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Influence of pore water in the seabed on dynamic response of offshore wind turbines on monopiles

M. Bayat[a,b,*], L.V. Andersen[a], L.B. Ibsen[a], J. Clausen[a]

[a] Department of Civil Engineering, Aalborg University, Thomas Manns Vej 23, DK-9220 Aalborg Ø, Denmark
[b] Liftra, Stationsmestervej 81, DK-9200 Aalborg SV, Denmark

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ABSTRACT

The well-known *p-y* curve method provides soil-structure interaction that does not account for the pore pressure effect for dynamic analysis of offshore wind turbines (OWTs). In order to avoid overly conservative designs, reliable estimates of the dynamic response should be taken into account. The turbine is introduced using a simplified model to assess the eigenfrequencies and modal damping, accounting for pore water flow and excess pore pressure around the monopile. Thus the effect of pore pressure and load frequency are illustrated by implementing a poroelastic model to present more realistic dynamic properties and compare them with results obtained by the *p-y* curve method. A cyclic loading is considered and the soil stiffness based on the Winkler and Kelvin models is calculated and compared while the soil damping for the Kelvin model is computed. Developed finite element programs are employed to present the results for a two-phase system consisting of a solid skeleton and pore fluid, based on the $\mathbf{u}$-P formulation. Here, $\mathbf{u}$ is grain displacement and P is pore water pressure. The developed codes have been validated with commercial software and are implemented to perform free vibration tests to evaluate the eigenfrequencies. A linear poroelastic material model is utilized. An equivalent masses-dashpots-springs system at the pile-cap level is calculated and compared by using Winkler and Kelvin models to highlight the effect of pore pressure and load seepage damping.

1. Introduction

Several foundation concepts such as monopile, suction caisson, jacket, tripod and gravity foundations have been developed for offshore wind turbines (OWTs). The monopile foundation is analyzed in this paper, since it is the far most used foundation concept for OWTs. A monopile foundation consists of a tubular support structure that extends into the seabed. Offshore wind turbine foundations (OWTFs) are subjected to time-varying loads from waves, wind and ice, and during operation blade passage across the tower as well as imbalances in the rotor cause cyclic loading. It is vital to capture the integrated effect of the total loads. However, the total loading can be significantly less than the sum of the constituent loads. This is because the loads are not coincident, and because of the existence of different kinds of damping such as aerodynamic and soil damping which damp the motions due to the loads. The overall weight of the modern wind turbines is minimized, which makes it more flexible and corollary more sensitive to dynamic excitations at low frequencies. Based on Det Norske Veritas (DNV) [1] and Risø [2] as a design guideline, the deformation of a monopile can be calculated by using the Winkler approach; hence, the soil is modelled as non-linear springs attached along the pile, and the pile is modelled as beam elements. In the lateral direction, the non-linear springs represent the relationship between the lateral deflection distance y, and the mobilized resistance from the surrounding soil p [3]. This method was originally developed for static analysis of piles, and it therefore needs modifications to provide reliable results for OWTFs subjected to dynamic and cyclic loads. In order to have better assessment of soil-structure interaction, the coupled flow and deformation associated with the motion of fluid and solid grain particles should be considered. The *p-y* curve method has been implemented to account for soil-pile interaction [4–12] and theoretical results are compared by experimental investigation [13–16]. Design guidelines such as American Petroleum Institute (API) [3] or DNV [1] and Risø [2] present *p-y* curves for sand and clay. However, these curves were originally developed and intended for use in projects with piles having a large slenderness ratio as found, typically, in other fields of offshore engineering, e.g. jackets and oilrigs, and on land. However, application of the *p-y* curve method for OWTFs has many shortcomings, cf. [17–19]. Firstly, monopiles are not slender. They have length-to-diameter ratio of 5–7 and usually exhibit “toe kick”, whereas slender piles have no movement at the toe

* Corresponding author.
E-mail addresses: Bayat_me@yahoo.com, Bayat.me@gmail.com (M. Bayat).

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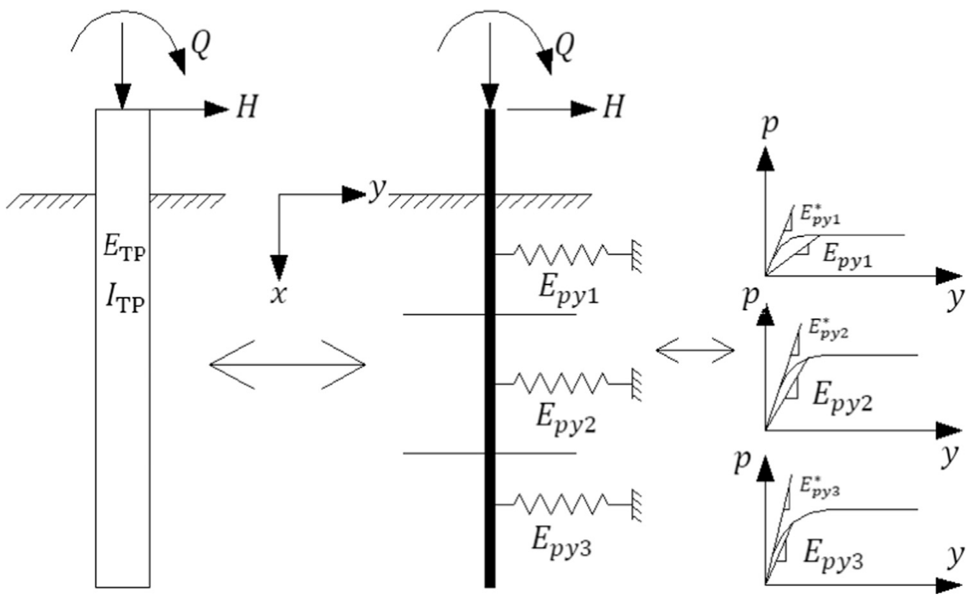

Fig. 1. Winkler model approach and definitions of $p-y$ curves [1].

