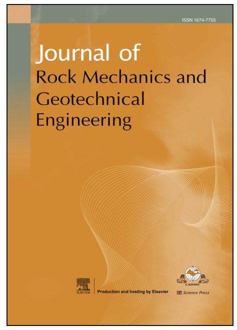

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PII: S1674-7755(17)30284-6
DOI: 10.1016/j.jrmge.2017.11.004
Reference: JRMGE 398

To appear in: *Journal of Rock Mechanics and Geotechnical Engineering*

Received Date: 1 August 2017
Revised Date: 27 September 2017
Accepted Date: 13 November 2017

Please cite this article as: Stacul S, Squeglia N, KIN SP: A boundary element method based code for single pile kinematic bending in layered soil, *Journal of Rock Mechanics and Geotechnical Engineering* (2018), doi: 10.1016/j.jrmge.2017.11.004.

KIN SP: A boundary element method based code for single pile kinematic bending in layered soil

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Received 1 August 2017; received in revised form 27 September 2017; accepted 13 November 2017

Abstract: In high seismicity areas, it is important to consider kinematic effects to properly design pile foundations. Kinematic effects are due to the interaction between pile and soil deformations induced by seismic waves. One of the effect is the arise of significant strains in weak soils that induce bending moments on piles. These moments can be significant in presence of a high stiffness contrast in a soil deposit. The single pile kinematic interaction problem is generally solved with beam on dynamic Winkler foundation approaches (BDWF) or using continuous models. In this work, a new boundary element method (BEM) based computer code (KIN SP) is presented where the kinematic analysis is preceded by a free-field response analysis. The analysis results of this method, in terms of bending moments at the pile-head and at the interface of a two-layered soil, are influenced by many factors including the soil-pile interface discretization. A parametric study is presented with the aim to suggest the minimum number of boundary elements to guarantee the accuracy of a BEM solution, for typical pile-soil relative stiffness values as a function of the pile diameter, the location of the interface of a two-layered soil and of the stiffness contrast. KIN SP results have been compared with simplified solutions in literature and with those obtained using a quasi-three-dimensional (3D) finite element code.

Keywords: kinematic bending; KIN SP; discretization; boundary element method (BEM); pile-soil interaction; soil-structure interaction

1. Introduction

1.1. Literature overview

In seismic areas, piles are commonly designed to resist inertial forces due to the superstructure. Nevertheless, it is important to consider the kinematic effects to properly design pile foundation.

Arise of kinematic interaction phenomena is due to the seismically induced deformations of the soil that interacts with the pile. One of the main important effects of these deformations is the arise of significant strains in soft soil that induce bending moments (kinematic bending moments) on piles.

Pile kinematic response has been studied, among others, by Blaney et al. (1976), Flores-Berrones and Whitman (1982), Kaynia and Kausel (1982), Dobry and O'Rourke (1983), Nogami et al. (1991), Kavvadas and Gazetas (1993), and Tabesh and Poulos (2001). These studies have focused on the motion of the pile-head and only more recently pile bending and curvature have been explored.

Further studies proposed simplified formulations and methods to estimate the maximum kinematic bending moment at the interface of a two-layered soil and/or at the pile-head (Castelli and Maugeri, 2009; Dezi et al., 2010; Dobry and O'Rourke, 1983; Kavvadas and Gazetas, 1993; Maiorano et al., 2009; Mylonakis, 2001; Nikolaou et al., 2001; Sica et al., 2011) using beam on dynamic Winkler foundation (BDWF) approaches.

On the other hand, some authors proposed methods able to study the single pile kinematic problem using continuum-based approaches, such as the boundary element method (BEM) (Tabesh and Poulos, 2001; Liang et al., 2013), the finite element method (FEM) (Bentley and El Naggar, 2000; De Sanctis et al., 2010; Di Laora et al., 2013; Di Laora and Rovithis, 2015; Maiorano et al., 2007; Wu and Finn, 1997a, b) or procedures based on the stiffness method and dynamic stiffness matrices of layered soils (Cairo and Dente, 2007) and hybrid BEM-BDWF approaches (Kampitsis et al., 2013).

Considering the available technical literature about the pile kinematic interaction, it can be outlined that the internal forces generated due to the seismic waves propagation in a pile are affected by the pile-soil relative stiffness (E_p/E_s), the pile-head restraint condition (free-head, fixed-head), the thickness and the mechanical properties of the subsoil layers, and the seismic event used as input, while the pile slenderness ratio (L/D, where L is the length, and D is the diameter) has a minor effect on layered soils with respect to the above aspects. It is well-established that for pile embedded in a layered soil deposit, the bending moment values along the pile-shaft increase at the interface between two adjacent soil-layers with different shear moduli (G) and that the bending moment increment becomes higher as the mechanical impedance increases. More recently, Di Laora et al. (2012) investigated the effect of pile-soil stiffness ratio, interface depth and stiffness contrast in static and transient dynamic conditions on pile bending. In this work, it was found that while the bending strain becomes maximum at resonance, the strain transmissibility function (ε_p/γ_1), relating the peak pile bending strain to soil shearing at the interface, increases with the excitation frequency.

All the research works on this topic have demonstrated that kinematic bending moments can be responsible for pile damage, especially in the case of high stiffness contrast in a soil deposit profile (Fig. 1).

1.2. Simplified design methods

Dobry and O'Rourke (1983) developed a BDWF method that assumes a linear elastic behaviour for the pile and the soil deposit, and the proposed equations are useful to estimate the maximum bending moment at the interface between two layers with different stiffnesses. In this method, it is assumed that the contact between pile and soil is perfect and the soil is subjected to a uniform static stress field.

Nikolaou et al. (2001) on the basis of a parametric study using a BDWF method proposed simplified expressions to evaluate the bending moment at the interface between two soil layers with different stiffnesses in steady-state condition with a frequency approximately equal to the natural frequency of the soil deposit. These expressions are valid when the interface between the two soil layers is located at a depth greater than the pile active length (L_a). L_a can be estimated using the formulation suggested by Randolph (1981).

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