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Analysis of Response of the Monopile Foundations of Offshore Wind Turbines

Michail S. Spyridis, Susana Lopez-Querol
University College London, London, United Kingdom

ABSTRACT

The bearing structure of wind turbines in offshore environments is composed of two domains, the steel superstructure and its steel hollow pile foundation which transfers pressures to the soil. The interaction between these domains is of great importance for the dynamic behaviour of the wind turbines. Nevertheless, usual design considerations assume solid pile section of equivalent material properties affecting the accuracy of their analysis. Thus, this study aims at comparing the response of simplified (more efficient from the computational point or view) and complete numerical models, including all the actual geometrical features, under both static and dynamic conditions. In view of this development, detailed Finite Element Method (FEM) models are created within ANSYS, emphasising in the soil-structure interaction effect. For this purpose, material and geometrical nonlinearities are considered into the models. Herein, comparative results of the pile-foundation response of the actual geometry with state-of-practice solutions are presented for both static loadings and dynamic excitations.

INTRODUCTION

The onshore wind turbines are of limited energy production in comparison with the offshore ones. This depends on the stronger and more stabilised wind conditions which exist in the offshore environment. As a consequent of that, the energy industry has started to build offshore wind farms, with the focus to be on the installation of greater energy production wind turbines (Cuéllar, 2011). This results in greater dynamic loadings for the wind turbine superstructure. In addition, the offshore environment exposures the wind turbines not only to wind loading but also to sea waves. Therefore, such systems are subjected to amplified and long term dynamic pressures which are transmitted to their foundations, causing the gradual degradation of the soil stiffness which can induce changes in the dynamic characteristics of the bearing structure (Bhattacharya, Lombardi, & Muir Wood, 2011). This effect is of great importance in monopile foundations, with a trend of increasing research efforts to be concentrated in the long term analysis of soil-pile interaction [(Achmus, Kuo, & Abdel-Rahman, 2009);(Leblanc, Houlsby, & Byrne, 2010);(Cuéllar, 2011);(Cuéllar, Georgi, & Baeßler, 2012)].

The long term numerical analysis of such systems demands high computational time. This is mainly due to both materials and contact nonlinearities, in addition to the high number of elements required to achieve convergence and an accurate solution. On the other hand, state-of-practice considerations neglect such effects providing design solutions with the well-known p-y curves. The focus of this study is to analyse the response of monopile foundations, considering the mentioned nonlinearities, and to compare it with equivalent systems developed based on the elastic theory. Initially, the response of the systems is investigated under static conditions, and further on their dynamic simulation is carried out.

NUMERICAL MODELLING

The wind turbine-monopile foundation system is composed of two domains, the soil and the steel hollow cylindrical section, as shown in Figure 1 (a). Advanced numerical modelling of such systems necessitates the simulation of the sliding in the interface between them. In view of this development, contact elements are employed with a friction coefficient of 0.4, as it is provided by (Abdel-Rahman & Achmus, 2005). These elements add nonlinearities to the system, in addition to those of the plastic nature of the soil material. For the latter nonlinearities, the Mohr-Coulomb elastic-plastic law is adopted for the soil, (see Table 1 for the values of the parameters), whereas the pile section is examined by means of elastic analysis.

Table 1 Mohr-Coulomb elasto-plastic law properties for the soil

Cohesion, c(Pa)	**Friction Angle, φ(˚)**	**Dilatancy Angle, ψ(˚)**	**Residual Cohesion, c΄(Pa)**	**Residual Inner Friction Angle, φ΄(˚)**
10^3	35	5	10^3	35

The analysis of the described numerical systems demands significant computational effort. This is mainly induced by the high number of elements, in addition to the material and sliding nonlinearities. Furthermore, the slender hollow section introduces numerical instabilities, especially when it is combined with the friction elements. Hence, the need for a model which reduces the computational time and neglects the numerical issues, arises. For this purpose, this study examines an equivalent 3-dimensional equivalent monopile, as it is proposed by Lopez-Querol et al. (2019), Figure 1(b). The assumptions for the estimation of the elastic properties of the equivalent solid pile are based on elastic theories, and they can be found in Table 2.

In more detail, the mentioned elastic properties of the equivalent solid pile are distinguished into two parts, the properties of the substructure and the properties the foundation, Figure 1. The properties differentiate due to the consideration of the inner part of the soil into the calculations. The first step is referred to the evaluation of the density of the equivalent solid area. Secondly, the moment inertia of each component is estimated by equation 1, with the ultimate objective to be the evaluation of flexural rigidity (EI) of each section. Finally, the Young’s modulus of each part of the equivalent solid pile can be found equalising the flexural rigidity of it with the corresponding one of the hollow pipe.

$$I = \int_0^M r^2 \, dm \tag{1}$$

Table 2 Material Elastic Properties

Elastic Properties	**Soil**	**Hollow Steel**	**Solid Foundation**	**Solid Substructure**
E [kPa]	40000	$2.1 \cdot 10^8$	$6.7 \cdot 10^7$	$4.1 \cdot 10^8$
I [m^4]	140.93	56.45	176.86	28.91
v [-]	0.25	0.3	0.3	0.3
ρ [ton/m^3]	2	7.85	2.277	0.372

The examined geometry of the monopile foundations is based on the latter reference, and takes into consideration the substructure of the wind turbine. Differences of minor importance can be observed between the two models, which may induce localised deviations in the response of them, but they cannot affect the total dynamic behaviour. These differences are referred to the inner soil part of the hollow section where nonlinearities take place due to the interaction between them. Moreover, this inner soil part is a continuum body with the rest of the foundation, whereas the solid pile provides only frictional resistance at the bottom of the pile. At this level the elements of the hollow pile and the soil foundation can be assumed bonded, as they tend to move jointly, providing to the model numerical stability. Finally, the numerical models are restrained by elementary boundary conditions at the side abutments of the soil foundation.