(bottom). Secondly, as further addressed in this paper, the effect of pore pressure is not comprised in the *p*-*y* curve method. In order to include the effect of pore pressure, coupled equations for the soil and pore fluid are needed. Furthermore, to analyze short piles the described method in [71–73] and references in there can be referred. Likewise, research attention has been focused to investigate the soil-structure interaction for laterally loaded piles s based on experimental modeling studies [74–76]. These studies deliver valuable information for a better understanding of the piles' behaviour

In this context, the estimation of a reliable first natural frequency of the combined foundation and turbine structure is presented. To avoid dynamic amplification of the response, the first natural frequency of the wind turbine structure, including its foundation, must lie within a narrow range. Unfortunately, accurate and realistic natural frequencies cannot be quantified by a *p*-*y* curve method. Several studies have presented dynamic response and calculated natural frequencies of OWTs based on a single-phase soil model and the *p*-*y* curve method. Traditionally, simplified soil stiffness functions (*p*-*y* curves) are developed for small-diameter piles, not accounting for dynamics and representing the soil stiffness incorrectly for monopiles. The damping is also not very well predicted in this traditional approach. The inaccuracy in prediction of soil stiffness and damping implies significant safety margins in design. Therefore, additional modeling and research into this field is required. In this research the effect of pore pressure and damping will be considered to estimate the first three natural frequencies. The existing *p*-*y* curve method does not account for two phase material and excess pore pressure in the soil stratum during cyclic loading. In this study a combination of springs and dashpots is employed to interpret the visco-elastic response of pile-soil interaction. For simplicity, the linear poroelastic model is employed. Consequently, a linear viscoelastic model in the reduced formulation can be represented. Serviceability requirements for offshore wind turbines allow rotations of 0.5° at the mudline. Rotation of this magnitude is typically reached within the elastic, rather than the plastic, strain regime in the soil, leading to the assumption of elastic behaviour in this paper. Essentially, small settlement and rotation of offshore foundations are controlled by viscous linear elastic behaviour [20].

In order to have the effect of pore pressure and soil deformation, two-phase coupled equations are needed. Three general coupled and dynamic formulations, based on the soil and pore fluid (water) displacements and the pore water pressure, are the **u**-*P*-**U**, **u**-*P*, and **u**-**U** equations, where**u**, *P*, and **U** are the soil skeleton displacement, pore water pressure (PWP), and pore water displacement, respectively [21]. Cheng and Jeremić [22] used a fully coupled, inelastic **u**-*P*-**U** formulation to simulate the dynamic behaviour of piles in liquefiable soils

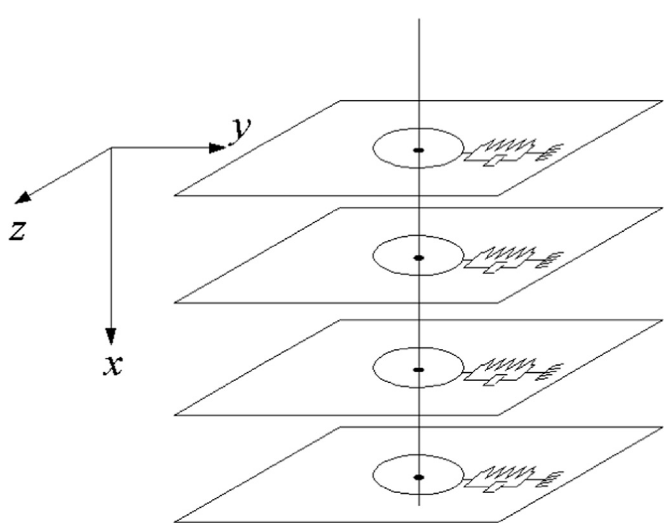

Fig. 2. Kelvin model consisting of a spring and a dashpot in each depth.

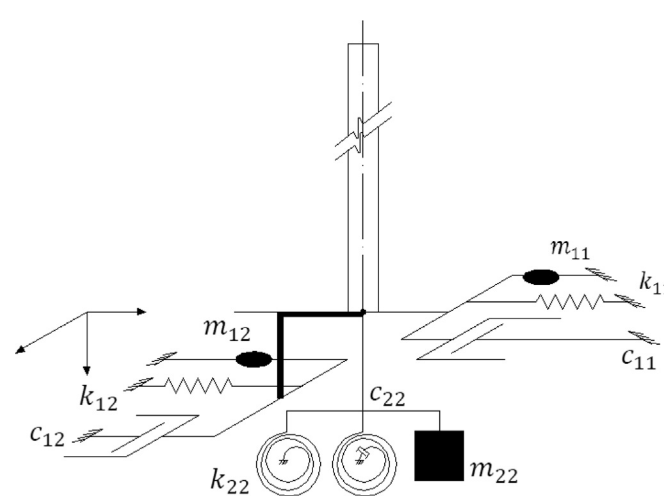

Fig. 3. Equivalent mass-dashpot-spring ($\mathbf{M}_{cap}$, $\mathbf{C}_{cap}$ and $\mathbf{K}_{cap}$) model at pile cap.