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Original Study

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Vertical and horizontal dynamic response of suction caisson foundations

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Abstract: In this article, the dynamic response of suction caisson foundations is studied using a three-dimensional finite element model with an absorbing boundary. The adopted formulation is based on the substructuring method. This formulation has been applied to analyze the effect of soil–structure interaction on the dynamic response of the suction foundation as a function of the kind of load. The suction caisson foundations are embedded in viscoelastic homogenous soils and subjected to external harmonic forces. For each frequency, the dynamic impedance connects the applied forces to the resulting displacement. The constitutive elements of the system are modeled using the finite element volumes and shell elements. The numerical results for the dynamic response of the suction foundations are presented in terms of vertical and horizontal displacements as well as vertical and horizontal dynamic impedances. The results indicated that the overall dynamic response is highly affected by the suction caisson diameter, the soil stiffness variation, and the suction caisson length.

Keywords: Suction Caisson Foundation; Dynamic Impedance; Soil–Structure Interaction; Numerical Model; Absorbing Boundary.

1 Introduction

With the rapid increase in energy consumption, many countries have studied the best way to use the ocean as an energy resource. The development of offshore wind energy is a clean method with significant advantages, including use of wind energy, saving of valuable lands, and reduced pollution. In recent years, an increasing number of offshore wind turbines have been built (He et al.2017a, b). However, installing the necessary physical facilities to extract wind energy is not an easy task, as the offshore environment is different from the onshore one. The forces are almost all dynamic in nature, like waves and winds, in addition to earthquakes (He et al.2017a, 2017b). For anchoring wind turbines in the seabed, offshore foundations are the most preferred.

This article is dedicated to one kind of these offshore foundations: the suction caisson foundations. A thorough study of the suction caisson foundation dynamic behavior is necessary to design this kind of structure. The dynamic response of deep suction caisson foundations has been studied for many years. Methods with different degrees of accuracy and efficiency have been developed and proposed to study the dynamic behavior of suction caisson foundations (Latini and Zania 2017). The majority of the research studies have focused on investigating the dynamic response of piles. Therefore, several analytical and numerical studies are based on the dynamic impedance estimation of the vertical and horizontal responses of a single pile and groups of piles. Winkler-type analytical solutions were proposed by Novak et al.(1977), Nogami et al.(1980), Novak et al.(1974), and Mylonakis et al.(2001) to study single piles and groups of piles under a lateral loading. The soil was modeled as a homogeneous layer with a hysteretic material damping. For dynamic problems, Novak et al. (1974) recommended the use of Winkler foundation coefficients based on the Baranov's equation. In the frequency domain, several methods have been already presented for determining the impedance functions of foundations. Using the boundary element method, numerical models were developed and a group of piles was analyzed by Sen et al. (1985), Maeso et al. (2005), Kaynia et al. (1982), and Kaynia and Kausel (1991).

Vibration isolation by a row of piles has been analyzed by Kattis et al. (1999a, b), and dynamic impedances of pile groups have been studied by Vinciprova et al. (2003) and Maeso et al. (2005). Piles were modeled using the

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finite element method (FEM) as beam-type elements based on the Bernoulli hypothesis to study the dynamic impedance of a pile group(Padron et al.2007). Moreover, the consistent infinitesimal finite element cell method (CIFECM) (Emani et al.2009) was used for calculating the dynamic impedances of a group of piles. In this context, Messioud et al.(2011,2016, 2019) used FEM with absorbing boundaries to determine the vertical and horizontal dynamic impedances of a group of floating and rested piles on a rigid substratum. Using the boundary element method with FEM (BEM–FEM), the vertical and coupled sliding–rocking vibrations of suction caissons were studied by Liingaard et al. (2007). The dynamic impedance is considered as the foundation dynamic stiffness. Nonlinear, three-dimensional, finite element analyses were proposed by Kourkoulis et al. (2014) to study the response of a soil–foundation–wind turbine system subjected to an earthquake shaking. Nine centrifuge tests were carried by Wang et al. (2017)to investigate the seismic response of suction bucket foundations under an earthquake loading. The results provided insight for the optimized design of suction bucket foundations for wind turbines.

In this work, a three-dimensional modeling using FEM with absorbing boundaries is proposed to study the dynamic response of suction caisson foundations. The formulation is based on the substructuring method. The soil is modeled by finite element volumes and the suction caisson is modeled by shell elements intended for calculations in small deformations and small displacements of thin curved or plane structures. The vertical and horizontal forces are applied separately at the foundation center (the center of the cylinder slab).The dynamic response is studied and analyzed through the force–displacement principle. The displacement response is obtained by taking the product of the function of the excitation force and the transfer function amplitude of the displacement. The vertical and horizontal dynamic impedance functions are examined for different lengths and diameters of the foundation. Then, the real part (dynamic stiffness of the system) and the imaginary part are studied separately.

2 Methodology

This category of methods uses the principle of superposition. The idea is to analyze the soil–structure interaction problem in a succession of steps. Each step considered will permit to solve in an easier way than the global problem (Kaynia et al.1982; Kausel et al. 1978;Viniprova et al. 2003; Messioud et al. 2016,2019;Pecker et al.1984).The substructures considered are composed of soil,on the one hand, and of the structure,on the other hand, as shown in Figure1a. The soil and structure have been separated and the balance is suitable by the application of inertial forces P_b, P_f (Figure1a), The model is subject to an arbitrary excitation along the boundary (Figure 2a). P_f=-P_b: Vector of forces (moments) derived from the inertial effect of the superstructure (Figure1a), P_f^*: Vector of forces (moments) caused by the movement of the free field, U_f: Vector of displacements corresponding to the soil–foundation interface, U_f^*: Vector of displacements corresponding to the free field at the soil–foundation interface.

The foundation impedance is essential for the seismic calculation of a structure by the substructure method (Pecker et al. 1984, Kausel et al. 1978). In general, the impedance of a foundation can be expressed as

$$K=K_s\,[K_1\,(\omega)+ia_o\,C_1\,(\omega)] \tag{1}$$

This dynamic contribution includes a real and an imaginary part. The coefficients K_1 and $C_1$are dependent on the frequency ω. K_s is the static rigidity of the foundation, K_1 and C_1 are dimensionless parameters varying with the frequency, $a_0=(\omega r_0)/C_s$, with r_0 beinga dimension characteristic of the foundation (radius, half-width, …), C_s is the shear wave velocity, and ω isthe excitation frequency. In the frequency domain, the matrix equations relating forces and displacements are of the form $(-\omega^2 M+i\omega C+K_i)U=P$, where M is the mass matrix, C the damping matrix, and K_i the stiffness matrix; P and U are the force and displacement vectors, respectively; and ω is the angular frequency.

For the sake of simplicity, the frequency-dependent complex submatrices of the dynamic stiffness matrix ($K_d=K_i+i\omega C-\omega^2 M$) will be denoted by the subscript K (Kaynia and Kausel 1991; Kausel et al. 1978; Pecker et al. 1984).

