

Stiffness Coefficients for Caisson Foundations Supporting Offshore Wind Energy Converters

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Abstract—A wide range of novel Offshore applications are emerging in the energy sector. Actually, Offshore Wind Energy is one of the most attractive sources of renewable energy. During the last decade, Offshore Wind Turbines were extensive application throughout the worldwide. However, the efficiency of Offshore Wind Turbines especially foundations in one of the currently challenges.

In the past, suction caissons have been widely used in oil and gas structures. Recently it is attempted to be used as support structures for Offshore Wind Turbines.

Similarly to conventional monopiles, suction caissons supporting Wind Turbines experience lateral displacement mainly due to wind and waves, though studies show that caissons have more long term performance against loading.

This paper aims for highlighting the stiffness behavior of caissons in the elastic domain supporting Wind Turbines using the Fourier Series Aided Finite Element Method (FSAFEM) through sensitivity analysis considering the geometry of the caisson and variation of the soil stiffness with depth.

Keywords— Caissons, Wind Turbines, Stiffness, Finite Element Analysis.

I. Introduction

Monopiles and gravity base foundations are the most commonly used as support structures for Offshore wind turbines, although caisson foundations are used increasingly for offshore structures (Cassidy *et al.*, 2006) due to their economic advantages and usability in the recent few years.

The main objectif of this paper is to predict the response of laterally loaded cylindrical caisson by mean of stiffness coefficients in the elastic domain using Fourier Series Aided Finite Element Method (FSAFEM) which combines the conventional finite element method in the radial discretisation with the expansion of displacements and strains in Fourier series in the circumferential direction (Amar Bouzid *et al.*, 2004; Abed *et al.*, 2016; Aissa *et al.*, 2017). The present study takes into account the slenderness ratio of the caisson and variation of soil stiffness with depth. Finally, we provide a simple illustration showing the usefulness of these stiffness coefficients.

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II. Fourier Series Aided Finite Element Method (FSAFEM)

This so called semi analytical approach was proposed in a first time (Wilson, 1965) for FE analysis of axisymmetric structures loaded non-axisymmetrically. The main idea of this method is to use Fourier Series to resolve three dimensional problems as a two dimensional harmonic model and superposing each term result. We can found many applications of Semi-Analytical Approach in practical cases (See for example Kim *et al.*, 1994; Zienkiewicz and Taylor, 2000). This method finds its applications in the present problem.

The nodal loads applied to a cylindrical caisson can be expanded in Fourier series as:

$$\begin{aligned} R &= \bar{R}_0 + \sum_{n=0}^{\infty} \bar{R}_n \cos n\theta + \bar{\bar{R}}_n \sin n\theta \\ Z &= \bar{Z}_0 + \sum_{n=0}^{\infty} \bar{Z}_n \cos n\theta + \bar{\bar{Z}}_n \sin n\theta \\ T &= \bar{T}_0 + \sum_{n=0}^{\infty} \bar{T}_n \cos n\theta + \bar{\bar{T}}_n \sin n\theta \end{aligned} \quad (1)$$

Where R , Z and T are the radial, axial and circumferential components respectively with respect to the $\theta = 0$ as plane of symmetry.

The displacement can be expressed in the form of Fourier series:

$$\begin{aligned} u &= \sum_{n=0}^L \bar{u}_n \cos n\theta + \sum_{n=1}^L \bar{\bar{u}}_n \sin n\theta \\ v &= \sum_{n=0}^L \bar{v}_n + \sum_{n=1}^L \bar{\bar{v}}_n \sin n\theta \\ w &= \sum_{n=0}^L \bar{w}_n \cos n\theta + \sum_{n=1}^L \bar{\bar{w}}_n \sin n\theta \end{aligned} \quad (2)$$

Where \bar{u}_n , \bar{v}_n , \bar{w}_n are the amplitudes of displacements that are symmetric with respect to the $(\theta = 0)$ plane and $\bar{\bar{u}}_n$, $\bar{\bar{v}}_n$, $\bar{\bar{w}}_n$ are the amplitudes of displacement that are antisymmetric with respect to the $(\theta = 0)$ plane, n is harmonic number, and L is the total number of harmonic terms considered in the series.

