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SEISMIC ANALYSIS FOR BUILDING STRUCTURES UNDER DYNAMIC SOIL-PILE INTERACTION USING SIMPLIFIED MODELS

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Abstract

This paper presents the application of a new simplified model to simulate dynamic soil-pile interaction undergoing coupled sliding and rocking motions. The developed model's components and parameters are calculated using the theory of equivalent models developed in the previous work. A parametric analysis has been carried out for structural responses using dimensionless parameters considering dynamic soil-pile-structure interaction (SPSI). The analyzed parameters include earthquake frequencies, pile tip conditions, story mass ratios, and story stiffness ratios. The results show that the simplified model accurately estimates the peak response of the SPSI system at low frequencies. The magnification factors analyzed by the simplified model also agree well with the analytical solutions at high frequencies when the pile tip is fixed. Besides, the simplified model slightly overestimates the dynamic responses at high frequencies for the SPSI system when the pile tip is considered simply supported. Hence, the simplified model proposed has a good potential to be applied to the seismic analysis for building structures considering dynamic SPSI.

Keywords: Pile Foundation, Soil-Pile Interaction, Discrete-Element Model.

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1 INTRODUCTION

In recent years, the development of high-rise urban buildings has been increasing with the rapid urban population growth. Since high-rise buildings are heavy structures, if they are located on soft shallow soil, it is often necessary to use pile foundations to support the various loads transmitted from the building. A pile foundation is usually composed of pile caps, which are connected to the superstructure. The load of the superstructure determines the distance and number of piles. The static analysis method is used in most of its designs. However, for essential high-rise structures, it is necessary to consider the dynamic effects caused by earthquakes and shock loads. The research on soil-pile interactions mainly started from Mindlin [1], who deduced the basic elastic solution for static analysis of soil-pile interaction. Later, many studies applied this elastic solution to explore the static behavior of pile groups. Currently, studies on soil-pile interactions considering dynamic effects can be mainly divided into three categories, including the Winkler-beam model [2,3], the continuous method [4,5], and the finite element method [6,7]. However, all the above methods may have their limitations. The Winkler-beam mode needs the inputs of soil spring to simulate the soil stiffness. In addition, the continuous method requires special Green functions, and the finite-element method requires appropriate viscous boundaries to simulate the semi-infinite soil medium.

Due to the complexity of dynamic soil-structure interaction (SSI), numerous simplified models have been developed to simulate the SSI efficiently. The simplified model for simulating soil dynamic behavior mainly began with Lysmer and Richart [8] using a single-degree-of-freedom system to simulate the dynamic characteristics of semi-infinite half-space. Subsequently, similar concepts have been further extended. Meek and Veletsos [9] added an additional degree of freedom (DOF) into the simplified model, which became a 2-DOF system to simulate the dynamic response of the foundation under horizontal and rocking vibration. Wolf and Somaini [10] and de Barros and Luco [11] also used the 2-DOF system to simplify the dynamic behavior of embedded foundations. Jean, Lin, and Penzien [12] used a simple model with three DOFs and ten parameters to simulate the vertical, horizontal, rocking, and torsional vibration of a rigid foundation. Wolf and Paronesso [13] also simulated the dynamic interaction between rigid foundations and soil using a simplified model using multiple DOFs. The consistent model developed by Wolf [14,15] and the nested model constructed by Wu and Lee [16] attempt to construct a multi-degree-of-freedom system systematically to simulate the interaction between soil and foundation. However, previous studies [14-16] also ignore the coupling behavior of the foundation subjected to horizontal and rocking vibration.

The previous work [17-19] recently proposed systematic, simplified models with adapted accuracies to simulate the dynamic interactions between embedded foundations and layered soils subjected to vertical, horizontal, and rocking vibrations. The developed model could simulate the coupling behavior between horizontal and rotational motion. This paper aims to present the application of the newly developed model to simulate dynamic soil-pile interaction subjected to coupled horizontal and rocking excitations. This study also performs a parametric analysis for structural responses using dimensionless parameters considering dynamic soil-pile-structure interaction (SPSI) in the frequency domain. The analyzed result will show the potential application of the newly developed model in dynamic SPSI analysis.

