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An iterative method to infer distributed mass and stiffness profiles for use in reference dynamic beam-Winkler models of foundation piles from frequency response functions

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Accurate characterisation of soil behaviour in Dynamic-Soil-Structure Interaction (DSSI) applications remains a significant challenge. Knowledge of the operational soil-structure interaction stiffness is important for applications ranging from earthquake engineering to offshore structures subjected to wind and wave loading. A number of methods have been derived to couple soil and structural properties using beam-Winkler models. One of the key drawbacks of these approaches is the disparity in predicted stiffness depending on the formulation chosen. Moreover, the contribution of soil mass in the dynamic motion of foundations is often neglected. In this paper, a method is presented that uses a Frequency Response Function (FRF) measured from a laterally-impacted pile to estimate operational stiffness and mass profiles acting along the pile. The method involves creating a beam-Winkler numerical model of the soil-pile system, applying a starting estimate of the soil stiffness and mass profiles and calculating weighting factors to be applied to these starting estimates to obtain a match between the measured FRF from the test pile and the calculated FRF from the numerical model. This paper presents the formulation of the iterative updating approach, and demonstrates its functionality using simulated experimental data of typical piles. Simulated data is used as it enables testing a wide range of circumstances including possible issues relating to the influence of the shape of the operational soil stiffness profile, soil density, effects of sensor noise and errors in damping estimation. The method may be useful in finite-element (FE) model updating applications where reference numerical models for soil-structure interaction are required.

1. Introduction

The dynamic response of soil-structure interaction (DSSI) systems is an area of growing research interest. It is a topic with applications in Earthquake Engineering [1,2], Offshore Engineering [3,4] and Structural Health Monitoring (SHM) [5–8], among others. The offshore wind energy sector is undergoing a phase of rapid expansion [9,10], with monopile foundations

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tending towards larger diameters, a phenomenon that is adding growing uncertainty regarding dynamic stability and lifespan of these systems and calling into question existing design approaches. The issue is complex as the dynamic response of soil is strongly dependent on the particle size, geological history, age of the deposit, degree of cementation and the nonlinear stress-strain behaviour among many other factors. Moreover, soil-structure interaction responses are heavily influenced by the nature of loading applied and are affected by load magnitude, rate of application, frequency of loading, stress-history, pore pressure accumulation and dissipation among other factors. In concert with this, there is increasing agreement that design procedures which were originally derived for flexible piles [11,12] may not offer a reasonable estimate of the operating soil-structure interaction stiffness in these stiffer systems [13].

In the field of vibration-based SHM, the dynamic response of a structure is used to infer the presence of damage, such as cracking or corrosion [14,15]. More recently, several authors have begun to look at detecting foundation damage, such as scour erosion, using the vibration-response of a structure [5–7,16,17]. Many of these methods rely on the creation of a reference numerical model of the system [5,8,18–20], for which accurate DSSI stiffness is paramount to obtain matches to experimental data [21]. Recent studies [22,23] have shown that the adoption of a variety of existing models to couple soil and structural properties in a beam-Winkler framework leads to a significant disparity in predicted responses. If reference DSSI models cannot obtain good matches under normal operation, damage effects cannot easily be separated from otherwise normal operating behaviour.

In addition to differences in the various models used to characterise SSI coupling stiffness, the inherently variable nature of soil means accurate characterisation of its properties is challenging. Predicted dynamic responses from numerical models incorporating soil stiffness will be heavily dependent on the accuracy of the soil response characteristics. Reducing the uncertainty will require either (i) a concerted effort to develop new testing practices that reduce or mitigate the errors and unknowns and/or, (ii) the development of suitable model updating approaches to evaluate operating soil characteristics (mass, damping and stiffness) based on simple experimental techniques. The focus of this paper is on the latter, so more attention is given over to existing methods developed herein.

Updating of numerical models using experimental data has received significant attention in the literature [24–32]. Imregun et al. [24] present a FRF-based FE updating method. Using a simple beam model and both simulated and real experimental data, they investigate several performance parameters such as the uniqueness of the updated model, performance against noisy and incomplete data and the effect of excitation direction, among others. They conclude that uniqueness of the solution remains an issue and that noise has a deleterious effect on the error location. Nalitolela et al. [25] present a method for updating model parameters by hypothesising the addition of an imagined stiffness to the structure. FRF data for the structure with imagined stiffness is obtained from the measured FRF of the actual structure. Using eigenvalues derived from the FRFs and from an analytical model of the system, the structural parameters are updated by a sensitivity procedure. The method is demonstrated using simulated and experimental data. Mottershead et al. [26] present a tutorial on the use of the sensitivity method in FE updating. The sensitivity method is based on linearization of the generally nonlinear relationship of measurement outputs (frequencies, mode shapes, displacements etc.) and the model parameters in need of adjustment. A large scale helicopter airframe model updating example is used to demonstrate the procedure. Esfandiari et al. [28] present a FRF-based method to update structural mass and stiffness using vibration data, for the purpose of damage identification. The procedure is demonstrated using a numerical truss model, with simulated noise presence. The method successfully identified location and severity of damage in stiffness and mass when high excitation frequencies are applied. Similarly, Hwang and Kim [27] present a FRF-based method to estimate the location and severity of damage in a structure, and present numerical examples of a simple cantilever and helicopter rotor blade.

Many of the updating procedures described previously are based on FRF data [24,27,28,30,31] and most are demonstrated with application to simple structural examples such as beams or trusses. A method capable of application to pile foundations, which can obtain a reasonable estimate of the operating soil stiffness and mass acting in the dynamic motion, is therefore of interest. In this paper, a method that establishes operational soil stiffness and mass profiles contributing to the dynamic behaviour of a pile in a soil-structure interaction problem is presented, using a FRF-based updating approach. The approach requires a single measured FRF from a target pile and the creation of a reference beam-Winkler model, with an initial guess of the operational soil stiffness and mass. The initial stiffness guess should be informed from geotechnical data, which broadly captures the distribution of stiffness with depth. The method minimises the difference in peak information between target and calculated FRF data of acceleration by updating the guess for the initial stiffness and mass by multiplying these by weightings. An iterative solution is postulated, as due to the distributed mass and stiffness properties of beam-Winkler models (piles), separately updating mass and stiffness is not possible. The developed approach is demonstrated using numerically generated pile FRF data and a range of conditions are trialled, including various pile geometries and distributions of soil stiffness. The effect of noise intrusion (in 'sensors') and measurement error in damping are also investigated. The goal of this study is to postulate an approach that can successfully estimate the stiffness and mass acting on a pile with a view to informing a reference damage model or to enable more insight into operating parameters for improved design procedures. For DSSI applications, inferring distributed mass and stiffness using a single FRF (force-acceleration pair) is reasonable due to the relatively crude approximations required for these applications in reality. Section 2 presents the theoretical background behind the modelling methods employed and information on the target pile models developed to test the procedure, Section 3 presents details of the iterative procedure developed for updating soil stiffness and mass using FRFs, Section 4 presents the results of the analysis, and Section 5 describes how to apply the procedure to real piles.