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1st Ishihara Lecture: An overview of the behavior of pile foundations in liquefiable and non-liquefiable soils during earthquake excitation

W.D. Liam Finn

Department of Civil Engineering, University of British Columbia, Vancouver, BC, Canada

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ABSTRACT

The seismic response of a pile foundation is usually analyzed by approximate methods in practice. These methods typically neglect one or more of the important factors that affect seismic response such as inertial interaction, kinematic interaction, seismic pore water pressures, soil nonlinearity, cross stiffness coupling and dynamic pile to pile interaction. A nonlinear 3-D analysis is used to show how all these factors affect pile response, to demonstrate some of the consequences of using various approximate methods and to provide a comprehensive overview of how pile foundations behave during earthquakes in liquefiable and non-liquefiable soils.

1. Introduction

Performance based design of structures is design for controlled levels of damage. In order to deliver the expected performance at competitive cost, it is essential to be able to assess reliably the performance of a proposed design, while taking into account all significant factors affecting structural vulnerability. The evaluation may be done using a nonlinear dynamic response analysis. The value of such an analysis depends on how well the structural model represents the real structure. A major weakness in some models is the inadequate representation of the effects of the foundations on the structure, especially of pile foundations. Usually pile foundations are replaced by discrete, single valued springs to model rotational and linear stiffnesses and any coupling between these springs is often ignored. The spring stiffnesses are frequently estimated using approximate, simplified methods of unknown reliability. This is a natural consequence of the complexity of a full 3-D nonlinear dynamic analysis of pile foundations. Even for the elastic case, only a limited number of 3-D parametric studies have been published. These have focused mainly on providing dynamic interaction factors between piles in small groups or frequency dependent stiffnesses and damping for single piles.

A complete picture of the effects of the foundation on the structure during strong earthquake shaking requires taking simultaneously into account many factors such as soil non-linearity, seismically induced pore water pressures, kinematic interaction between piles and soil, inertial interaction of the superstructure with soil and piles and dynamic interaction between the piles themselves. All of these factors can be taken into account by a non-linear, effective stress, dynamic continuum analysis. Such an analysis provides time histories of direct and coupled foundation stiffnesses and demonstrates the effects of kinematic and inertial interactions, the effects of pore water pressures and soil nonlinearity. One prime benefit of such analyses, in addition to their use in the context of a specific design, is that results of parametric studies provide the data base for evaluating the effectiveness of the various approximate methods in use.

The purpose of this paper is to present a comprehensive overview of the behavior of pile foundations during earthquakes in both liquefiable and non-liquefiable soils using non-linear dynamic effective stress continuum analysis. It is hoped that the paper will useful in providing a preliminary basis for a better understanding of the limitations of approximate methods used in practice and when their use is appropriate.

2. Methods of analysis

The pile foundation–structure system vibrates during earthquake shaking as a coupled system. Logically it should be analyzed as a coupled system. However this type of analysis is generally not feasible in engineering practice. Many of the popular structural analysis programs do not include the pile foundation directly into a computational model. Therefore the pile head stiffnesses are typically calculated by analyzing the pile foundation without any mass contribution from the superstructure. The analysis is done usually for a single pile and the group stiffnesses are evaluated using pile interaction factors, often static factors, or a group reduction factor.

Seismic analysis of a pile foundation for design purposes is often conducted by applying the base shears and moments from a fixed base analysis of the structure to the pile head and using

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a static analysis to estimate moments, shears and displacements in the piles. The most common approach to such an analysis is to use a Winkler spring computational model. A general Winkler model is shown in Fig. 1 which can be used for static or dynamic analysis. For static analysis, only the pile and the near field springs are used.

The springs may be elastic or nonlinear. Some organizations, such as the American Petroleum Institute [1], gives specific guidance for the development of nonlinear load-deflection (*p–y*) curves as a function of soil properties to represent nonlinear springs. The API (*p–y*) curves, which are widely used in engineering practice, are based on data from static and slow cyclic loading tests in the field. Murchison and O'Neill [2] suggest that the reliability of the Winkler (*p–y*) model may not be high.

The simple static analysis neglects many important factors that affect the seismic response of the structure–soil–foundation pile system. Inertial interaction between structure and foundation are neglected. This interaction increases the nonlinear behavior of the soil and reduces pile head stiffnesses. These effects increase the period of the system and change the spectral response and hence the base shears and moments. The kinematic moments are also neglected. These moments arise from the pressures generated against the pile to ensure that the seismic displacements of soil and pile are compatible at points of contact along the pile. These moments, which can be captured by a full dynamic analysis, can be very significant. Finally the effects of high pore water pressures and liquefaction on the base moments and shears are treated very approximately. The effects of the neglected factors on pile design vary with the intensity of shaking, site conditions and the details of the pile foundation. As will be seen later, sometimes these factors are important and sometimes not. Intelligent use of the static method requires a good understanding of how pile foundations behave during earthquakes. The prime objective of this paper is to provide such an understanding.