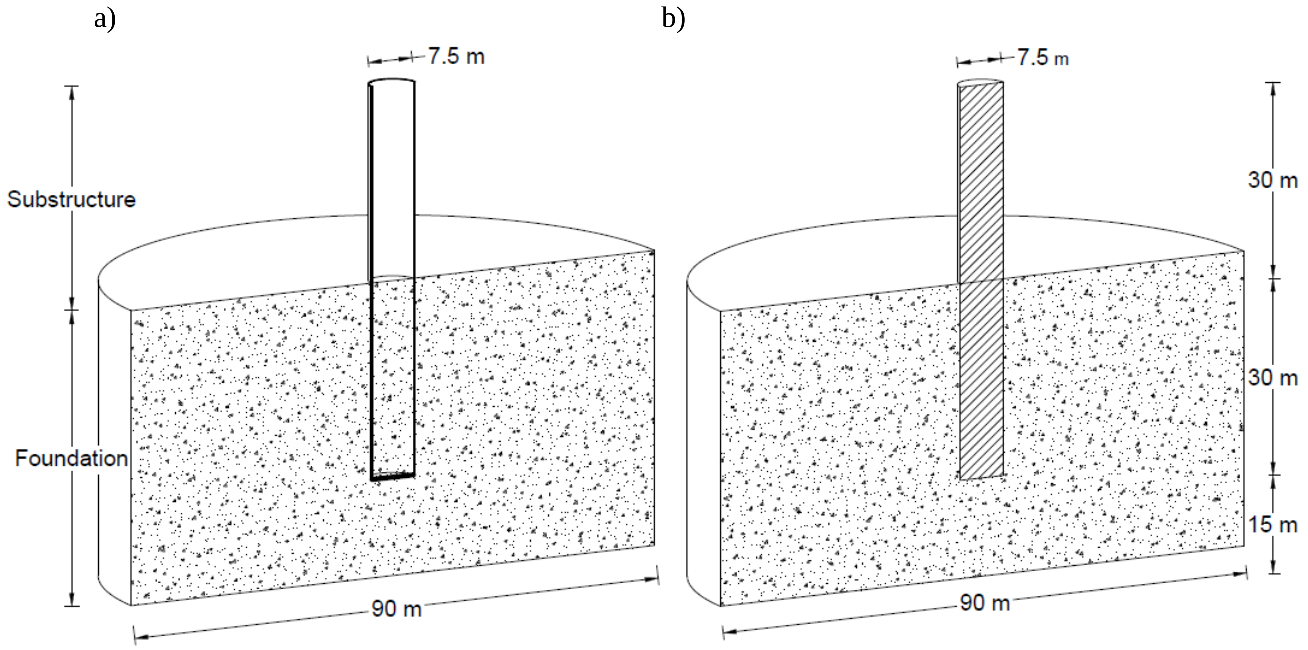


Figure 1. Wind Turbine-Foundation System: a) 3D Hollow Steel Section b) 3D Equivalent Solid Section

STATIC RESPONSE OF MONOPILE FOUNDATIONS UNDER STATIC CONDITIONS

Initially, the validation of the equivalent solid pile is examined under static conditions. The model is symmetric, for this reason, an equivalent lateral load of 4MN and a vertical load of 3MN are applied at the top of the substructure. The resultant behaviour of six vertical profiles for the foundation and the pile are examined herein, and their location can be found in Figure 2(a).

As it can be observed from Figure 2(b), the simplified model with the equivalent solid section tends to describe the horizontal deformations of the pile in regards to the initial one. Although, its resultant behaviour tends to describe a rigid body in contrast with the hollow pile, both of them have identical point of rotation. This provides reliability to the equivalent solid pile under static conditions, but more importantly implies the great contribution of the soil material in the response of the pile.

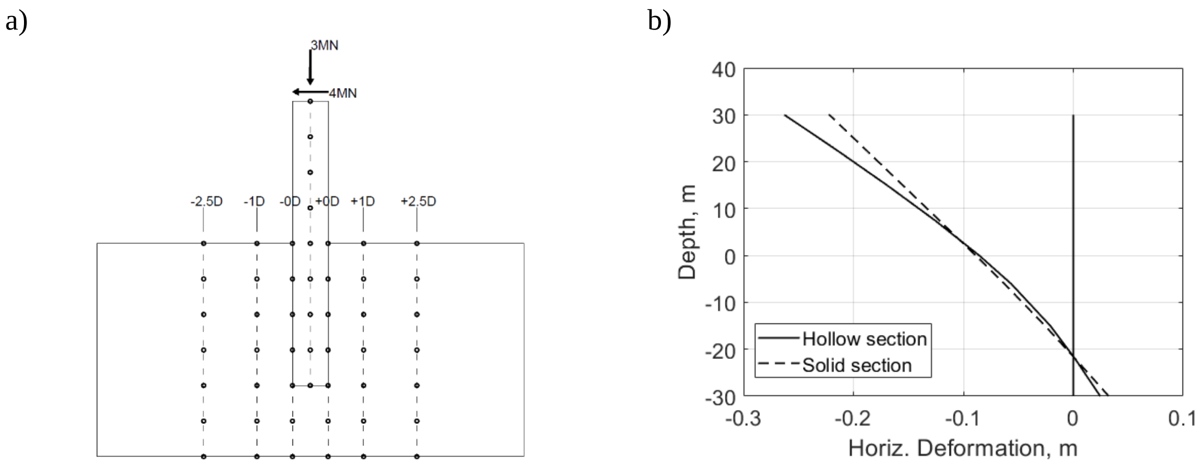


Figure 2. a) Geometrical definition of nodal results b) Horizontal response of pile