Note that both the free field problem and the soil–structure interaction problem are subjected to the same excitation U_r^*. However, in general, $P_r \neq P_r^*$ unless the boundary is far away from the structure. The force–displacement relationship including the soil–structure interaction and the free field solution are shown in Figure 1 (Kaynia and Kausel 1991; Kausel et al. 1978;Pecker et al. 1984).

$$\begin{bmatrix} K_{ff} & K_{fg} & K_{fr} \\ K_{gf} & K_{gg} & K_{gr} \\ K_{rf} & K_{rg} & K_{rr} \end{bmatrix} \begin{Bmatrix} U_f - U_f^* \\ U_g - U_g^* \\ 0 \end{Bmatrix} = \begin{Bmatrix} P_f - P_f^* \\ 0 \\ P_r - P_r^* \end{Bmatrix}. \tag{2}$$

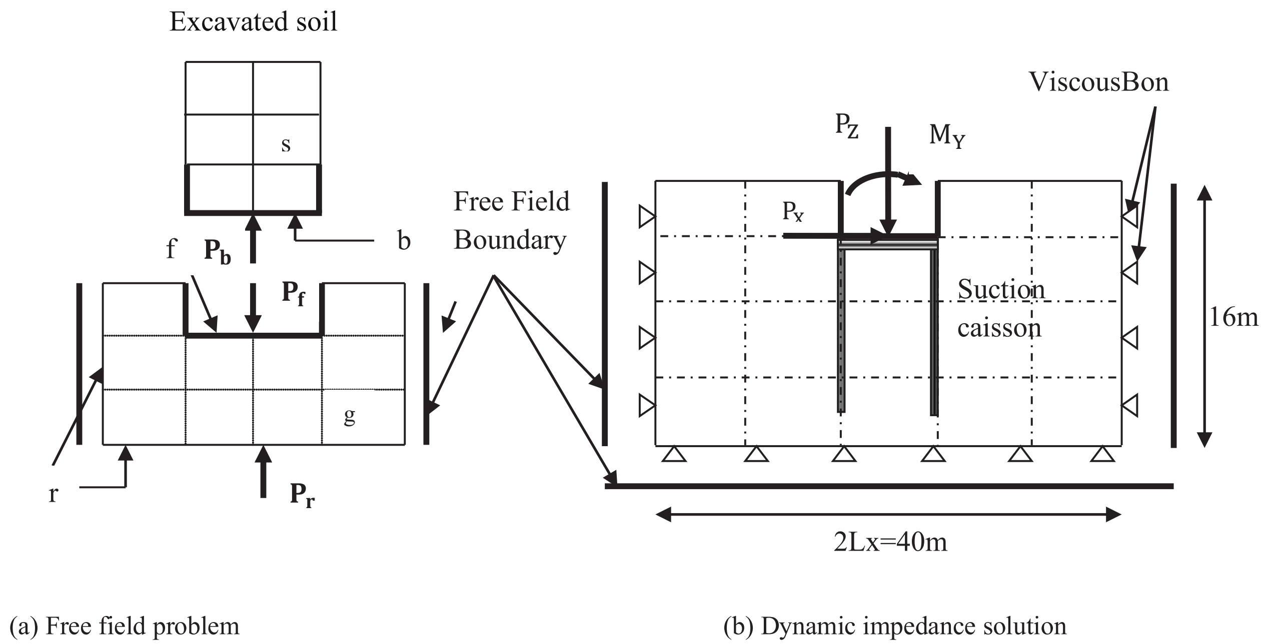


Figure 1: Sub-structure method.

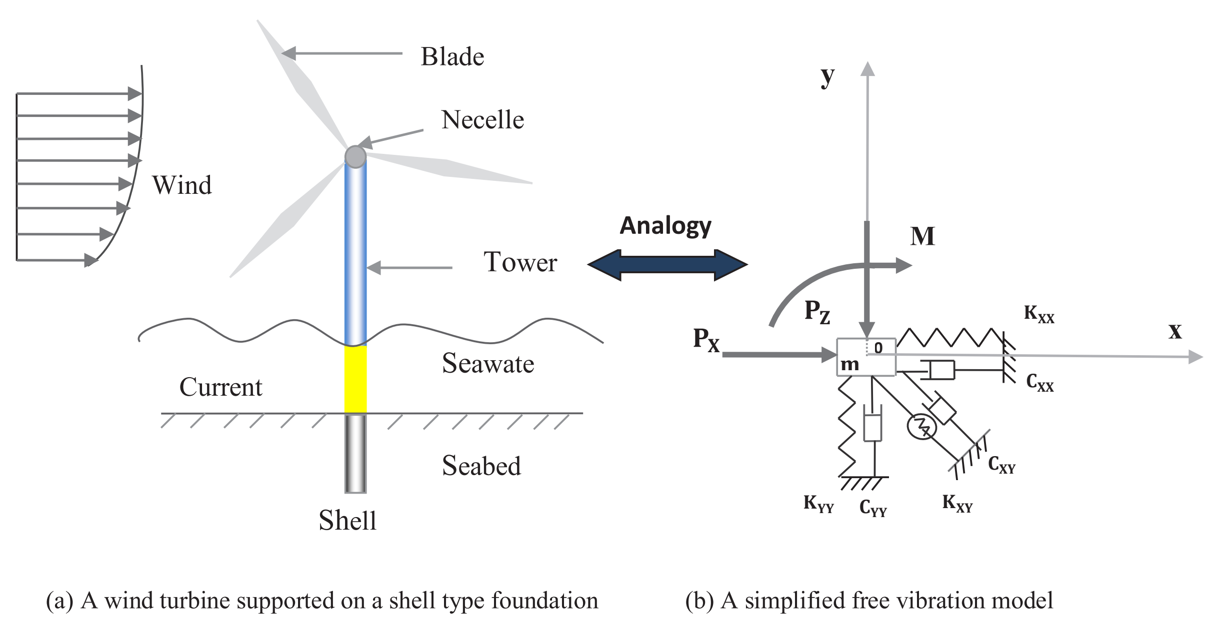


Figure 2: Impedance functions.

Here, f is the subscript for the soil nodes interface, excluding the soil–structure interface; g, for the soil nodes, excluding the interface and the boundaries; r, for the nodes along the boundary; and P_r, P_r^* vector of loading at the boundary of the model.

