysed for different soil profiles, considering a stiffness distribution with depth.

2. Methodology

A series of 3D finite element models in the commercial software ABAQUS [39] were deployed to analyse the dynamic impedances of suction caissons. The numerical models accounted for the following hypotheses: 1) linear elastic isotropic behaviour of the foundation; 2) linear viscoelastic isotropic behaviour of soil with hysteretic type damping (frequency independent) and 3) perfect contact between the foundation and the soil during the analysis.

Only half of the foundation and the surrounding soil were taken into account in the model, as a result of the symmetry of the problem, see Fig. 1. Two different foundation modelling approaches were used: 1) shell cylinder, where the foundation was discretized by shell elements (S4) and 2) equivalent solid cylinder, for which equivalent material properties were applied to 3D continuum elements (C3D8) in order to