Having the focus on the response of the foundation, the comparison of vertical profiles of horizontal deformation, normal stress and shear stress are presented at different distances of the pile axis, Figure 3. The resultant behaviour under static condition of both numerical models is identical. The main differences can be identified in locations where the response changes abruptly due to the interaction of the slender hollow pile with the soil. As it was described earlier, the hollow pile interacts with the soil from its inner and its outer side differentiating its lateral stiffness gradually as the nonlinearities in the soil increasing. On the other hand, the solid pile has only frictional connection with the soil at its bottom affecting the sliding stiffness at that level. Hence, this results in deviations of their resultant response around that depth of the soil foundation.

The maximum percentage differences of the numerical models can be found for the shear stresses within a range of distance ±1D from the pile, especially at depth of -22.5m to -37.5m. As it was described earlier, the evaluation of the response at the bottom of the pile is expected to have deviations, and this can be noticed not only by the response of shear stresses but also from the normal stresses. At this level, especially for the elements of soil which interact with the pile directly, the normal stresses and the shear stresses difference can reach up to 22% and 35% respectively. The static response of the piles tends to become identical as the distance of the examined vertical profile from the pile increases, Figure 3(c).

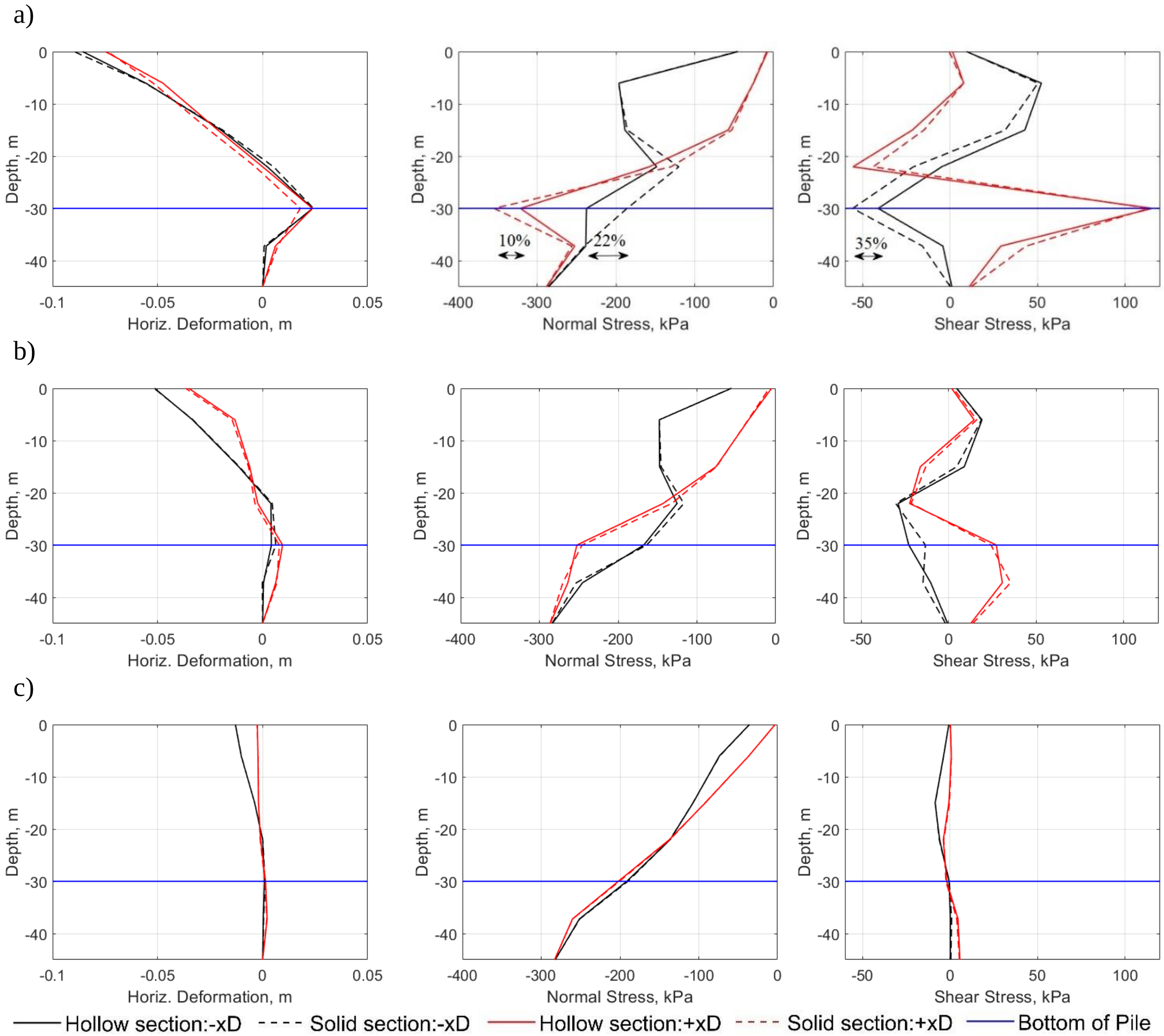


Figure 3. Vertical profiles of horizontal deformation, normal stress and shear stress: at: a)±0D b)±1D c)±2.5D (in the legend, +xD denotes the result x diameters on the right of the pile, while –xD means results at x diameters on the left, from the pile axis).