Subtracting equation (2)by dynamic condensation, the following matrix equation can be obtained:

$$K_{ff}\,(U_f\text{-}U_f^*)+K_{fg}\,(U_g\text{-}U_g^*)=(P_f\text{-}P_f^*) \tag{3a}$$

$$K_{gf}\,(U_f\text{-}U_f^*)+K_{gg}\,(U_g\text{-}U_g^*)=0 \tag{3b}$$

Equation (3b) means that the displacements of soil nodes are affected by those of the interface; in this case, the displacement of the soil nodes is given by the following expression:

$$(U_g\text{-}U_g^*)= K_{gg}^{-1}\text{-}K_{gf}(U_f\text{-} U_f^*) \quad (4)$$

Substituting Equation (4) in Equation (3a), the relation between the applied forces and the resulting displacements is given by Equation (5) as follows:

$$(K_{ff}+K_{fg} (K_{gg}^{-1}\text{-}K_{gf}))(U_f\text{-}U_f^*)= (P_f\text{-}P_f^*) \quad (5)$$

with

$$K=K_{ff}+K_{fg} (K_{gg}^{-1}\text{-}K_{gf}) \quad (6)$$

$$K(U_f\text{-}U_f^*)=P_f\text{-}P_f^* \quad (7)$$

$K=K_{ij}$ (w):the impedance function matrix of this can be written in the following form:

$$K_{ij}(\omega) = \frac{(P_f - P_f^*)e^{i\omega t}}{(U_f - U_f^*)(\omega)}. \quad (8)$$

The dynamic impedances are presented in the form K_{ij} (ω)=[K_{ij}^r (ω)+iK_{ij}^i (ω)], consisting of a real part (K_{ij}^r) and an imaginary part(iK_{ij}^i).

The impedance functions have been given with respect to the static stiffness K_s as follows:

$$K_{ij} (\omega)=K_s [K_{ij}^{'} (\omega)+iK_{ij}^{''} (\omega)], \quad (9)$$

where K_s is the static impedance (ω =0) or static rigidity, K' affects the elastic behavior and takes into account the rigidity and inertia of the medium, and K'' indicates the vibratory movement and damping.

Using the relation shown in equation (8), the impedance functions are calculated after determination of the result displacements at the harmonic force point of application. The displacement response is obtained by the product of the exciting force function and the amplitude of the transfer function of the displacement (Messioud et al. 2011). In this study, the displacement (U_f-U_f^*) is replaced by the obtained displacement Ui (i=X,Z).

The vertical dynamic impedance is

$$K_{ZZ}(\omega) = \frac{(P_0)e^{i\omega t}}{(U_Z)(\omega)}, \quad (10)$$

where P_0 is the amplitude of the vertical force applied to the foundation center (the center of the cylinder slab) and U_z is the resulting displacement.

The horizontal dynamic impedance is

$$K_{XX}(\omega) = \frac{(P_0)e^{i\omega t}}{(U_x)(\omega)}. \quad (11)$$

To calculate the dynamic displacements, harmonic forces are applied at the center of the suction caisson (the center of the cylinder slab). Calculations are performed for each excitation frequency between 1.5 and 35 Hz. The dynamic response of the massless foundation is expressed as

$$|u_0| = \left|\frac{P}{K_s[k(a_0) + ia_0c(a_0)]}\right|, \quad (12)$$

where $|u_0|$ is the dynamic displacement amplitude, P is the force amplitude, K_s is the static stiffness, k (a_0) is the stiffness coefficient, and c (a_0) is the damping coefficient with $a_0$being the dimensionless frequency (Pradhan et al. 2004).

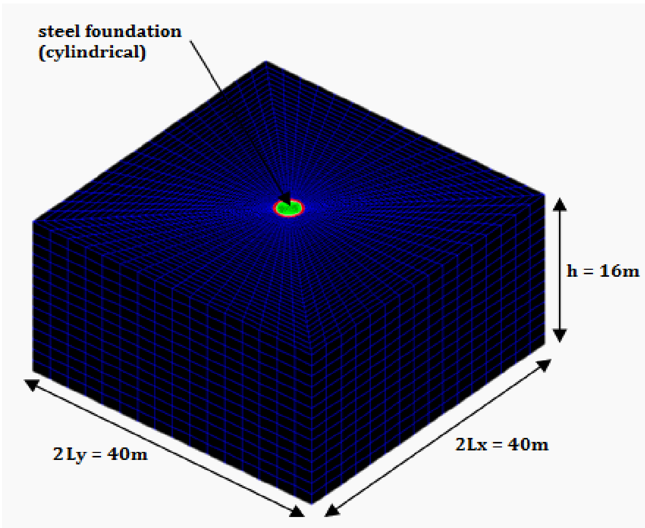
To simplify the analysis and the comparison between the results of the numerical calculations and the experimental data, the ratio Uj j =F is used, i.e., the amplitude of displacement is

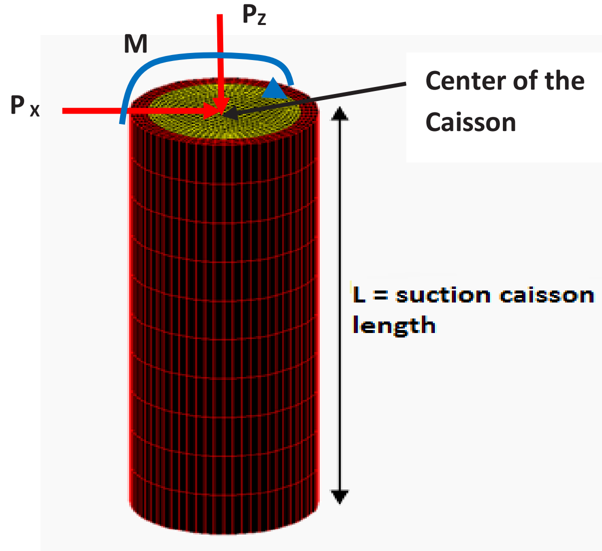
$$\left|\frac{1}{K(a_0)}\right| = \left|\frac{U_0(t)}{F_0(t)}\right| = \frac{1}{K_S\sqrt{[k(a_0)]^2+[a_0 c(a_0)]^2}} = \frac{U}{F}, \quad (13)$$

Where $|\ .\ |$ corresponds to the modulus operator.

3 Numerical model and material

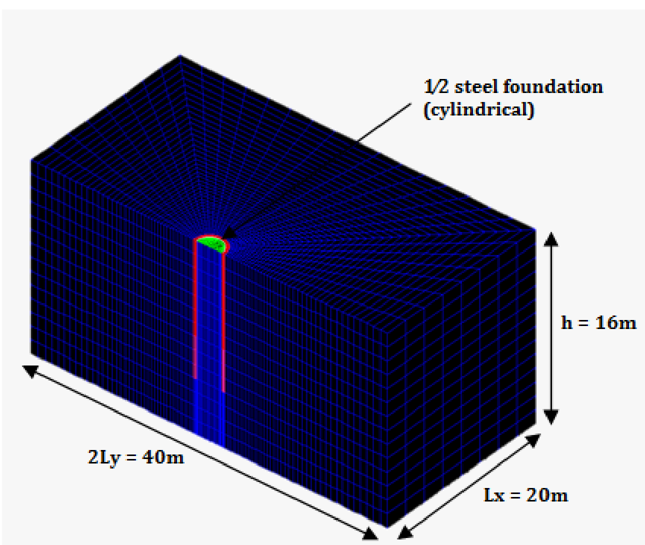
Figure 3 shows the3D numerical model by the finite element software code ASTER 10.2. This model permits to study the behavior of suction caissons subjected to vertical and horizontal harmonic forces (Figure 2) embedded in a homogeneous medium. The thickness of the homogenous soil layer is equal to 16 m and its width is equal to 40m. Quiet boundaries are placed at the boundaries of the model to avoid wave reflection. The foundation is represented by shell-type elements. The shell elements are bonded to the volumetric elements of the model (suction and homogenous soil). To approach the behavior of soils, the elastic constitutive laws are quite usable if the amplitude of the strain does not exceed 10^{-05}. Due to its simplicity, the linear elastic model with damping is the most widely used, especially in the frequency domain.

