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A comparison of initial stiffness formulations for small-strain soil–pile dynamic Winkler modelling

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ABSTRACT

Dynamic Soil-Structure Interaction (DSSI) is an area of much ongoing research and has wide and varied applications from seismic response analysis to offshore wind foundation response. DSSI covers a wide range of load regimes from small-strain vibrations to large-strain cyclic loading. One of the most common ways to model DSSI uses the Winkler model, which considers the soil as a series of mutually independent springs. The difficulty with modelling DSSI arises with the inelastic and nonlinear load–displacement response of soil with increasing strain, therefore modelling of large-strain DSSI relies on the specification of many interrelated parameters. The relative magnitude of these parameters can have a significant effect on the modelled response. In this paper, the specification of an initial stiffness coefficient to model the elastic (small-strain) response of a soil–pile system is investigated. The coefficient of subgrade reaction method can be used to generate spring stiffness moduli for Winkler type models. A number of subgrade reaction theories have been proposed and their application to the problem of static loading has been widely studied. However, relatively little research concerning the application of these models for small-strain dynamic loading has been undertaken. This paper describes a sensitivity study in which a number of subgrade reaction models were used to estimate the frequency response at small-strain levels for a range of pile geometries and ground conditions. A field investigation was undertaken on two piles with different slenderness ratios to estimate the frequency response and damping ratios. The experimental results were compared to predictions of damped natural frequency obtained from numerical models using the force input and measured damping ratio from each experiment. The ability of each subgrade reaction formulation to model the response at small-strain levels is evaluated.

1. Introduction

1.1. Dynamic soil-structure interaction (DSSI)

Dynamic Soil-Structure Interaction (DSSI) is a vital aspect of the design of many structures subjected to variable external excitation as part of their in service operation. The response of soil–pile systems to lateral loading is an area of growing research interest. The term 'dynamic' covers a broad spectrum of structural schemes ranging from large-strain cyclic loading to small-strain system vibrations. The response of a soil–pile system is heavily dependent on the nature and magnitude of the loading and a variety of modelling approaches exist that aim to predict the response of these systems under various load schemes. In particular, DSSI is an integral part in the design of offshore wind turbines, which experience periodic excitation from a combination of environmental loading (wind and wave action) and structural effects. The rotor spinning at a given rotational velocity creates an excitation force with a frequency termed the 1P frequency. For a standard, three-bladed, wind turbine, the blades passing the tower induce a second excitation force, the frequency of which is termed the 3P frequency. Waves typically affect wind turbines with excitation frequencies lower than the 1P band, (see Fig. 1). Flexible monopiles are often designed in such a manner as to ensure that the global system has a natural frequency between the 1P and 3P range and it is critical that a designer can accurately predict the system's natural frequency and avoid resonance [1,2]. However, recent field measurements suggest that the soil stiffness values recommended in offshore design codes [3,4] may result in significant errors in estimating the structure's natural frequency.

Understanding a soil's dynamic stiffness is also very important with regard to Structural Health Monitoring (SHM). Recent advances in SHM use changes in the modal properties of

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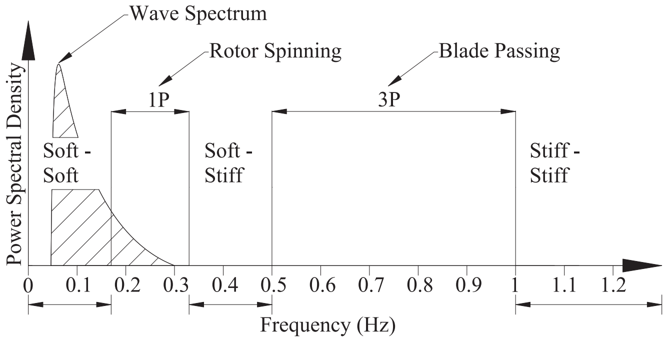

Fig. 1. Frequency bands for typical offshore wind turbines.

structures in order to infer some form of damage [1]. In the case of bridges, most of the work to date has focused on monitoring the superstructure. More recent research has begun to focus on using these damage detection methodologies on sub-structural elements (see [5–7]). In these cases, the analyses can be quite sensitive to the soil stiffness assumed in the design where the dynamic oscillations typically remain in the small-strain region.

DSSI is also very important in the field of earthquake engineering where propagating ground motion waves can generate high stresses in a pile foundation. The stiffness contrast between a pile and the surrounding soil tends to modify the transmitted excitation from seismic shear waves leading to an effect known as kinematic interaction. Coupled with this phenomenon, the dynamic response of a superstructure to a seismic excitation leads to additional deformations in the pile foundation, an effect known as inertial interaction [8]. It is very important to be able to accurately model the various components of a soil–pile dynamic system so that the detrimental effects of external actions may be mitigated by design. There are a variety of methods available to model the dynamic behaviour of soil–pile systems.