DYNAMIC ANALYSIS OF OFFSHORE MONOPILE FOUNDATIONS

The monopile foundation of wind turbines is subjected to long term dynamic loads over its design life period, such as dynamic wind and wave loads. This necessitates the focus to be in the analysis of their

response under dynamic conditions. For this purpose, this study brings into light: a) their eigen-properties, and b) their transient response.
The dynamic characteristics of a structural system depend on the material and geometrical properties as well as on the boundary conditions. This is due to the fact that the dynamic stiffness matrix of a system is shaped by the mentioned parameters. In nonlinear systems the aforementioned matrix can be changed incrementally. Therefore, the dynamic properties of a structural system can be affected along its whole design life. It is well-known that the behaviour of soil materials is mainly nonlinear. Hence, the dynamic properties of systems that consist of such materials depend of the amplitude and the frequency content of the external loading.

Eigen-analysis of monopile foundations

Prior to a full nonlinear dynamic analysis, a parametric eigen-analysis of the monopile foundations is carried out by neglecting the material nonlinearities and the contact interaction in the interface of the soil with the pile. This analysis brings into fore the influence of the elastic parameters of the soil material in the dynamic properties of the system. A parametric eigen-analysis for a set of Young's modulus ratios of soil material to steel material (E_{soil}/E_{steel}) is performed, keeping the latter value constant. This provides significant knowledge regarding the dynamic characteristics of the aforementioned systems.

Under the mentioned considerations of a linear system, the first and second eigen-frequencies of the monopile foundation are gradually rised as the stiffness of the soil material increases. This leads to the conclusion that the elastic properties of the soil determine the dynamic behaviour of the monopile foundation (Figure 4). Finally, it should be noted that the pile's diameter and depth have also considered in the parametric eigen-analysis, with the main conclusion to be that they have no significant effect on the eigen-characteristics. This reinforces the statement that the dynamic properties of monopile foundations are mainly defined by the soil material.

a) b)

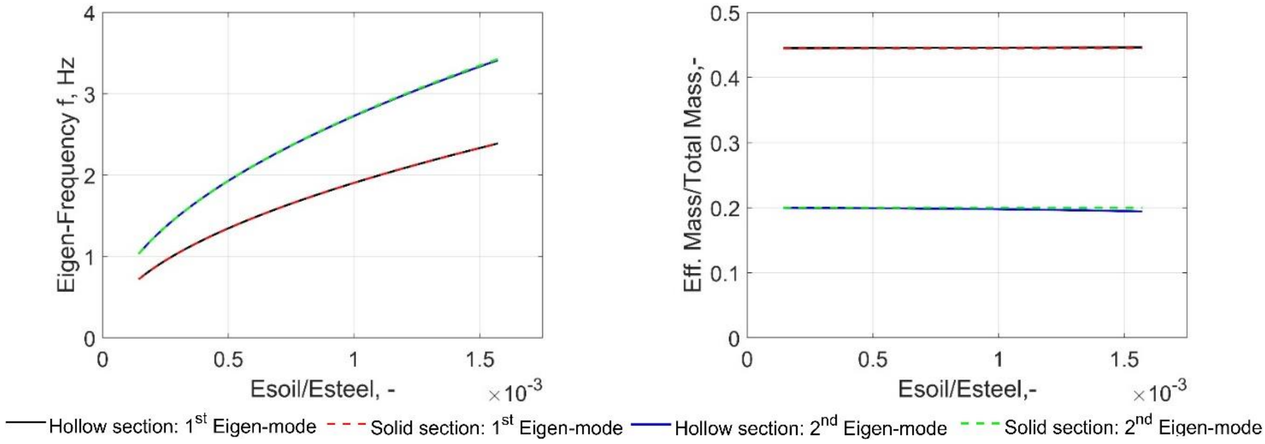
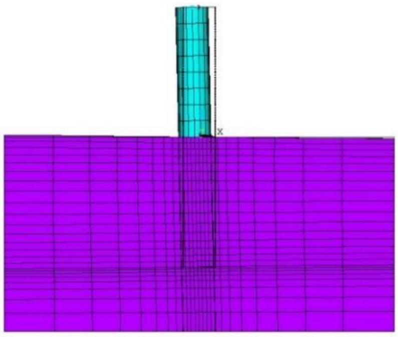


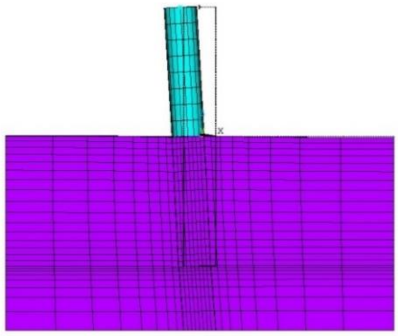
Figure 4 Eigen-properties of monopile foundations system: a) Eigen-frequency b) Ratio of effective mass to total mass

Moreover, this analysis can provide useful information regarding the correlation of the dynamic properties of the two aforementioned examined piles, that is to say, the hollow and the equivalent solid. In fact, not only the two first eigen-frequencies are identical for all the range of the examined Young's modulus ratio, but also the ratio of effective mass to the total mass of the system. The latter ratio remains constant approximately at 45% and 20% for the first and second eigen-mode respectively. Additionally, in Figure 5 it can be observed that the eigen-shapes of the examined systems are similar. As a matter of fact, the eigen-shape of the pile is controlled by the deformability of the soil foundation. In more detail, the relatively flexible foundation absorbs the energy of the system forcing the pile to rotate almost as a rigid body.