For a cylindrical caisson subjected to a lateral and/or an overturning moment, only the second term for $i=1$ survives, because this loading has a plane of symmetry. In this situation the components of loading in Eq. (1) reduce to:

$$R = \bar{R} \cos \theta, \quad Z = \bar{Z} \cos \theta, \quad T = \bar{T} \sin \theta \quad (3)$$

Where \bar{R} , \bar{Z} and \bar{T} are the amplitudes of nodal loading on the first harmonic. The load system displacements of Eq. (2) will reduce to:

$$u = \bar{u} \cos \theta, \quad v = \bar{v} \cos \theta, \quad w = \bar{w} \sin \theta \quad (4)$$

III. Validation of the Computer Code CAISSON_LID

A computer program called CAISSON_LID has been written in Fortran language (Fortran 90) for analyzing a cylindrical caisson subjected to lateral load and moment applied at the lid of the caisson.

The model adopted for this study consists in a caisson with a slenderness ratio $d/R=2$. The thicknesses of the lid and skirt are respectively $t_{lid}=0.1m$ and $t_{skirt}=0.03m$. The Young's modulus of the caisson material is $E_c=2.10^5MPa$ with a Poisson's ratio $\nu_c=0.25$, these values are corresponding to a steel material.

The soil material is considered as non homogeneous with a stiffness which varies linearly with depth (Gibson's soil). The elastic behavior of the medium is characterized by Young's modulus $E_s=60MPa$ and Poisson's ratio $\nu_s=0.499$

The geometric model adopted for this analysis consists of 848 eight nodes quadrilateral elements, therefore 2663 nodes including 29 elements in the r direction and 28 in the z direction. Limits of the geometrical model are in the order of $20R$ in the r direction and $2d$ in the z direction (Figure 1).

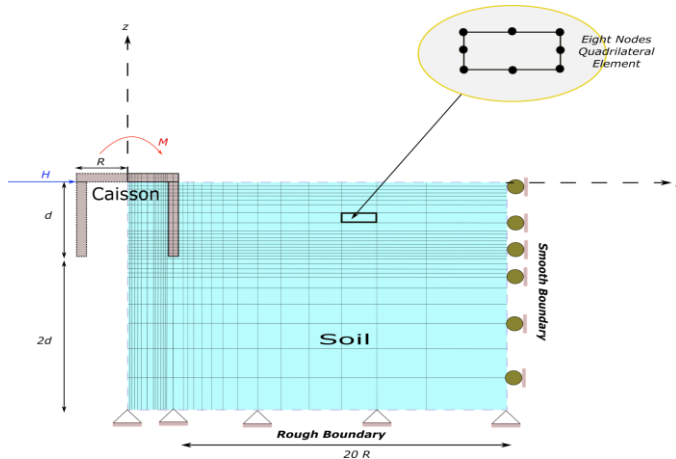


Fig. 1 Geometric Model adopted in this study.

Due to the large diameter of the caisson, we ensure a good accuracy by refining the mesh in caisson structure and in the interface area between the caisson and the soil

The computed stiffness coefficients K_H , K_M and K_{MH} are mentioned and compared with the results obtained by Doherty *et al.* (2005) in the Table I:

It is assumed that the flexible or the rigid behavior of a caisson is controlled by a parameter S , this dimensionless parameter is equal to:

$$S=2(1 + \nu_s). (E_s. t_{skirt})/E_s. R \quad (5)$$

To check this assumption, a parametric study is conducted firstly by variation of the Young's modulus of the soil E_s , Soil Poisson's ratio ν_s and the ratio t_{skirt}/R are kept constant. However, the Young's modulus of the soil is varied to obtain different values of stiffness coefficients .

