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Dynamic stiffness of monopiles supporting offshore wind turbine generators

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ABSTRACT

Very large diameter steel tubular piles (up to 10 m in diameter, termed as XL or XXL monopiles) and caissons are currently used as foundations to support offshore Wind Turbine Generators (WTG) despite limited guidance in codes of practice. The current codes of practice such as API/DnV suggest methods to analysis long flexible piles which are being used (often without any modification) to analyse large diameter monopiles giving unsatisfactory results. As a result, there is an interest in the analysis of deep foundation for a wide range of length to diameter (L/D) ratio embedded in different types of soil.

This paper carries out a theoretical study utilising Hamiltonian principle to analyse deep foundations ($L/D \geq 2$) embedded in three types of ground profiles (homogeneous, inhomogeneous and layered continua) that are of interest to offshore wind turbine industry. Impedance functions (static and dynamic) have been proposed for piles exhibiting rigid and flexible behaviour in all the 3 ground profiles. Through the analysis, it is concluded that the conventional Winkler-based approach (such as *p–y* curves or Beam-on-Dynamic Winkler Foundations) may not be applicable for piles or caissons having aspect ratio less than about 10 to 15. The results also show that, for the same dimensionless frequency, damping ratio of large diameter rigid piles is higher than long flexible piles and is approximately 1.2–1.5 times the material damping. It is also shown that Winkler-based approach developed for flexible piles will under predict stiffness of rigid piles, thereby also under predicting natural frequency of the WTG system. Four wind turbine foundations from four different European wind farms have been considered to gain further useful insights.

1. Background, introduction and a brief literature review

1.1. Challenges in the design of monopiles for offshore wind turbines

Very large diameter steel tubular piles (known as XL or XXL monopiles) and caissons with very low aspect ratio (length-to-diameter) are currently used as foundations to support offshore Wind Turbine Generators (WTG). Around 70% of the world's offshore WTG foundations are large diameter monopiles (3–7 m in diameter installed 15–40 m into the seabed) and accounts for about 20% to 33% of the project costs. The high costs are due to uncertainty in the design (i.e. limited design guidance in codes of practices) as well as fabrication and installation of these relatively new types of foundations. While load and moment carrying capacities (Ultimate Limit State i.e. ULS design which is essentially the moment carrying capacity i.e. strength design) is a necessary condition, the governing design criteria is the SLS (Serviceability Limit State) and FLS (Fatigue Limit State) conditions which requires the estimation of the stiffness of the foundation i.e. pile head stiffness.

Stiffness of the foundation dictates the deformation of the wind turbine tower (which is restricted to 0.5° rotation at the mudline level based on the current DnV code) under operational and extreme loads. Stiffness of the foundation also determines the natural frequency of the whole system which is another design constraint, if not the most challenging aspect of the design process. WTG structures are dynamically sensitive due to the fact that the first natural frequency of these systems (typically 0.25 to 0.35 Hz) are very close to the forcing frequencies imposed upon them by the wave, 1P (rotor frequency) and 2P/3P (blade passing frequency). As a result, obtaining natural frequency of the system is an important design calculation. Further details on the challenges in designing foundations for offshore wind turbines can be found in Bhattacharya [1].

Current design of monopiles is based on the analysis methods

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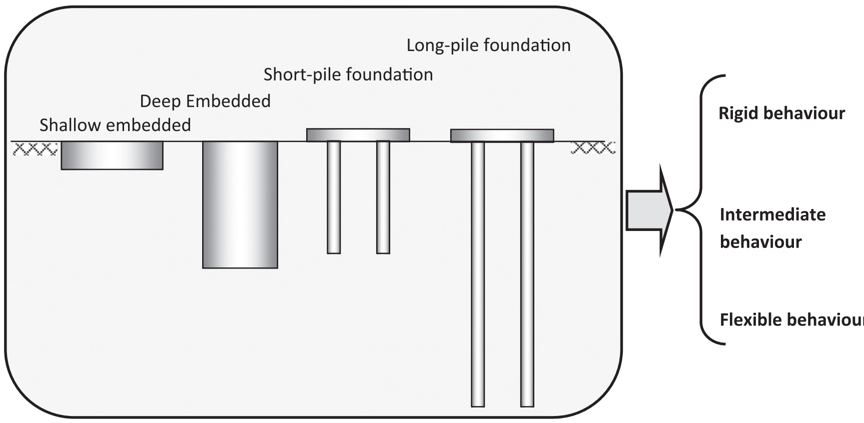

Fig. 1. Foundations category as their behaviours.

for laterally loaded piles (Beam on Winkler Foundations) using non-linear Winkler springs (so called *p*–*y* curves) to model the pile-soil interaction as suggested in API code [2]. It is widely accepted that this approach does not provide satisfactory results in terms of prediction of natural frequency of whole wind turbine system when compared to the measured, see Kallahave and Thilsed [3] in Walney wind farm site. In other words, the stiffness prediction of the foundation is very uncertain which lead to the ongoing joint industry project PISA (Pile-Soil Analysis) [4]. One of the questions raised is the applicability or upscaling of API *p*–*y* curves which were derived for very small diameter piles (high aspect ratio representing long or flexible pile) to large diameter monopiles (low aspect ratio representing rigid pile behaviour). As a result, it is of interest to carry out a systematic study of this problem for a range of aspect ratio (L/D) and relative pile-soil stiffness ratio, as shown in Fig. 1. It is worth noting that this is the motivation behind the work. The next section briefly reviews the literature on this subject.