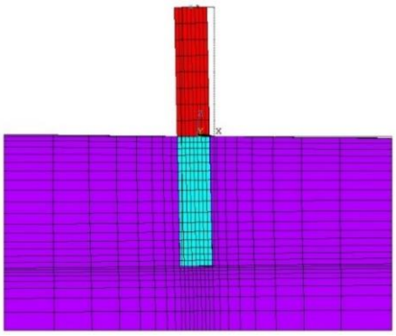
a)



b)



c)



d)

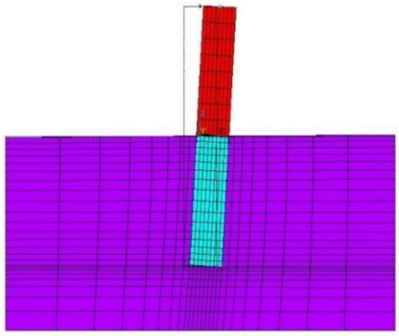


Figure 5 Hollow pile a) 1st Eigen-shape b) 2nd Eigen-shape. Solid pile: c) 1st Eigen-shape d) 2nd Eigen-shape

Dynamic response of wind turbine monopile foundation

Taking into consideration the nonlinearities of the system which are described earlier, the dynamic analysis of the monopile foundation is now investigated. For this purpose, a lateral external force of 4MN (representing half of the total load of 8MN in the symmetric model) with a frequency of 1Hz is applied at the top of the substructure for 50 cycles, additionally to the vertical load of 3MN (half of the total 6MN). It should be noted that the evaluation of the dynamic response is carried out neglecting the damping of the system. This will provide evidence on the correlation between the dynamic responses of the examined piles.

Figure 6 (a) and (b) present the response in terms of horizontal displacement on the top of the superstructure and at the level of the mudline, respectively. From this figure, it can be noticed that both systems have the same frequency response, as it was expected from the eigen-analysis. Nevertheless, important deviations are estimated at the top of the superstructure, which are induced by the differences on the flexural rigidity of the examined piles. On the other hand, identical is the response of them at the level of mudline. This brings into light the great contribution of the soil foundation into the dynamic response of piles.

a)

b)

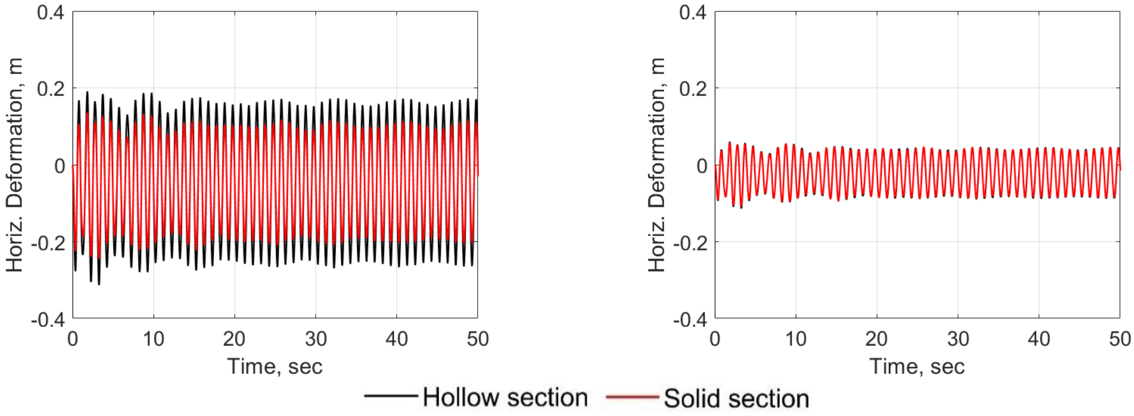
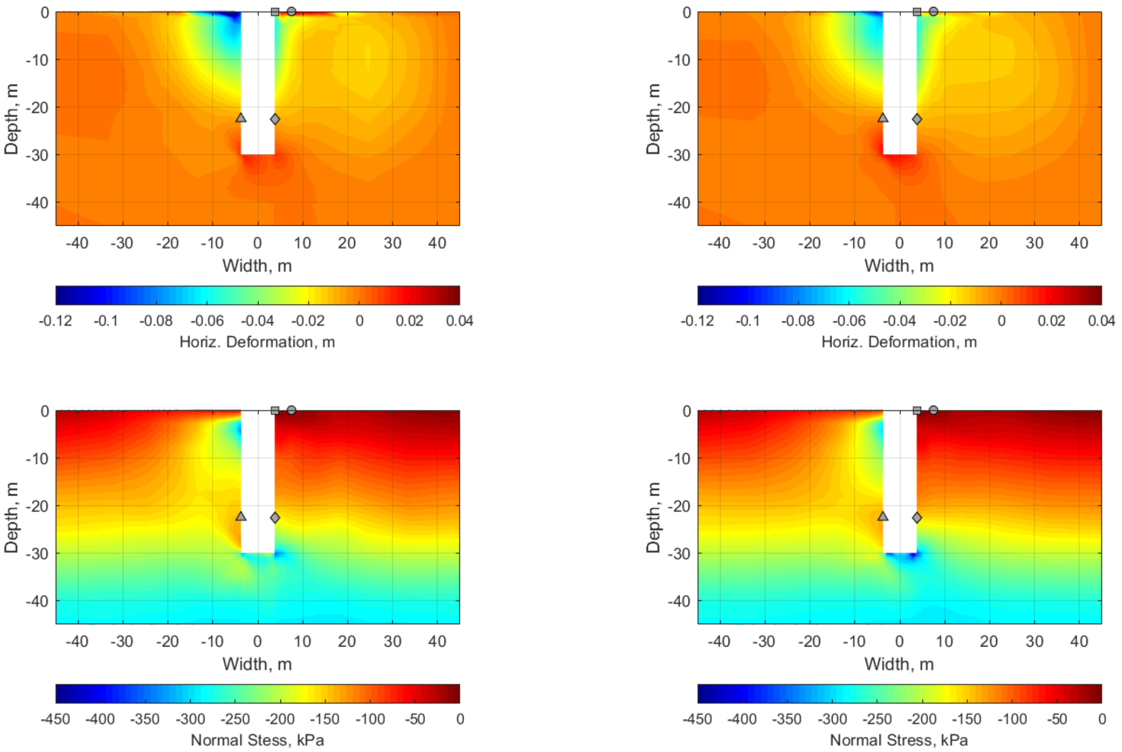