Thereafter, The stiffness coefficients (K_H, K_M and K_{MH}) are computed and plotted as function of S . The results of the present study are showed in the Figure 2 and compared with those obtained by Doherty *et al.* (2005):

iv. Analysis and discussion of the results

Table I shows a negligible difference of stiffness coefficients between the computed results and results provided by Doherty *et al.* (2005), for a caisson with a radius $R=4m$ and a skirt having a thickness $t_{skirt}=0.03m$.

It is useful to introduce a parameter which depends on the characteristics of the soil and the caisson. This parameter is symbolized S representing the overall rigidity of the system, putting S this parameter.

As shown in Figure 2, the stiffness coefficients K_H , K_M and K_{MH} vary exponentially as function of S . But, there is a domain for S (Between 1 to 10^{-2} and between 10^3 to 10^5), which stiffness coefficients become constant and the curve constitute almost a horizontal line.

The increase of stiffness coefficient as function of S explain how this parameter control the overall rigidity of the system soil-foundation, we can check from the graphs that the behavior of the caisson becomes rigid for a high values of S and contrary for a small values of S the behavior becomes flexible.

The comparison of the results obtained in the present study against those of Doherty *et al.* (2005) reflects that the Scaled Boundary Finite Element Method underestimates K_H and K_{MH} for a high values of S it means in the rigid domain, furthermore, this method underestimate K_M for a small values of S it mean in the flexible domain.

I. Illustrative Example

In the present application, we take a caisson with a radius $R=12m$ and a slenderness ratio $d/R=1$ as shown in the Figure 11.

The shear modulus of the soil $G_s=3.10^3kN$ and his Poisson's ratio $\nu_s=0.2$. The thickness of the skirt $t_{skirt}=0.01m$ and that of the lid $t_{lid}=0.1m$

Assuming a horizontal load $H=4.10^3kN$ acting at a height of 20m from the seabed level, resulting in overturning moment $M=8.10^4kN$.

The stiffness coefficients which correspond for this example are: $K_H=10.7035$, $K_M=18.4574$ and $K_{MH}=-8.9605$.

Furthermore it is easy to obtain the lateral displacement u and his deflection θ :

$$u = (K_M/K_M K_H - K_{MH}^2) (H/G_s R) - (K_{MH}/K_M K_H - K_{MH}^2) (M/G_s R^2) \quad (6)$$

$$\theta = (K_H/K_M K_H - K_{MH}^2) (M/G_s R^3) - (K_{MH}/K_M K_H - K_{MH}^2) (H/G_s R^2) \quad (7)$$

By substituting the stiffness coefficients K_H , K_M and K_{MH} , the shear modulus G_s and the poisson's ratio of the soil ν_s , the caisson's radius R , the horizontal loading H and the overturning moment M in eq.(6) and eq.(7), we have:

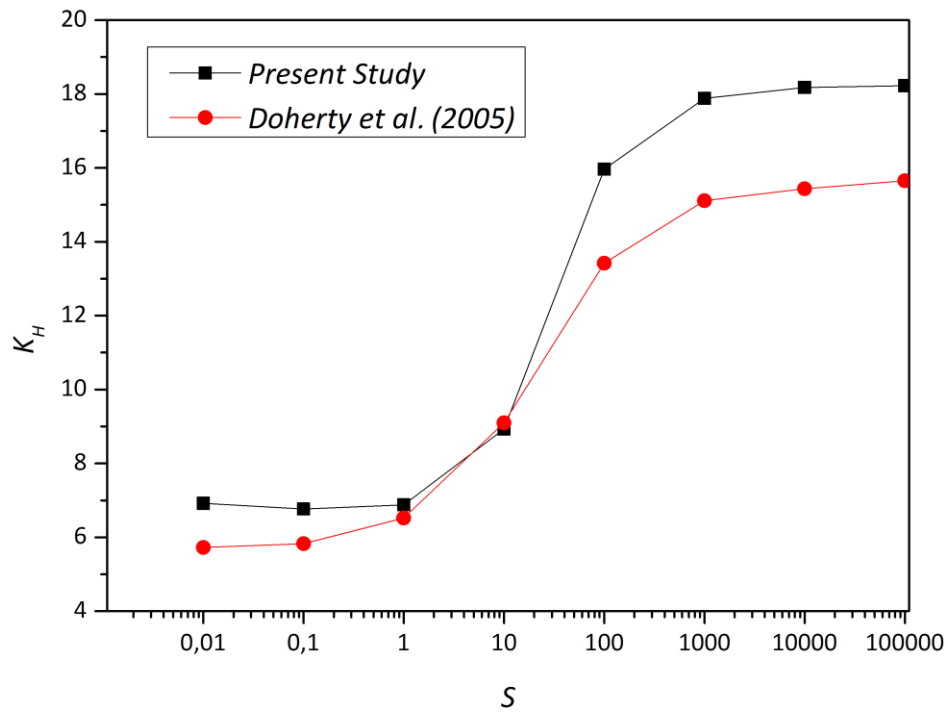
$$u = 3,5. 10^{-2}m$$

$$\theta = 23,3. 10^{-4}rad$$

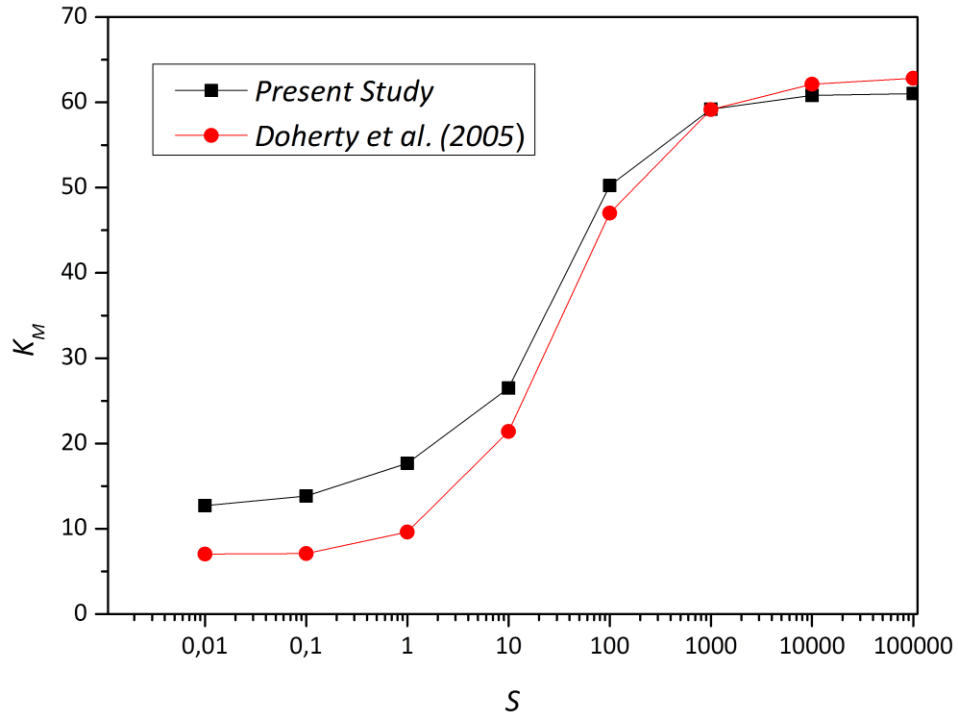
Table II provides a comparison between the computed results and those obtained by Doherty and Deeks (2003):

TABLE I. Computed stiffness coefficients for an embedded caisson in Gibson's soil.