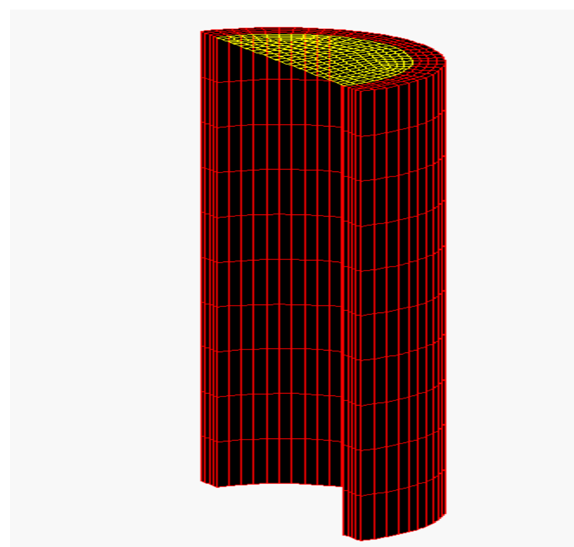




(a) Numerical model

(b) Zoom on the suction caisson





(c) HalfNumerical model

(d) Zoom on the half suction caisson cylinder

Figure 3: Used numerical model.

The constitutive models of the materials are considered as linear viscoelastic. The mechanical properties of the soil layers are presented in Table 1.

This mesh size depends on the used frequencies, and the wave propagation velocity affects the precision of the numerical solution. Kuhlemeyer and Lysmer(1973) showed that the size of the element used must be lower than one-tenth of the wavelength λ. As a result, the maximum frequency that may be correctly modeled for a mesh is given by

$$f=C_S/10\Delta l \text{ with } f=\omega/2\pi, \tag{14}$$

where C_S is the shear wave velocity, Δl the size of the mesh element and ω the frequency of excitation.

Compared to typical offshore oil and gas applications, wind turbine foundations differ in respect of their environmental conditions and required performance. The vertical loading on the foundations is relatively small; consequently, the horizontal and moment loadings are a much larger fraction of the total loading and are also highly dynamic. This is important as the capacity of suction foundations to resist tensile and moment loading could be sensitively dependent on the dynamic characteristics of the loading (Liingaard et al.2007).

The dynamic interaction between the wind-induced loading of the turbine rotor and the wave-induced loading on the structure results in complicated dynamic loading on the foundation. This is very different from the wave and current loading that dominates the design of typical oil and gas installations. To simplify the problem, the vertical forces P_Z and the shear forces P_X are considered harmonic. The results of these forces are used for determining the dynamic impedance of a cylindrical foundation (Figure 4). To study the dynamic behavior of the suction caisson foundations, several analytical and numerical studies can be used for estimating dynamic impedance of the vertical and horizontal responses of a single pile and a group of piles. In this context, the numerical results for the proposed numerical model are compared and validated in the different numerical solutions formulated for groups of piles (Messioud et al.2011,2016). The results of the dynamic stiffness matrix K_{ij} of a pile group are in good agreement with the results obtained by Padron et al. (2007).

In this study, the geotechnical and mechanical properties are selected based on the study by Latini et al. (2016), while the rationale for their selection was to examine foundations (suction caisson) with different lengths (L) embedded in a homogenous soil layer, the shear wave velocity (Cs=250 m/s), thickness (t=d/100), hysteretic material damping (ζ=5.0%), and Poisson's ratio (ν=0.30).The elasticity modulus of homogeneous soil is determined as a function of the shear wave velocity $G_s=C_s^2.\rho$ and the Poisson's ratio ν.

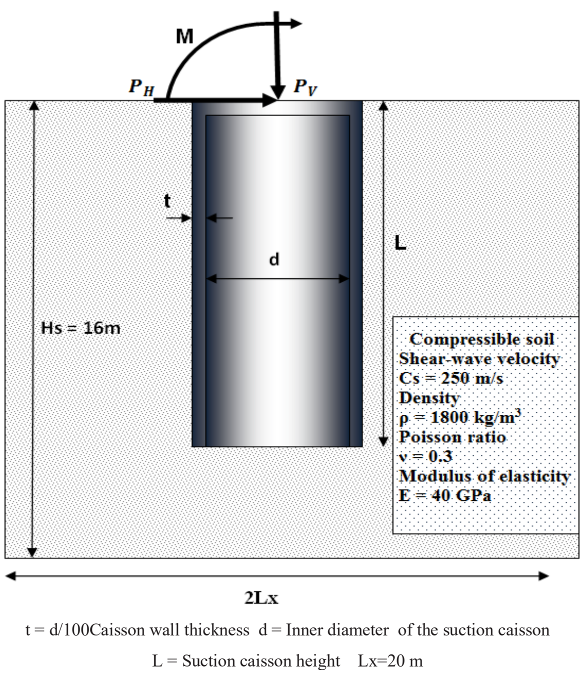


Figure 4: Geometry of the numerical model.

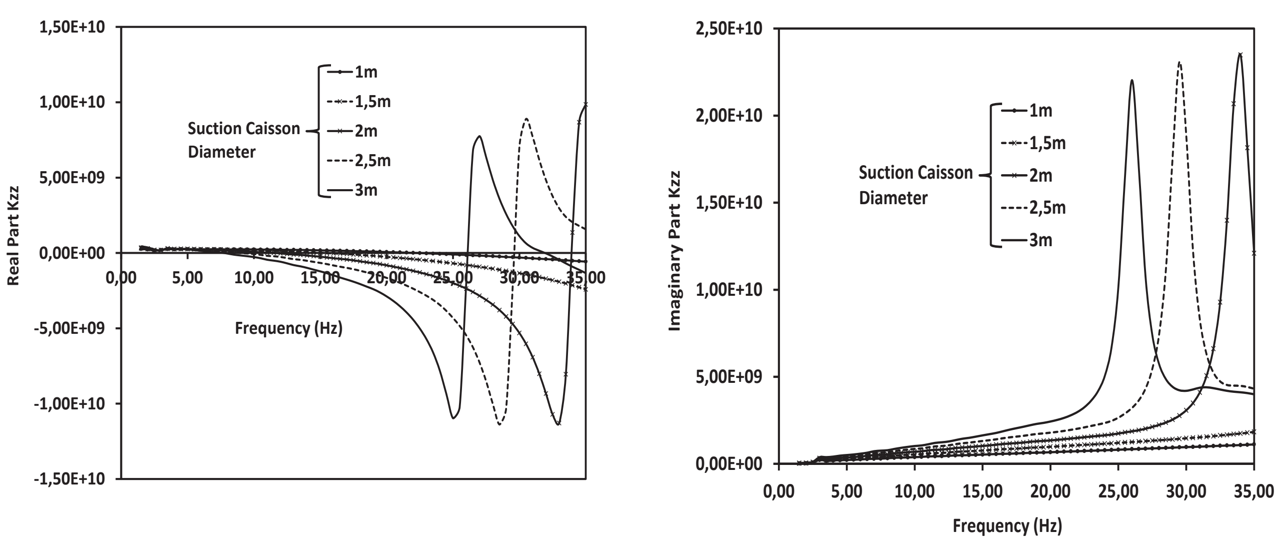


Figure 5: Influence of the suction caisson inner diameter on the vertical dynamic impedance.