Figure 6 Horizontal deformation of the pile: a) At the top of the substructure b) At the level of mudline

It is recalled that this study mainly focuses on the response of the foundation. For this reason, the horizontal deformation, the normal stress and the shear stress at the peak deflection of the pile at the 50th cycle are illustrated in Figure 7. As it was expected, the greater percentage of disagreement, in terms of horizontal deformation, can be found at the level of mudline within a distance of ±1D. On the other side, similar is the response of the normal and shear stresses, with the main differences to be located at depth of -30m (bottom of pile) due to local effects.

a) b)



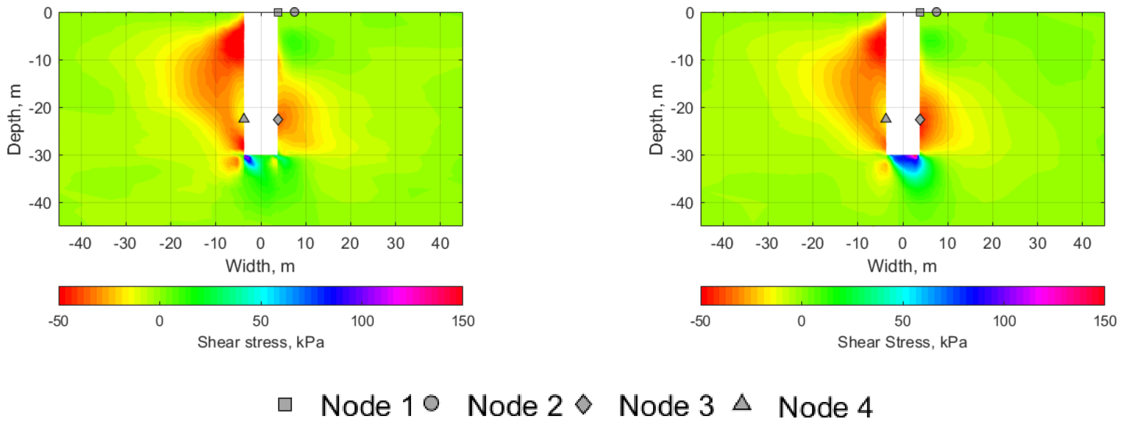
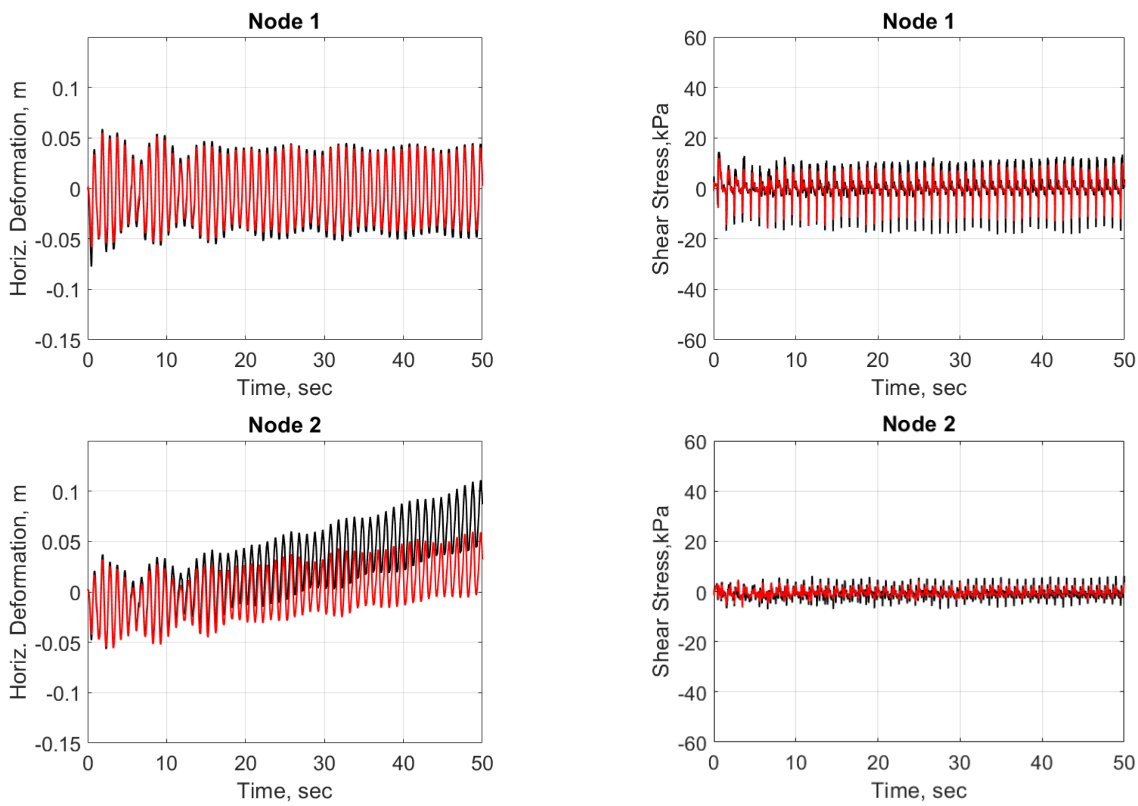


