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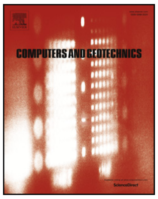

Research Paper

Simplified method of estimating the dynamic impedance of a piled raft foundation subjected to inertial loading due to an earthquake

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ABSTRACT

Simplified method of estimating the dynamic impedance of a piled raft foundation subjected to the seismic forces of building is presented. Parametric analysis was first performed to calculate the impedance of piled raft, spread, and pile foundations in the frequency domain. Base on calculated impedances, arbitrary functions were newly derived to describe the dynamic interaction factor between the raft and the pile group that constitute the piled raft foundation. It is possible to easily evaluate the impedance of piled raft foundations using the equation for the dynamic interaction factor along with the impedances of the corresponding spread and pile foundations.

1. Introduction

The piled raft foundation design combines the features of spread and pile foundations, allowing greater optimization of foundations than can be achieved in previous designs. For example, the foundation slab thickness, pile length, pile diameter, and number of piles can be reduced by using piled raft foundations instead of spread or pile foundations. However, because piled raft foundations are most often employed in soft soil by the very nature of the design concept, the evaluation of the seismic response of a building must incorporate the dynamic interactions between the building and the soil to account for the building, foundation, and soil as a coupled system. The piled raft foundation has the interaction between raft and pile, its behavior becomes more complicated than spread foundation and pile foundation.

Previous studies have involved the investigation of dynamic coupled system problems focusing on the seismic behavior of the piled raft foundation. Experimental approaches have been applied to models on shaking tables. Horikoshi et al. [11], Matsumoto et al. [17], and Unsever et al. [25] have carried out vibration experiments in a 1-g field, and Nakai et al. [20] have conducted a vibration experiment in a 30-g field on a centrifugal loading device. These studies involved the examination of the vibratory characteristics of piled raft foundations, the stresses in the piles, and how they differed from the findings for pile foundations. Observations of actual buildings during earthquakes have been carried out, and Yamashita et al. [26,27] and Hamada et al. [9] have reported the seismic behavior of piled rafts with ground improvement supporting a base-isolated building. Hamada et al. [10] have reported the seismic performance of a piled raft subjected to asymmetric earth pressure. Mendoza et al. [18] have reported the influence of piles and the foundation slab on the distribution of vertical loads during an earthquake, and Dash et al. [3] have investigated earthquake damage and presented an analysis of the factors affecting it. However, these aforementioned studies represent a low total number of reports, and many matters remain to be explained. Furthermore, analytical approaches to seismic response have also been employed by Eslami et al. [6], Ngyuen et al. [21], Kumar et al. [15], and others. Their analyses were performed using the finite element method (FEM). FEM analysis enables detailed calculations to be carried out, but a large-scale 3D analysis requires a huge computational capacity and long calculation times. Thus, it is desirable to establish a convenient evaluation method that can be applied during the design of an actual building.

One simple coupled model is the sway–rocking model. However, this model requires the identification of the dynamic impedance, which represents the resistance of the soil to the horizontal motion (sway) and rotational motion (rocking) of the foundation. There are many previous studies on the impedance of spread foundation and pile foundation, eg. Kausel and Roesset [13], Kaynia and Kausel [14], Dobry and Gazetas [4]. On the other hand, there are few studies on the impedance of piled raft foundation. Nakai et al. [19] have reported the dynamic impedance of piled raft foundations to horizontal motion based on three-dimensional finite element analysis using the dynamic substructure method. Fukuwa and Wen [8] have investigated the horizontal, vertical, rotational, and horizontal–rotational components of the dynamic impedance of piled raft foundations using a method combining the FEM and the thin layer method. Nguyen et al. [22] have also estimated the dynamic impedance of a piled raft foundation using the FEM incorporating the principles of multiphase models but only observed its vertical component. These studies were investigated under a semi-

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infinite soil mass with limited number of piles and pile spacing constituting the foundation, and went no further than comparing pile foundations with spread foundations.

This paper presents an attempt to develop a simplified method of estimating the dynamic impedance for simulations of both the horizontal and rotational motions of a piled raft foundation composed of a spread foundation and friction piles subjected to the inertial forces of a building due to an earthquake. Parametric frequency response analysis was first performed to evaluate the dynamic impedance of piled raft, spread, and pile group foundations when the dynamic stiffness is calculated by assigning various foundation shapes and soil conditions for excitation frequencies of up to 40 Hz. This numerical analysis was performed assuming a linear viscoelastic model using an analytical method combining the FEM and the thin layer method. From these calculated impedances, a formula for the dynamic interaction factor between the raft and pile group that relates the dynamic impedance of the piled raft foundation to the dynamic impedance of the spread and pile foundations was newly derived and analyzed.

2. Calculation of dynamic impedance using analytical method

2.1. Analytical method

Fig. 1 shows a schematic diagram of the analytical method used in this study. This analytical method combines the FEM and the thin layer method.

The equation of motion for the foundation–soil system in the frequency domain is

$$([K^{*}]-\omega^{2}[M])\cdot\{U(\omega)\} \;=\{F(\omega)\} \tag{1}$$

where $\{U\}$ is the displacement vector of the foundation, $\{F\}$ is the external force vector acting on the foundation, ω is the circular frequency, $[K^{*}]$ is the stiffness matrix, and $[M]$ is the mass matrix.