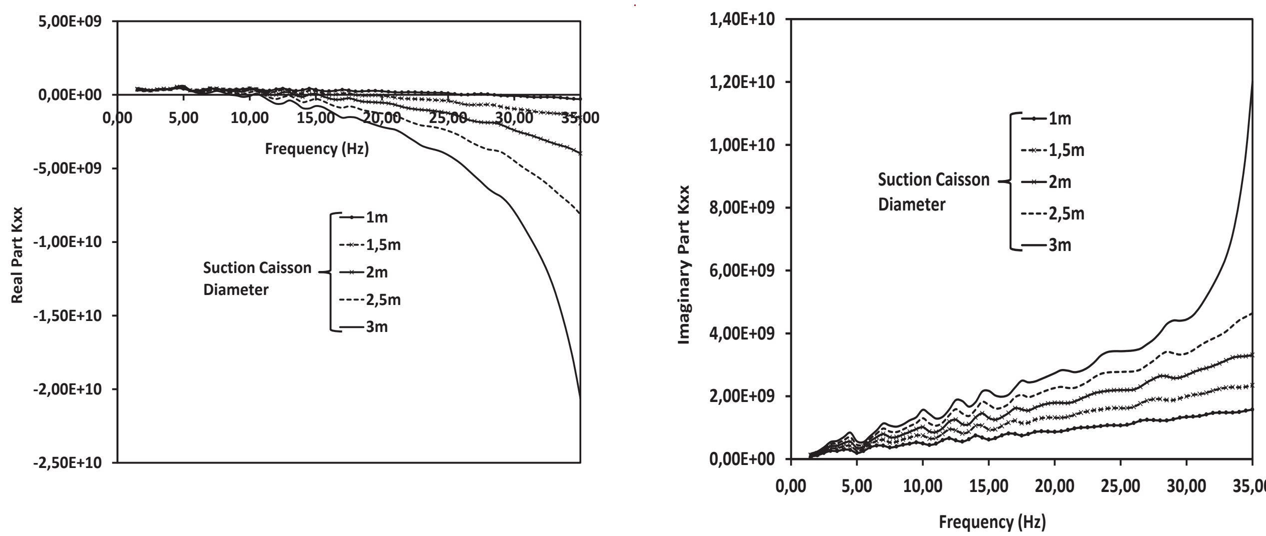


Figure 6: Influence of the suction caisson inner diameter on the horizontal dynamic impedance.

4 Dynamic suction foundation response

4.1 Effect of suction diameter

The geometrical dimensions of the model (Figure 4) are 40 m×40 m×16 m; the suction caisson length is fixed to10 m, and by varying the foundation diameter from 1 to 3 m, the dynamic response is obtained by applying a load of 1MN to the center of the caisson foundation center. The obtained results are presented in terms of vertical and horizontal dynamic impedances and displacement amplitudes according to the formula by Pradhan et al.(2004). In this study, the unit of dynamic rigidity is N/m.

The variation of the vertical dynamic impedance versus frequency for different values of diameter is presented in Figure 5.The obtained results show that the dynamic impedances are strongly affected by the increase in suction caisson diameter. Beyond a diameter of 1.5 m, the real and imaginary parts of the dynamic impedance are reduced according to the increase in diameter. This is due to increase in the vibrating mass of the shell.

Figure 6 shows the variation in horizontal dynamic impedance Kxx versus the excitation frequency. By increasing the diameter of the foundation, the real part of dynamic stiffness is strongly attenuated and it becomes negative. The effect of diameter is more important for the translation component of the horizontal dynamic impedance. The percentage of attenuation (evolution rate) is very high, especially for the horizontal dynamic impedance. The obtained results show that the horizontal

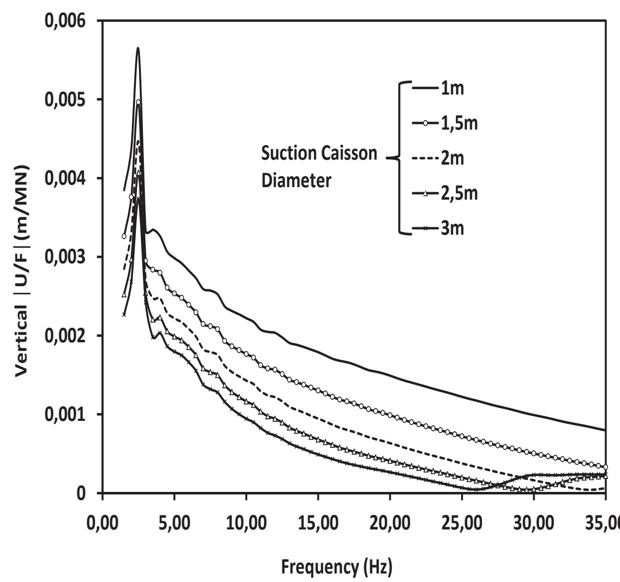


Figure 7: Vertical displacement amplitude |U/F|

dynamic impedances are more strongly affected by the inertia of the shell than the vertical dynamic impedances (Figure 5). The inertial effect is marked by a high attenuation for the real part of dynamic impedances, especially for high frequency.

Figures 7 and 8 show the effect of the suction caisson diameter on the amplitudes of the vertical and horizontal displacements versus the excitation frequency. The obtained results show that the displacement amplitudes are strongly affected by the increase in cylinder diameter. The displacements are significantly reduced as the cylinder diameter increases.

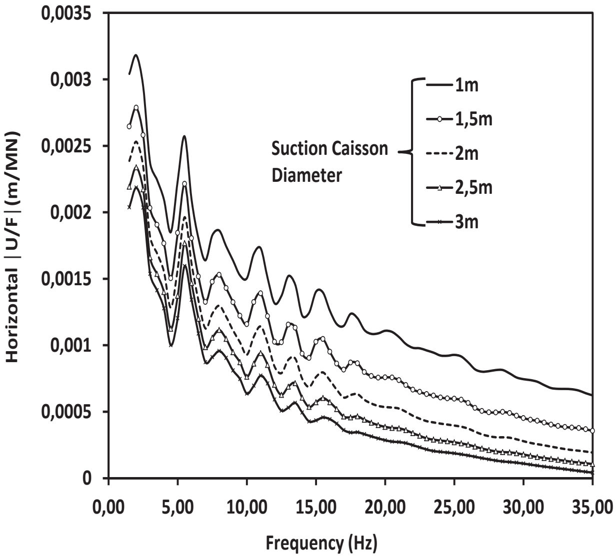


Figure 8: Horizontal displacement amplitude |U/F|.