Figure 7 Horizontal deformation, normal stress and shear stress at the peak deflection of the pile at the 50th cycle: a) Hollow pile-foundation b) Solid pile-foundation

In order to have a better perspective regarding the main differences of the response between hollow and equivalent solid piles in the foundation, the responses vs. time at the nodes indicated in Figure 7 are plotted in Figure 8. In more detail, the horizontal deformations and the shear stresses of the selected nodes are illustrated in Figure 8 (a) and (b) respectively.

Concerning the resultant behaviour of the examined piles, it can be stated that they have identical response, with the simplified model to provide smaller displacements and stresses, especially at the level of the mudline. In addition, the difference in the response of the investigated piles can increase with the development of nonlinearities, as it can be noticed from the resultant behaviour of the second examined node. This implies the need of further analysis of the simplified model under large strain conditions.

a) b)



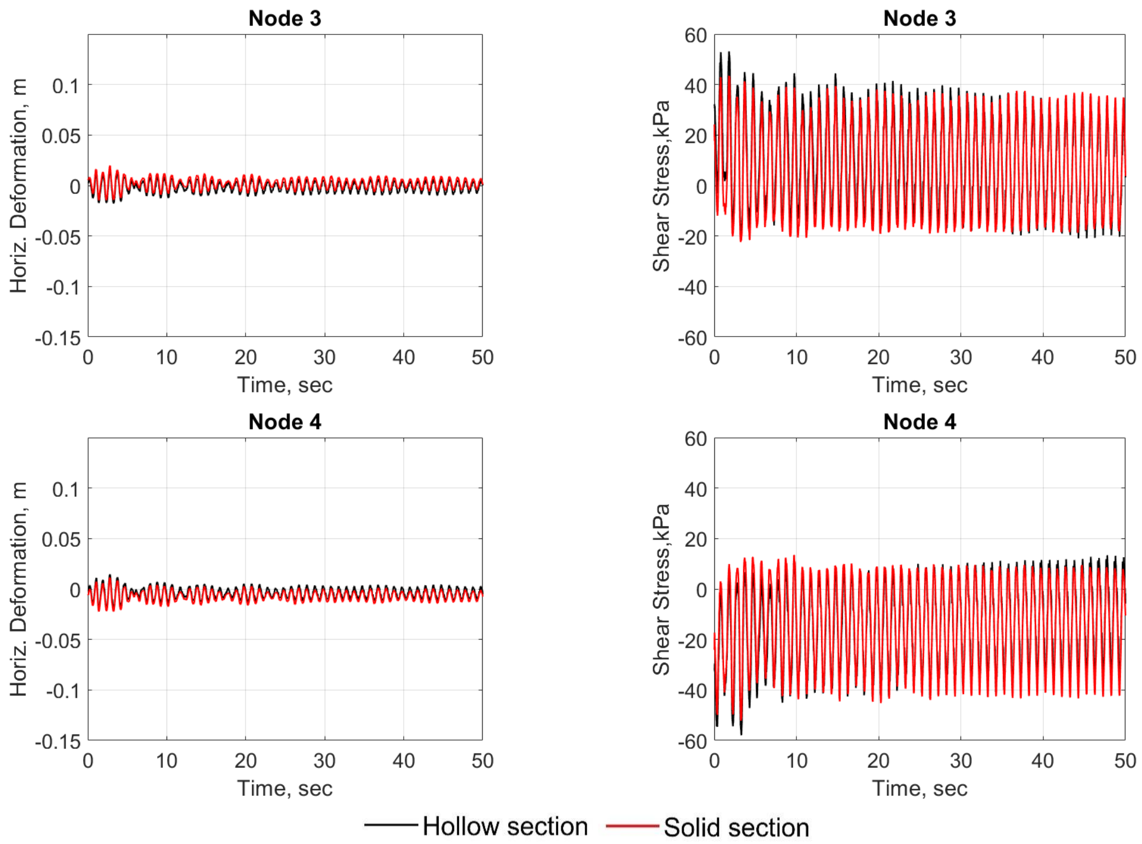


Figure 8 Response vs time: a) Horizontal deformation b)Shear stress

COMPARATIVE RESULTS

Summarizing the results of this study in Figure 9, the accuracy of the equivalent solid monopile foundation for static loading and dynamic excitation can be observed. The coordinates of the points represent the response of the equivalent solid foundation versus the response of the hollow steel monopile. Investigating initially the response of the systems under static conditions, it can be stated that the equivalent solid monopile foundation provides sufficient accuracy.

