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On the verification of superposition method of kinematic interaction and inertial interaction in dynamic response analysis of soil-pile-structure systems

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ABSTRACT

A simplified analytical formulation has been used to verify the superposition method of two components of soil-structure interactions (SSI), namely-the kinematic interaction and the inertial interaction for estimating the dynamic response of soil-pile-structure systems (SPSS). The dynamic response analysis is conducted in the frequency domain and the soil behavior ranging from elastic-to-inelastic state is covered. The effective foundation input motion (EFIM) is obtained from shaking table model testing under 1g conditions for the kinematic interaction and the pile head impedance functions (IFs) are estimated from pile-head loading test for the inertial interaction, respectively. The EFIM and pile head IFs both have frequency and loading amplitude dependent characteristics. These experimentally recorded EFIM and pile head IFs are used as inputs in the analytical formulations to compute the dynamic response of the SPSS by superimposing the kinematic and inertial interaction. Superimposing adopts a linear interpolation method for appropriate use of the pile head IFs. The analytical (superimposed) dynamic response is then compared with experimentally measured dynamic response for verification purpose of superposition method and the comparison shows good agreement indicating that with appropriate use of EFIM and IFs, superposition method is reasonably good to produce the frequency and amplitude dependent dynamic response characteristics of SPSS. Certain discrepancies in amplification ratio and in resonant frequency particularly around the dominant vibrating modes have been observed in the comparison. The reason for such observed disagreements is possibly the difference between soil damping (hysteretic and radiation) and the difference between soil-pile stiffness.

1. Introduction

Numerical procedures such as finite-element method (FEM) and the boundary-element method (BEM) have been adopted over the years for understanding the effects of soil-pile-structure interactions (SPSI) on the response of piles and as well as the response of structure supported on piles. However, studies have indicated that the use of discrete methods of analysis such as FEM requires huge computational effort and also yields discrepancies between the results of the numerical analysis and the classical analytical solutions especially when embedded foundations are considered [1]. Inherently, the nature of SPSI is frequency dependent and as such, the complex dynamic impedance functions (IFs) are affected by the frequency of incoming seismic motion and also influenced by its amplitude on the supporting foundation, particularly as the soil shows inelastic behavior [2,3]. To clarify the source of inconsistencies observed between numerical and analytical method results, and the desirability of a relatively simple analysis method to appropriately consider the frequency dependency of SPSI, led to the development of the three-step solution technique for solving the SPSI problems [1]. This technique fundamentally uses the superposition of kinematic and inertial interaction effects, as in Kausel [4], Seed et al. [5], and Kausel et al. [6]. In a nutshell, the analysis

Abbreviations: K_f^*, pile head impedance functions (IFs); k_f, real part of pile head IFs; C_f, imaginary part of pile head IFs; ω_m, circular loading frequency on model; ω_p, circular loading frequency on prototype; η, density scaling ratio; λ, geometric scaling ratio; ρ_m, density of the model; ρ_p, density of the prototype; l_m, linear dimension of the model; l_p, linear dimension of the prototype; d, pile diameter; s, pile-to-pile spacing; s/d, spacing to diameter ratio; f_{ns}, natural frequency of superstructure; ζ_s, superstructure damping ratio; m_s, mass of superstructure; m_f, mass of footing; K_s, stiffness of superstructure; $\ddot{u}_g$, input ground excitation; $\dot{u}_{eff}$, effective foundation input motion in terms of velocity; $\dot{u}_f$, footing response in terms of velocity; $\dot{u}_s$, superstructure response in terms of velocity; q_k, generalized coordinate; T, kinetic energy; U, strain energy; D, dissipation function; C_s, damping coefficient of superstructure; T_s, total response of superstructure with respect to the base excitation; ϕ_s, phase corresponding to the total response of superstructure; T_f, total response of footing with respect to the base excitation; ϕ_f, phase corresponding to the total response of footing; $\dot{u}_r$, relative acceleration response at footing

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procedure of the three-step solution technique are - (a) to determine the effective foundation input motion (EFIM) in response to the base excitation discarding superstructure's inertia; (b) to obtain frequency dependent IFs, which expresses the dynamic force-displacement ratios at the pile head level; and (c) to analyze the dynamic response of superstructure supported on the springs and dashpots of step (b) and subjected to the EFIM of step (a) at its base. For the first two steps, several formulations have been developed for pile foundations and have been reviewed by Novak [7], Pender [8] and Mylonakis [9]. Makris et al. [10] presented an integrated procedure for three-step solution of SPSI problems using the available theories to calculate the dynamic IFs and kinematic interaction factors of pile foundations. Lesgidis et al. [2] and Chai et al. [11] shows the necessity of adopting frequency dependent approach in the SPSI analysis through extensive parametric study and efficient numerical modeling in their recent works.