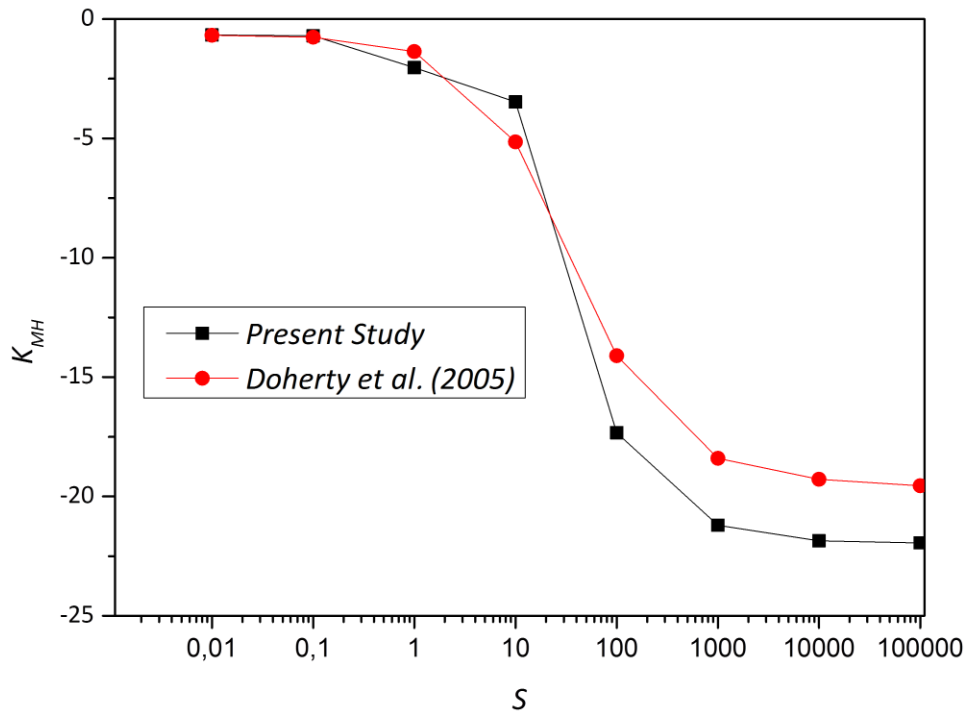
Stiffness Coefficient	Present Study	Doherty <i>et al.</i> (2005)	Difference (%)
K_H	13.13	12.67	3.50
K_M	45.59	42.09	7.67
K_{MH}	-12.31	-12.75	3.45



(a)



(b)



(c)

Fig. 2 Stiffness Coefficients, (a) K_H , (b) K_M and (c) K_{MH} for a skirted caisson embedded in a Gibson soil with $\nu_s=0.499$

TABLE II. Displacement and Deflection Computed in the present example.

	Present Study	Doherty and Deeks. (2005)	Difference (%)
$u (m)$	$3,5 \cdot 10^{-2}$	$3,3 \cdot 10^{-2}$	5,71
$\theta (rad)$	$23,3 \cdot 10^{-4}$	$20,0 \cdot 10^{-4}$	14,16

As we can see in table II, a small difference is noticed between results of the present study and those obtained by Doherty and Deeks (2005).

• Conclusion

The linear behavior of a skirted caisson laterally loaded in the elastic domain has been exploited in this paper. Fourier Series Aided Finite Element Method is used in this work to address the problem. This approach combines the finite element method which is based on the use of 2D discretisation in the radial direction with the expansion of displacements and loads in Fourier series in the circumferential direction. This method is used to identify the overall behavior of the system caisson-surrounding soil by means of stiffness coefficients. Different soil profiles and caisson's geometries are considered to achieve this analysis. The present study gives excellent results compared with previous existing works. This confirms the efficiency of the method used in the analysis. Finally, a simple example is provided to show the utility of the proposed solutions.

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