The stiffness matrix is given by

$$[K^{*}]=[K_r]+[K_p]+[K_{rp}]+[K_s]-[K_s{}^{ep}] \tag{2}$$

where $[K_r]$, $[K_p]$, $[K_{rp}]$, $[K_s]$, and $[K_s{}^{ep}]$ are the stiffness matrices of the raft, piles, pile head connections, free field soil, and soil that would fill the same volume as the pile bodies, respectively. The raft and piles are modeled as a thin-plate element and beam elements, respectively. The connections between the raft and the pile heads are modeled as spring elements that transmit axial forces, shear forces, and bending moments. The soil is treated as the inverse matrix of three-dimensional Green's functions derived from the excitation solution in the thin layer method [8,23]. The ring excitation solution is used when the vertical axes of the points at which the excitation force acts coincide with the vertical axes of the points at which the vibration occurs; otherwise, the point excitation solution is used. The horizontal and rotational behavior of a rigid disk in a half-space were presented by Fabrikant [7], Jin and Liu [12], Eskandari et al. [5] and Ahmadi and Eskandari [1], and those solutions are exact closed form. On the other hands, this solution is given by the mode superposition of the frequency-dependent normal modes of generalized Rayleigh waves as well as generalized Love waves in the layered soil [23]. Furthermore, the stiffness of each component is assumed to be represented by a linear viscoelastic model consisting of a spring and a dashpot mounted in parallel.

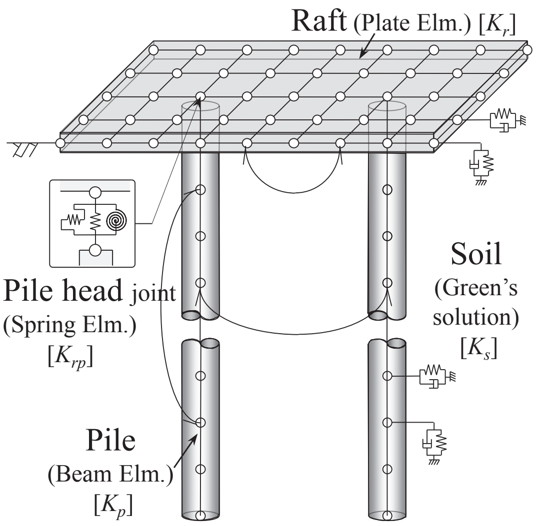

Fig. 1. Schematic of analytical method.

The mass matrix is given by

$$[M]=[M_r]+[M_p]-[M_s{}^{ep}] \tag{3}$$

where $[M_r]$ is the mass matrix of the raft (assumed to be zero in this study), $[M_p]$ is the mass matrix of the pile, and $[M_s{}^{ep}]$ is the mass matrix of the soil corresponding to the integral of the pile bodies.

2.2. Analytical model

Fig. 2 shows the models used for this investigation. A semi-infinite soil mass was assumed, and the foundation slab was defined as a rigid, massless, flat square not embedded in the soil. The piles were cast-in-place concrete piles with diameters of $d = 1$ m. The raft–pile head connection is represented as a rigid connection. The behavior of soil-pile system assumes perfect contact between pile and soil. The investigated parameters were the number of piles n, the pile spacing s/d, the pile length L/d, and the pile–soil stiffness ratio E_p/E_s, as listed in Table 1. Case 2 is defined as a basic model. One parameter was varied during each given calculation while all other parameters were held constant at the basic values. In addition to piled raft foundations (PR), two other foundation types, spread foundations (SF) and pile group foundations (PG), were analyzed. The pile group foundation has the same pile length as the piled raft foundation, but the raft is not in contact with the soil. When analyzing the pile group foundation, the springs between the raft and the soil were omitted from the analysis. In each considered case, the dimensions of the spread and pile group foundations were set to be the same as the corresponding dimensions of the piled raft foundations.

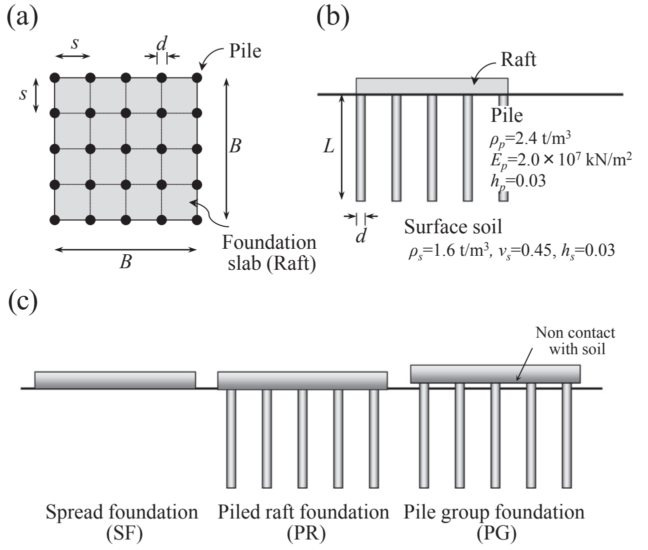

Fig. 2. Analytical model; (a) plan view; (b) elevation view; (c) foundation type.