Along with frequency and loading amplitude dependency, an important aspect of SPSI analysis is nonlinear behavior exhibited by the soil, the soil-pile interface and the structure under strong ground motion [12]. As an engineering approximation, the superposition could be applied to moderately non-linear systems [13]. To understand this approximation recalling that the amount of strain induced in the soil due to the response of superstructure may be significant near the ground surface as the pile deformations are expected to diminish with the depth; practically vanishing below the active pile length of the piles [14–18]. And on the contrary, displacements induced in soil due to kinematic loading are higher only at relatively greater depths [13,19]. In the light of such, the superposition concept in the three-step technique may be a reasonable approximation even under nonlinear conditions since strain in soil is controlled by inertial effects near ground surface and by kinematic effects at greater depths [20,21]. Nevertheless, it is important to validate this approximation by laboratory experiment results, inevitably in the frequency domain analysis framework. Only a limited number of experimental studies has been reported encompassing the SPSI effects along with the nonlinear behavior of soil [22,23], but no prior attempt has been found in the literature to verify the superposition method experimentally for computation of dynamic response of soil-pile-structure systems (SPSS).

This study focuses on a simplified analytical formulation considering single-sway model of SPSS for dynamic response computation based on the aforementioned three-step solution technique (i.e. the superposition of kinematic interaction and inertial interaction). The pile head IFs and EFIM are independently estimated through pile head loading test and shaking table model testing, respectively. And these experimentally measured pile head IFs and EFIM are employed as inputs in the analytical formulation to calculate the dynamic response of the SPSS. The analytically computed dynamic responses are then compared with experimentally measured dynamic responses of the SPSS obtained from shaking table model tests to verify the superposition method.

2. Model tests

Physical model testing under natural gravity condition (i.e.1-*g*) was carried out for estimating horizontal pile head IFs, EFIM and total response of SPSS. The scaling law derived by Kokusho and Iwatate [24] pertaining to 1-*g* conditions was employed in these experimental investigations. For the horizontal pile head IFs, pile head loading test of a scaled soil-pile model under low-to-high amplitude of pile head loading for a wide range of frequencies was carried out by Goit et. al. [3]. A soil-pile model consisting of 3 × 3 floating pile group embedded in dry cohesionless Gifu sand and encased in a laminar shear box was used for this purpose. The experimentally obtained pile head IFs are presented in Section 3.1.

In the present study, the EFIM of the same scaled soil-pile model (used by Goit et. al. [3]) and the total dynamic response of scaled SPSS model are measured experimentally by shaking table tests. The SPSS model additionally contains the superstructure resting on the pile cap of the 3 × 3 pile group. Detailed description of the prototype-model scaling relations (i.e. the Kokusho and Iwatate scaling laws), experimental setup, loading condition, data record, and processing employed in the aforementioned model tests (i.e. pile head IFs, EFIM and total response of SPSS estimation experiments) are presented in the following subsections.

2.1. Prototype-model scaling relations

The similitude law of Kokusho and Iwatate [24], considers the ratio of forces acting on model and prototype, providing the circular loading frequency relationship between the model and the prototype as

$$\frac{\omega_m}{\omega_p} = \eta^{-1/4}\lambda^{-3/4} \tag{1}$$

where, ω_m and ω_p represent the circular loading frequency on the model and the prototype, respectively. Subscripts m and p refer to the model and the prototype, respectively, for all the equations in this section.

In Eq. (1), η and λ are the density scaling ratio and the geometric scaling ratio, respectively, given by

$$\eta = \frac{\rho_m}{\rho_p} \tag{2}$$

And

$$\lambda = \frac{l_m}{l_p} \tag{3}$$

For the experimental investigations, λ was adopted as 0.05, i.e., the model is 20 times smaller than the prototype and η was adopted as 0.81.

2.2. Experimental setup

One degree of freedom shaking table with dimension of 1800 mm × 1800 mm and capacity of 5 (t-G) in full load was used for the experiments. A laminar shear box of inner dimension 1200 mm × 800 mm × 1040 mm was used to host the soil-pile model and SPSS model on the shaking table as shown schematically in Fig. 1 and Fig. 2, respectively. For the soil-pile model, cohesionless dry Gifu sand was employed as soil, standard properties of which are available in published material [25]. And nine solid acrylic piles (each with diameter of

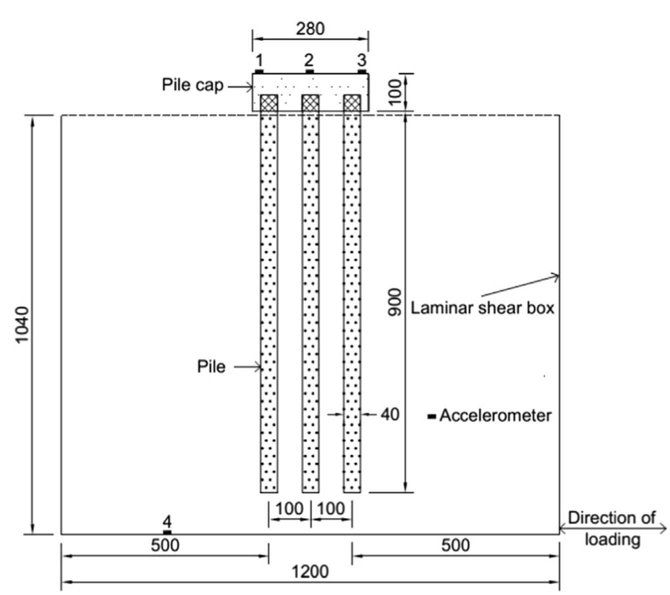

Fig. 1. Schematic layout of soil-pile model for estimation of EFIM (Dimensions in mm).