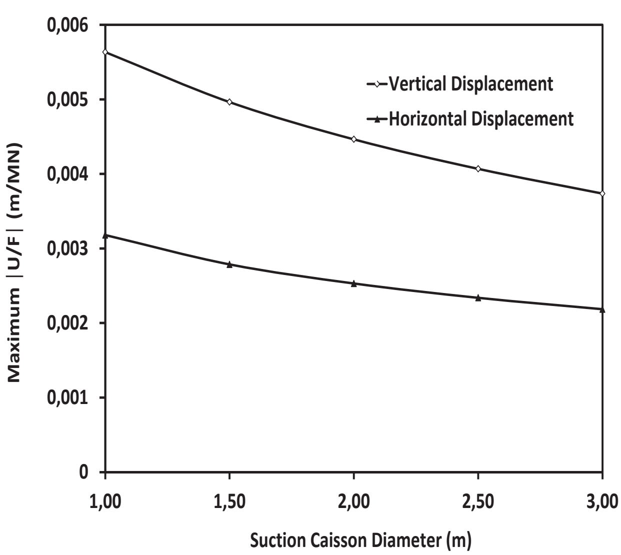


Figure 9: Vertical and horizontal response for the maximum |U/F|. Influence of the suction caisson diameter.

A fundamental characteristic is presented in Figure 8: the appearance of resonance peaks that are close to the fundamental frequency of 2.5 Hz. The same results are obtained in Figure 7 for the vertical displacements.

The evolution of the maximum amplitudes of displacements is proportional to the diameter of the suction caisson (Figure 9). The influence of the suction caisson diameter on the horizontal and vertical dynamic responses shows that increase in suction caisson diameter causes a decrease in vertical and horizontal displacements. The obtained results show that the evolution of the maximum amplitude of displacements versus diameter is almost linear.

4.2 Influence of the suction caisson length

In this calculation, the suction caisson diameter is fixed to 2.0m and the cylinder length varies from 2 to 10 m, andthe soil Young's modulus is fixed to 40 MPa. The dynamic impedances are calculated by applying vertical and horizontal forces at the center of the cylinder slab.

Figure 10 shows the variation in the vertical dynamic impedances versus frequency for different cylinder lengths. The obtained results show that the length of this type of foundation plays a very important role; also, the dynamic rigidity and damping are increased very significantly, especially for high frequencies, with an increase in cylinder length.

Figure 11 shows the variation in the horizontal dynamic impedances versus frequency for different values of cylinder length. The obtained results show that the variation in horizontal dynamic impedances is proportional to the increase in foundation length. The stiffness and damping are increased significantly with increase in the length foundation. For low frequencies, the dynamic stiffness is strongly attenuated for long lengths. This is not the case for high frequencies; the stiffness increases according to the suction caisson length, and the resonance peaks are more marked.

The effect of the length of suction caisson on the amplitudes of the vertical and horizontal displacements versus excitation frequency is presented in Figures 12 and 13. The obtained results show that the vertical and horizontal displacements are strongly affected by the cylinder length variation. The amplitudes of displacements decrease with increasing cylinder length. This may be due to the increase in lateral and tangential stresses along this type of foundation.

The maximum amplitudes of displacement are presented in Figure 14. The influence of the suction caisson length on the horizontal and vertical dynamic response is studied. The obtained maximum amplitudes of displacements are proportional to the length of the suction caisson. Increasing the length of the suction foundation causes a decrease in vertical and horizontal displacements.

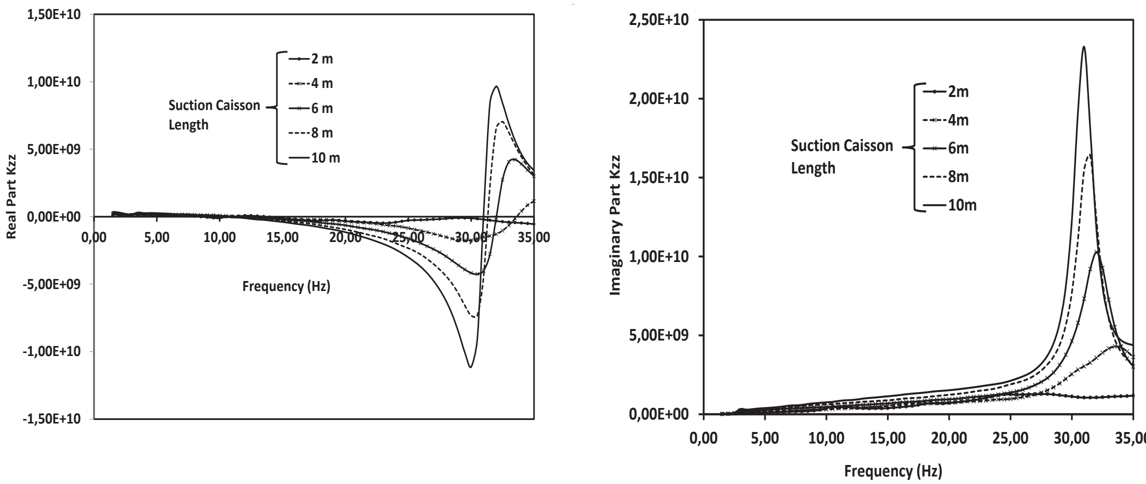


Figure 10: Variation of the vertical dynamic impedance as a function of the suction caisson length.

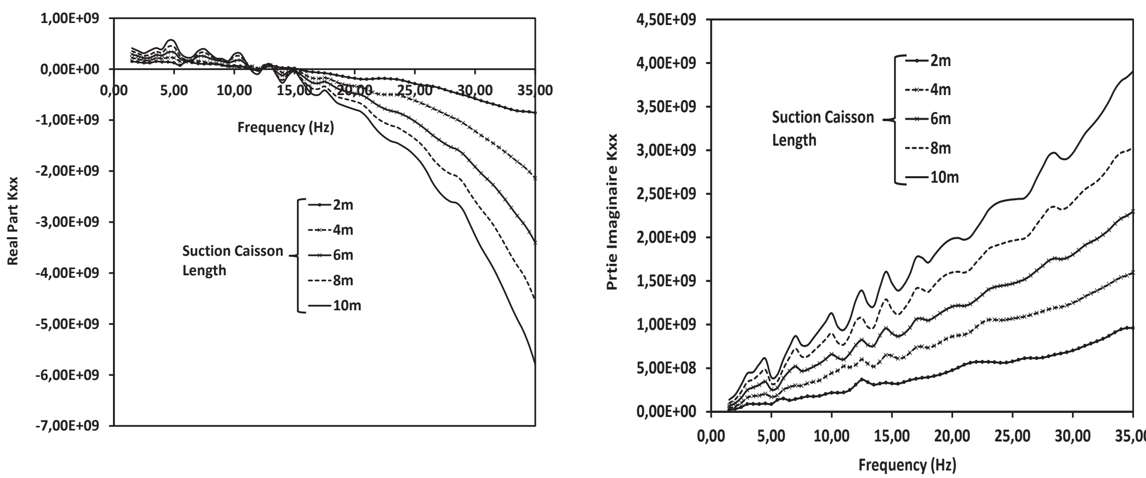


Figure 11: Variation of the horizontal dynamic impedance as a function of the cylinder length.