1.2. *Winkler modelling approach*

In this paper an approach, termed the Winkler model, commonly employed by structural engineers for both static and dynamic soil-structure interaction problems is considered. The model considers the soil as a system of discrete, mutually independent, closely-spaced, springs [9,10]. The pressure–deflection relationship at any point of the foundation element can be generally represented by the equation shown in Eq. (1), (in the absence of energy loss or inertial contributions).

$$p(x,t) = k\,w(x,t) \tag{1}$$

where $p(x,\ t)$ is the applied pressure ($\mathrm{N\,m^{-2}}$) at a given unit of time, $w(x,\ t)$ is the deflection (m) at a given time, and k is the coefficient of subgrade reaction ($\mathrm{N\,m^{-3}}$). The key uncertainty with using a Winkler model for dynamic applications lies with the specification of the parameters required to model the behaviour of the soil under dynamic motion. The issues arise due to the nonlinear and inelastic nature of soil when deformations are large. These parameters include, among others; the initial (elastic) stiffness, load–displacement response curves, cyclic degradation and hardening parameters, unload–reload stiffness parameters and radiation and hysteretic damping coefficients [11]. A number of authors have developed dynamic beam on nonlinear Winkler foundation (BNWF) models for the purposes of modelling the soil-structure response under large-strain dynamic loading. This topic has received much interest in recent times from researchers working in the area of earthquake engineering [8,12,13]. Both Nogami et al. [14] and Allotey et al. [11] give a good overview of the development of general nonlinear soil–pile interaction models for dynamic applications. In [11], a comprehensive discussion is given on the various soil-structure interaction response features and how they can be modelled in a BNWF model. In particular, the paper highlights the inefficiencies of static nonlinear models in accounting for cycle-by-cycle soil-structure interaction effects and kinematic interaction effects for seismic applications, hence the need for the improved dynamic model. A generic cyclic normal force–displacement scheme (cyclic p-y) incorporating backbone curves, unload–reload curves, cyclic degradation and radiation damping as well as other modelling aspects are discussed. Backbone curves are analogous to monotonic loading curves (static p-y, see [4]) and represent the nonlinear load–displacement response of the system due to the first application of the load (virgin loading). These can be represented by either a nonlinear or a multi-linear curve. Unload–reload curves represent the soil-structure behaviour when the load is removed and reapplied (as per a cyclic load regime). The purpose of modelling this aspect is such that the previous maximum force (stress) applied to the soil is memorised by the model. Some coupled BNWF models are capable of directly modelling cyclic degradation, however most other models require the specification of parameters that are a function of dissipated hysteretic energy or cumulative displacement ductility. Generally, cyclic degradation can be modelled by specifying stiffness or strength degradation factors to be applied to unload–reload curves. The rate of degradation for variable amplitude loading will depend on the number of load cycles. Radiation damping, caused by the propagation of waves away from the foundation, can be modelled using a linear or nonlinear dashpot attached in parallel with a Winkler spring. There are a range of methods available to specify damping constants for use with this model.

Kampitsis et al. [8] describe the development of an advanced dynamic BNWF model, developed based on Timoshenko beam theory, to investigate its accuracy in terms of modelling kinematic and inertial interaction of a soil-pile-structure system for seismic applications. The model encompasses the effects of geometrical nonlinearity, rotary inertia and shear deformation. A case study of a pile-column-bridge deck founded in two cohesive soil layers and subjected to earthquake excitation is investigated. The efficacy of the proposed model is investigated against a simplified beam finite-element (FE) model and a fully 3-D continuum FE scheme. The spring configuration in the model consists of a nonlinear p-y spring connected in series with an elastic spring-damper element. The near field plastification of the soil is accounted for by the nonlinear spring and the far-field confining stiffness (viscoelastic characteristics) is incorporated by the elastic spring-damper, known as a Kelvin–Voigt element (see [15]). The model is shown to be capable of producing accurate results with a fraction of the computational time required by the full 3-D FE model. Boulanger et al. [13] evaluates the performance of a dynamic BNWF model against the results of a series of dynamic centrifuge model tests, where two pile supported structures are founded in a soil profile comprising soft clay overlying sand and subjected to nine earthquake shaking events. A parametric study is undertaken to assess the sensitivity of the analysis results to the chosen dynamic p-y parameters and site response calculations. The backbone curves for the p-y analysis in the clay were based on Matlock's recommendation [16] for soft clay and the backbone curves for the sand layer were based on recommendations from the American Petroleum Institute (API) [4]. However, the initial stiffness component for the sand p-y curve was estimated using the elastic theory of Vesic [17], with the small-strain shear modulus (G_0) adopted in the site response analyses. The dynamic response of the free-field soil and the dynamic p-y analyses were undertaken separately. The results of the sensitivity studies suggest that there is a greater uncertainty associated with the site response calculations than