1.2. A brief literature review on analysis of piles

Using subgrade reaction approach (Beam-on-Winkler Foundation), Hetenyi [5] classified pile foundations as short, intermediate length, and long piles. The boundaries of classification had been refined by Poulos and Davis [6], but keeping the same concept. Adopting the terminology of effective length of laterally loaded pile [7], long-flexible pile was defined as the pile having the length greater than active length (L_{ac}) or effective length (L_c) ([8,9]). Carter and Kulhawy [10] extended the previous investigations by proposing three cases of behaviour for pile as: rigid behaviour, intermediate behaviour, and flexible behaviour. Two lengths were presented to differentiate pile behaviour as: (1) rigid length (L_r), and (2) effective length (L_c). The research presented in this paper examines the above concepts in the light of WTG foundations to be applied to a wide range of elastic soils (homogeneous, linear-inhomogeneous and parabolic-inhomogeneous). To generalize the behaviour of the laterally loaded foundations and piles, the concept of classification (as shown in Fig. 1) will be used.

Piles or general deep foundations can be categorized as embedded foundation, rigid pile, intermediate-stiff pile, and flexible pile depending on the length-to-diameter (aspect/slenderness) ratio and the pile-soil relative stiffness ratio. Finite element (FE) and boundary element (BE) methods are capable of analyzing piles numerically considering full 3D nature of the problem. While these three-dimensional (3D) numerical solutions are feasible, they are not commonly used in practice due to their associated costs and time/expertise required.

Analytical and semi-analytical methods for piles and foundations are not similar, and as a result, they need to be evaluated separately. For example, the response of a massless-rigid-cylindrical-shallow-embedded foundation ($L/D \le 2$) in a layered soil half-space can be analysed by Cone Model [11] Mass-spring-dashpot model [12] and dynamic impedance functions [13,14] developed by analytical or semi-analytical solutions are other simplified methods can be used to analyze shallow foundations. For caissons (drilled shafts, [15]) having length-to-diameter aspect ratio $2 \le L/D \le 6$, Varun et al. [16] has recently proposed Winkler-spring coefficients for side and base resistances. Similar modelling techniques were also to develop nonlinear Winkler springs for caissons [17]. Another example of the use of nonlinear Winkler springs to analyse monopile foundations supporting the OWTs has recently carried out by Bisoi and Haldar [18]. A limitation of the Winkler-based approach is that each soil spring responds independently of the adjacent ones and ignores the shear transfer between the soil layers. As a result, it may not be strictly valid for a layered stratum with sharp contrast of stiffness. Pile foundations may be evaluated by a number of coupled or uncoupled solutions reported in the literature such as [19,20,8,21,22,10,23–26].

Non-dimensional solutions for pile foundations as a practical alternative are based on flexibility functions or impedance functions, initially proposed by Barber [27] and subsequently by Reese and Matlock [28] through subgrade reaction approach. These were further developed by Poulos [29] using elastic continuum solutions based on Mindlin solution, Banerjee and Davies [30] using BE (Boundary Element) methods and Randolph [8], using axisymmetric FE model. These solutions represent a simple method for predicting the pile deflection and rotation at ground level (mudline). Poulos [29] and Banerjee and Davies [30] presented static results in terms of pile-flexibility factor ($K_R = E_p I_p / E_s L^4$) and slenderness ratio (L/D). Since the effect of E_p/E_s is difficult to be distinguished through K_R and effect of slenderness ratio (L/D) is also difficult to be readily visualized [31], Randolph [8] presented a more effective representation for flexible piles where the flexibility functions are expressed as a function of E_p/E_s. Subsequently, Carter and Kulhawy [10] updated Randolph's representation for rigid piles where the flexibility functions are mainly affected by slenderness ratio. In another development, Gazetas and his co-workers [32–34] presented the pile-head impedance functions (as an inverse of flexibility matrix) for static and dynamic loading conditions including swaying, rocking and coupled swaying-rocking terms. Non-dimensional and uncoupled solutions are obtained by fitting curves for practical use.

In many cases, elasto-dynamic solutions are also used as an efficient method for calculating the soil and pile responses as an alternative to the sophisticated-numerical solutions (such as FE models), see for example [26] for long-flexible piles. In this study,