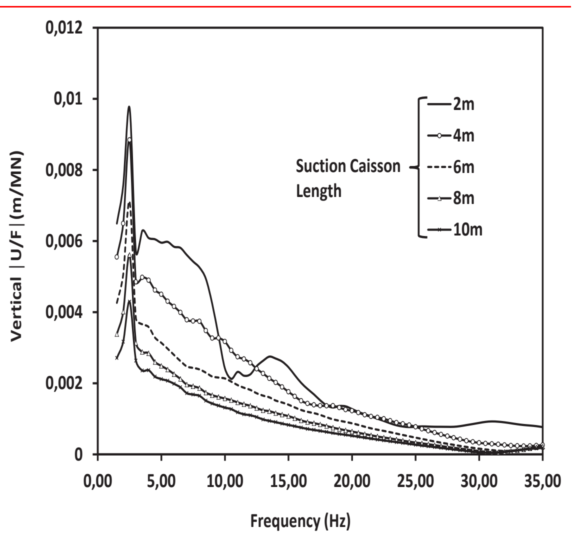


Figure 12: Vertical displacement amplitude │U/F├.

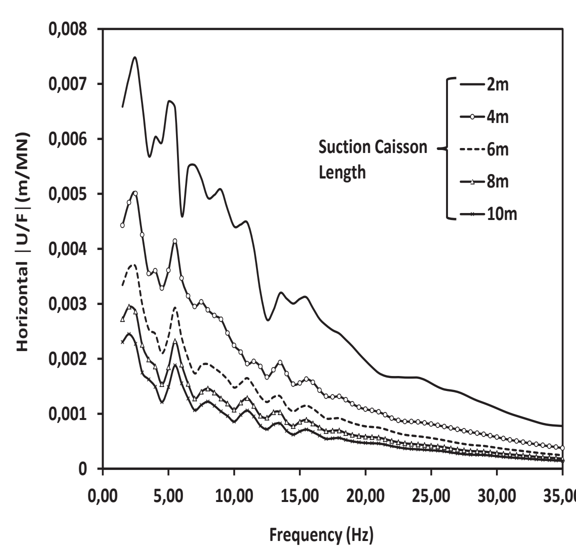


Figure 13: Horizontal displacement amplitude │U/F├.

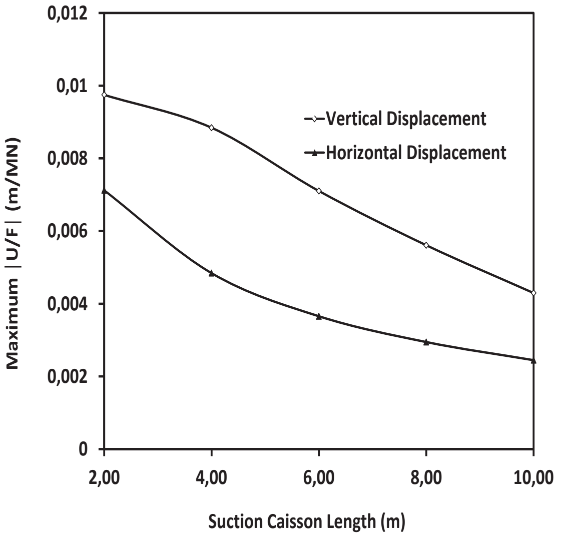


Figure 14: Vertical and horizontal response for the maximum │U/F┼ Influence of the cylinder depth.

4.3 Influence of the homogenous soil elastic modulus

By varying the modulus of elasticity of the soil between 10, 29, and 40 MPa, the dynamic response of the suction caisson foundation was analyzed. The obtained results are presented in terms of dynamic impedance and the amplitudes of displacements.

Figure 15 shows the influence of the soil elastic modulus on the vertical dynamic response. The figure shows that the real and imaginary parts of the dynamic impedance are highly increased as the elasticity modulus of soil increases.

The variation in the horizontal dynamic impedances is inversely proportional to the increase in elasticity modulus of soil (Figure 16). The real and imaginary parts increase in a very significant manner as the soil modulus decreases. This is not the case for vertical dynamic impedance (Figure15), though.

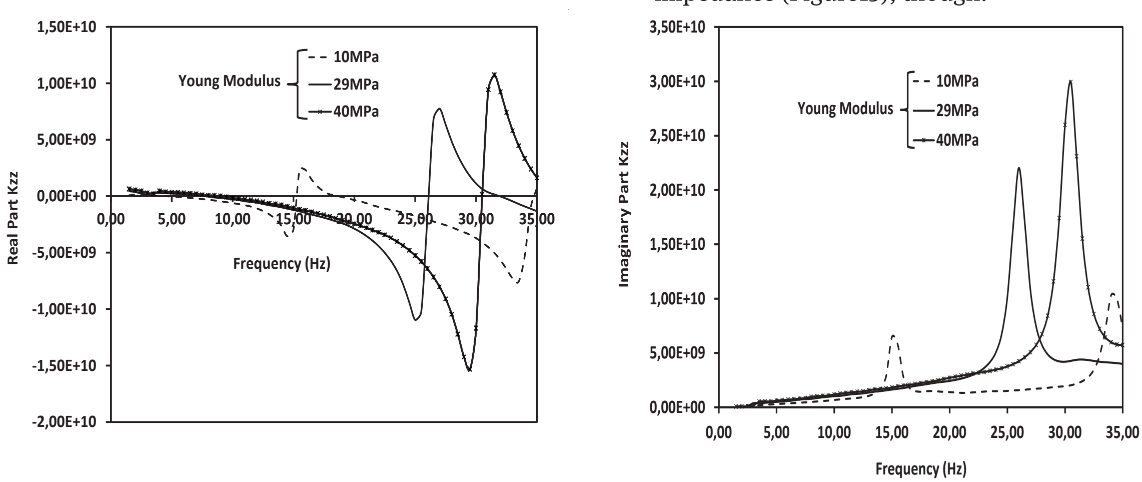


Figure 15: Influence of the Young modulus on the vertical dynamic impedance.