Nevertheless, the focus in the analysis of wind turbine systems should be on their dynamic response. For this purpose, the peak values of the dynamic response are compared with the corresponding ones under static conditions. Firstly, it can be observed that there is amplification of the response under dynamic excitation in comparison with static loadings. Secondly, the examined monopile foundation present deviations in their response, especially at the top of the substructure, as it was illustrated earlier. Therefore, it can be concluded that the consideration of a linear system for the development of an equivalent solid section provides relatively acceptable results under static conditions. However, the same cannot be stated regarding their dynamic response due to considerable deviations that can be noticed.

a) b)

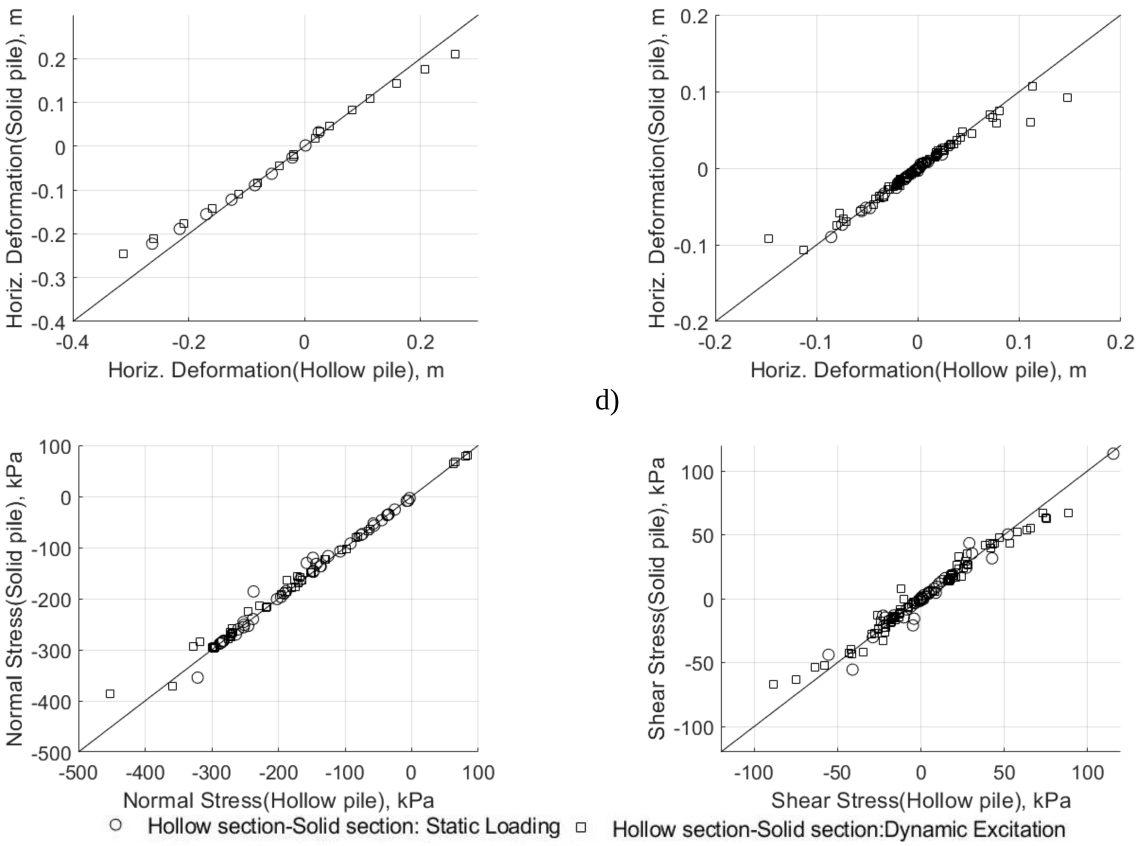


Figure 9 Comparative results of hollow steel monopile foundation and equivalent solid pile foundation: a) Horizontal deformation of pile b) Horizontal deformation of foundation c) Normal stress of foundation d) Shear stress of foundation

CONCLUSIONS

The analysis of response of the monopile foundations has been conducted using FEM models. A proposed equivalent solid pile section is examined herein and it is compared with a model which represents the actual geometry. For the pile-foundation interaction effect, material and geometrical nonlinearities are taken into calculation. Based on the response of the two numerical models, comparative results are presented bringing into light the accuracy of the simplified pile model.

Initially, the static response of the models was investigated resulting in satisfactory results. The maximum deviations in the behaviour of the piles can be found in terms of normal and shear stresses in relatively small distance from the them. This provides a simplified numerical solution for state-of-practice purposes in the design of such foundation systems under static conditions.

This work shows that the eigen-modes of the examined systems are determined principally from the elastic properties of their soil foundation. Although inertial effects from the superstructure have been neglected, the results of this analysis imply that the stiffness of the soil material is of great importance for the dynamic behaviour of the wind turbines. Therefore, the consideration of the soil-pile interaction effect becomes necessary in an accurate analysis of wind turbine systems.

Furthermore, the response under dynamic loading of the monopile foundations presented significant amplification in comparison with the static solution. Significant differences between the two numerical models are estimated at the top of the pile, but not in the soil foundation, especially when the elements are under small strain level. Hence, the equivalent solid pile is proved to be a useful tool for the evaluation of the response of monopile foundations, but it is concluded that it should not be used for their dynamic in critical projects. All the above imply that the dynamic amplification factor of such systems is of great importance: a) for the dynamic analysis of monopile foundations b) for future development of simplified models.

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