A more realistic computational model that is still relatively simple to use is the dynamic Winkler model in Fig. 1 [3]. The free field accelerations are computed using an 1-D program such as SHAKE [4] and applied to the ends of the near field springs. This ensures that the kinematic interaction of the vibrating ground with the pile is taken into account approximately. The problem with this method is that the reliability of the *p–y* curves used in practice for dynamic analysis has not been established.

Finn and Thavaraj [5] have shown that a dynamic analysis version of the Winkler model using cyclic *p–y* curves may prove quite unreliable for seismic response analysis during strong shaking on the basis of centrifuge tests on model piles in dry sand. Several investigators have studied the applicability of the standard North American *p–y* curves to pile foundations in liquefiable soils and found them unsatisfactory [6–9]. To take the effects of high pore water pressures into account, the *p–y* cures were degraded by multiplying the ordinates by a factor *p*, called the *p*-multiplier which ranged in value from 0.3 to 0.1 [6–8]. While it was possible to calibrate the *p–y* curves for a specific test [7], it was not possible to develop a general curve that could be used for all tests [9].

An alternative to the Winkler type computational model is to use a finite element continuum analysis based on the actual soil properties. Dynamic nonlinear finite element analysis in the time domain using the full 3-dimensional wave equations is not feasible for engineering practice at present because of the time needed for the computations. However, by relaxing some of the boundary conditions associated with a full 3-D analysis, Finn and Wu [10] found it possible to get reliable solutions for nonlinear response of pile foundations with greatly reduced computational effort. The results are accurate for excitation due to horizontally polarized shear waves propagating vertically. Wu and Finn [11,12] give a full description of this method and of numerous validation studies. The method is incorporated in the computer program PILE-3D. An effective stress version of this program, PILE-3D-EFF, has been developed by Thavaraj and Finn [13] and validated by Finn et al. [14] and Finn and Thavaraj [5] in cooperation the geotechnical group at the University of California at Davis. Seismic response analysis is usually conducted assuming that the input motions are horizontally polarized shear waves propagating vertically. The PILE-3D model retains only those parameters that have been shown to be important in such analysis. These parameters are the shear stresses on vertical and horizontal planes and the normal stresses in the direction of shaking. The soil is modeled by 3-D finite elements as shown in Fig. 2. The pile is modeled using beam or volume elements.

The pile is assumed to remain elastic, though cracked section moduli are used for concrete piles, when displacements exceed specified threshold values. This assumption is in keeping with the philosophy that the structural elements of the foundation should not yield. This requirement cannot always be met. If the pile shaft is projected upwards prismatically to act as a column, then any yielding is likely to occur in the buried portion of the shaft.

The constitutive soil model is equivalent linear with strain dependent shear modulus and damping. The strain dependence relations developed by Seed and Idriss [15] were used in the analyses described later. The equations of motion are formulated in the time domain. This allows the modulus and damping to be updated continually during earthquake shaking to maintain compatibility with shear strain level for the duration of analysis. A yield condition is incorporated consistent with the shear strength

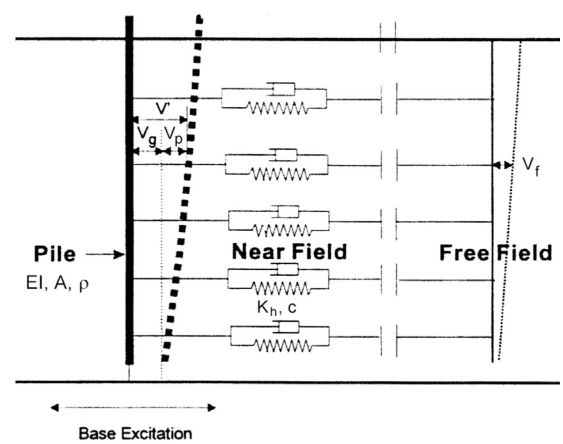

Fig. 1. Dynamic Winkler computational model for pile analysis.

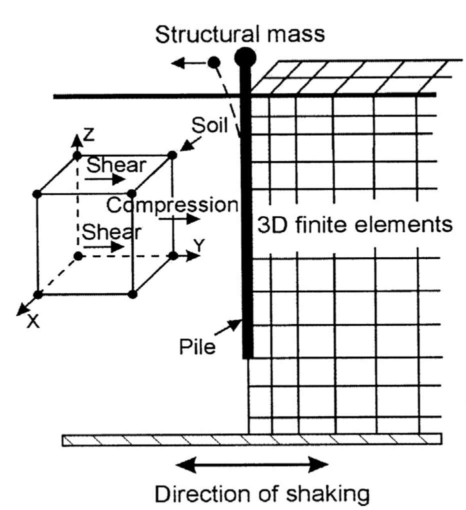

Fig. 2. Soil–pile model for analysis.