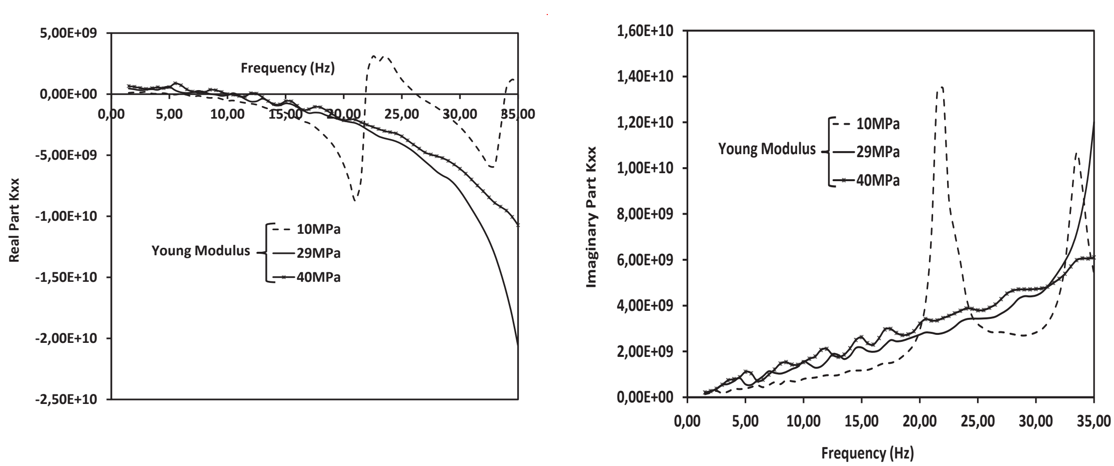


Figure 16: Influence of the Young modulus on the variation of the horizontal dynamic impedance.

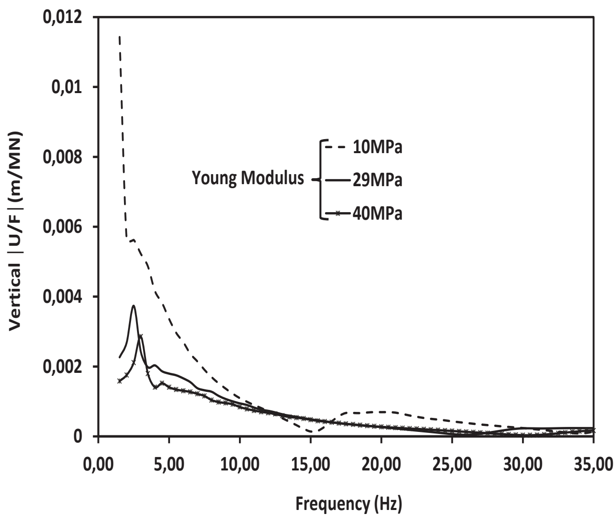


Figure 17: Vertical displacement amplitude │U/F├.

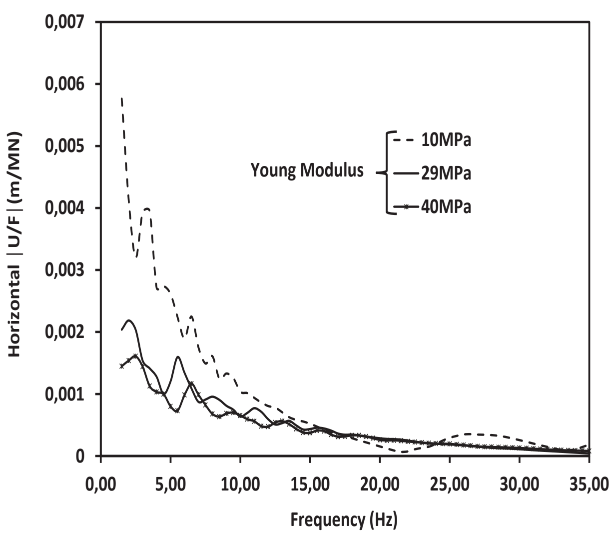


Figure 18: Horizontal displacement amplitude │U/F┼.

Figures 17 and 18 show the effect of the elasticity modulus on the variationsin vertical and horizontal amplitudes of displacements as a function of the excitation frequency. The maximum amplitudes of the displacements are observed for the lower modulus. These figures show that the amplitudes of the displacements are considerably affected by the effect of the modulus of elasticity. The displacement for the 10-MPa modulus of elasticity increases 10 times more than the 40-MPa one. In Figure 19,it is observed that the amplitudes of displacement decreaseon increasing the elasticity modulus of the soil. However, these results remain valid for a harmonic loading with a viscoelastic constitutive law. Cyclic loading in soils also leads to cyclic degradation–

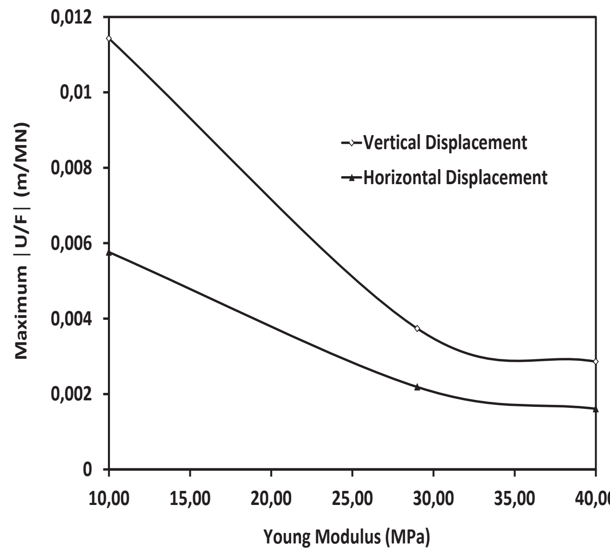


Figure 19: Vertical and horizontal response for the maximum │U/F┼ Influence of the suction module de young.

hardening mechanisms, which have considerable effects on the soil behavior. The reduction in soil modulus and in shear strength is the two main effects of cyclic loading in soils (Gerolymos and Gazetas 2005). The shear stiffness degradation of soil with cyclic loading leads to a reduction of the lateral load-carrying capacity of the foundation (Tuladhar et al. 2008;Heidari et al.2014). These effects are not considered in our study.

5 Conclusion

In this study, a 3D finite element numerical modeling with absorbing boundary was proposed to study the impact of vibrations on cylindrical offshore suction foundations. The substructure method was implemented to evaluate their dynamic response. The vibrations of the systems were studied by the principle of causality, applying vertical and horizontal loads to the suction caisson centers (center of the cylinder slab). The dynamic impedances were calculated, and a parametric study was done to investigate the geometrical influence of such foundations. The results were compared in terms of vertical and horizontal impedance functions and displacements. The influence of the length and foundation diameter on the dynamic impedances was studied. The main results obtained are the following ones:

The dynamic impedance is strongly affected by the foundation length, the foundation diameter, and the frequency; the variation in dynamic stiffness is proportional to the increase in foundation length. The augmentation of the dynamic impedance (real part and imaginary part) is proportional to the increase in foundation length,

The real and imaginary parts of the vertical dynamic impedance are highly increased as the elasticity modulus of soil increases. However, this is not the case for horizontal dynamic impedance; the real and imaginary parts are decreased/reduced on increasing the soil elasticity modulus.

The amplitudes of the displacements are considerably affected by the variation in the modulus of elasticity, the length, and the foundation diameter; the displacements are highly reduced as a function of increase in the length and diameter of the foundation. The evolution of the maximum amplitude of displacements versus diameter or length is linear.

The amplitude of displacement decreases with increase in modulus of elasticity of the soil. The maximum amplitudes of the displacements are observed for lower modulus of elasticity (10MPa).

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