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One-dimensional wave equation analyses for pile responses subjected to seismic horizontal ground motions

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Abstract

This paper presents a numerical one-dimensional wave equation analysis technique for piles and pile groups subjected to seismic horizontal ground motions in liquefiable zones. The so-called Earthquake Wave Equation Analysis for Piles (*EQWEAP*) procedure is introduced for piles subjected to horizontal earthquake excitations. Disregarding the effects of kinematic soil–pile interaction, the seismic responses of piles can be obtained by approximating the free-field ground response analysis, the ultimate earth pressure model, and the ground displacement profiles. The nonlinearities of the concrete piles were modeled using the approximate tri-linear moment–curvature relationships. A case study and application concerns were presented. Although the analysis is in one dimension, it is found to be effective and able to provide a rapid estimation in foundation design when seismic pile behaviors are of interest. The advantages of this analysis are the time efficiency of the seismic design of pile foundations and the relative simplicity of the analysis. In addition, it suggests alternative modeling for the dynamic analysis adopting the commonly known static models and/or methods.

Keywords: Pile; Seismic response; Wave equation; Time-domain analysis

1. Introduction

The seismic responses of piles during earthquakes have been studied extensively over the past few decades. The whole soil–pile structural system can be analyzed utilizing rigorous numerical techniques such as the Finite Element or the Boundary Element method. For simpler and more convenient solutions, Winkler's foundation model is often adopted in design practice. To resolve the pile responses during earthquakes, a simplified two-step uncoupled procedure, that disregards kinematic soil–structure interaction, has been suggested. In this procedure, the free-field ground motions caused by the earthquake are first obtained. The ground displacements are then applied to the piles to solve the corresponding pile displacements. Vertical and horizontal displacements of the piles can be analyzed separately without the influence from torsion. Fig. 1 illustrates the scheme of the uncoupled analysis.

In general, such analyses can lead engineers to find pseudo-static solutions for pile responses. The ground displacements obtained at arbitrary times can be treated as a prescribed displacement profile and can be solved for the pile displacements.

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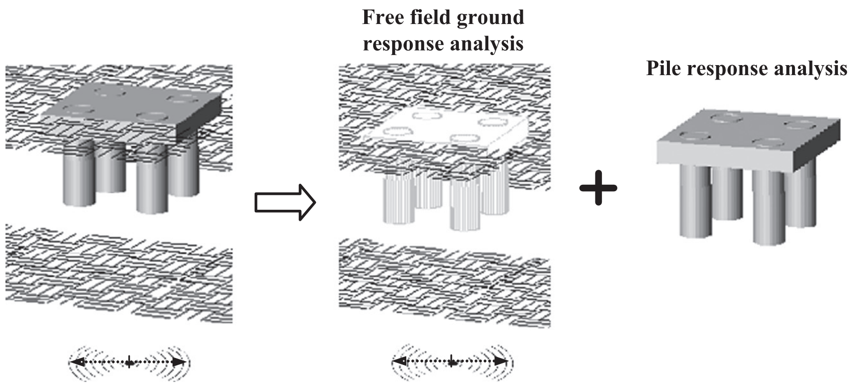

Fig. 1. Schematic layout of two-step procedure for the seismic analysis of pile foundations.

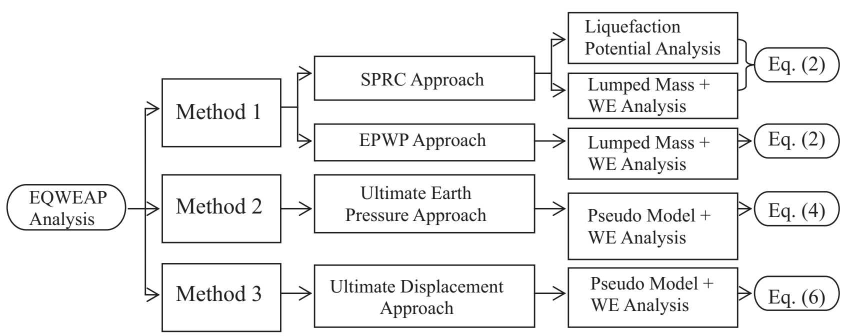

Fig. 2. Numerical schemes of alternate solutions for wave equation analysis.

This pseudo-static modeling can be found in the work of Arduino et al. (2005), Liyanapathirana and Poulos (2005), and Lin et al. (2005) using the static analyses of the Winkler foundation model. Such an analysis allows engineers to find the pile response at a specific time during an earthquake. On the other hand, a real dynamic solution for the pile responses has been suggested by Boulanger et al. (1999, 2003) and Brangenberg et al. (2007) using the dynamic Winkler foundation model. A finite element (FE) structural analysis was implemented and it has been used extensively for bridge pile foundations in California, USA.

Alternative dynamic solutions have been suggested by the authors (Chang et al., 2001; Chang and Lin, 2003; Chang and Lin, 2006) to solve the seismic responses of piles. Instead of FE schemes, explicit finite-difference schemes were first suggested to solve the wave equation of the pile. This procedure was called Earthquake Wave Equation Analysis for Piles (*EQWEAP*). For large earthquake excitations, where soil liquefaction and lateral spreading occurred, a number of soil models were created (Chang et al., 2007a,b, 2008a, b, c). In general, the approaches can include either one of the following models: (1) soil parameter reduction coefficient (SPRC), (2) excess pore-water-pressure (EPWP) model, (3) direct pseudo-dynamic earth pressure, and (4) indirect pseudo-dynamic earth pressure. Fig. 2 presents the numerical schemes of these solutions. The alternate forms of the analysis are discussed as follows.

The objectives of this paper are to introduce the *EQWEAP* analysis and to present the numerical details of such a technique on piles and pile groups subjected to seismic horizontal ground motions in liquefiable zones. The scope is of importance in engineering practice for the design of pile groups in seismically active zones with saturated loose granular media.

2. Wave equation analyses

2.1. Method 1

For a single pile subjected to horizontal ground motions, the equilibrium of the pile segments is shown in Fig. 3. The force terms used in the Winkler Foundation model (Reese and Van Impe, 2001) can be incorporated with the inertia forces of the pile to form a dynamic equilibrium. The dynamic resistance of the soil can include both spring and damping forces. The governing wave equation can be written as follows:

$$E_P I_P \frac{\partial^4 u_p(z,t)}{\partial z^4} + \rho_P A_P \frac{\partial^2 u_p(z,t)}{\partial t^2} + P_o \frac{\partial^2 u_p(z,t)}{\partial z^2} + C_s \frac{\partial u(z,t)}{\partial t} + K_s u(z,t) = 0 \quad (1)$$

where E_P is Young's modulus of the pile, I_P is pile's moment of inertia, ρ_P is the mass density of the pile, A_P is the cross-section area of the pile, P_o is the axial load of the pile, u_p is the absolute horizontal pile displacement, u_s is the absolute horizontal soil displacement, $u = u_p - u_s$ is the relative pile displacement, C_s and K_s is the damping coefficient and the spring constant of the soil along the pile, respectively, z is the depth, and t is the time. Using the central difference formula (explicit scheme), the