2 METHOD

The previous work [17-19] developed the theory of equivalent model to construct a simplified model simulating unbounded soil. The concept is first to calculate the parameters of the simplified model conforming to the equivalent condition for a single frequency point, which includes equivalent static displacement, equivalent dynamic amplification factor, and equivalent dynamic dissipation energy. Subsequently, the corresponding equivalent models was solved for N frequency points, and an error function was used to select the optimal model for simulating dynamic soil behavior from the N equivalent models. This paper uses the theory of equivalent model to establish the simplified model for simulating the soil-pile system subjected to horizontal and rotational motions, as shown in Figure 1(a). In addition, Figure 1(b) shows the simplified model, which uses the modulized units developed in the previous work [19], as shown in Figure 2. The equivalent parameters of the simplified model are determined by the governing equations based on the three equivalent criteria considering horizontal and rotational responses. The optimal model parameters are then found by using an error function regarding the magnification factors in the horizontal and rotational directions.

This study analyzes the dynamic response of building structures with pile foundations induced by seismic excitations. This study also performs dimensionless parametric analysis for the transfer function of structural displacements considering the influence of inertial interactions. A lumped-mass model is used to simulate the superstructure, as shown in Figure 3. When the building system is subjected to seismic excitations, the dynamic equilibrium equation for each floor at the superstructure can be constructed as follows.

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{C}\dot{\mathbf{U}}_{\mathbf{r}} + \mathbf{K}\mathbf{U}_{\mathbf{r}} = \mathbf{0} \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ are the mass matrix, damping matrix, and stiffness matrix of the superstructure, respectively; $\mathbf{U}$ and $\mathbf{U_r}$ are the vectors collecting the total displacement, U_j, and the relative displacement, U_{rj}, at each floor in the horizontal direction. The total horizontal displacement at the j-th floor is defined as

$$U_j = U_{rj} + U_b + h_j \Phi_b \tag{2}$$

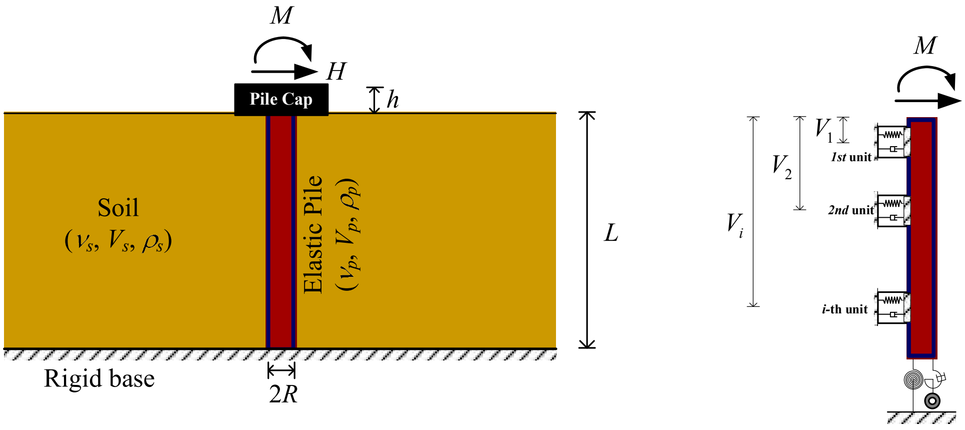
where U_b is the horizontal displacement at the foundation top and Φ_b is the rotation angle of the foundation. Further details could be found in the previous work [20]. As the building system is undergoing harmonic horizontal excitations, the transfer function for the horizontal response can be derived from the structural dynamics, as given below.

$$\frac{u_j}{u_g} = \frac{u_{rj}}{u_g} + \frac{u_b}{u_g} + \frac{h_j \phi_b}{u_g} \tag{3}$$

where u_g is the displacement amplitude of input motion; u_j is the total displacement amplitude at the j-th floor; ; u_{rj} is the relative displacement amplitude at the j-th floor; u_b is the displacement amplitude at the foundation top; ϕ_b is the rotational amplitude of the foundation; and h_j is the height measured from the j-th floor to the foundation top. Note that the transfer function defined in Eq. (3) depends on a dimensionless frequency ratio, $a_0 = \omega R/V_s$, with the exciting frequency ω, the soil density ρ, and the characteristic length of the foundation R. In this study, the superstructure is supposed to have identical lumped mass and lateral stiffness at each story. By doing so, two dimensionless parameters are defined below, which significantly affect the dynamic response of the building system.

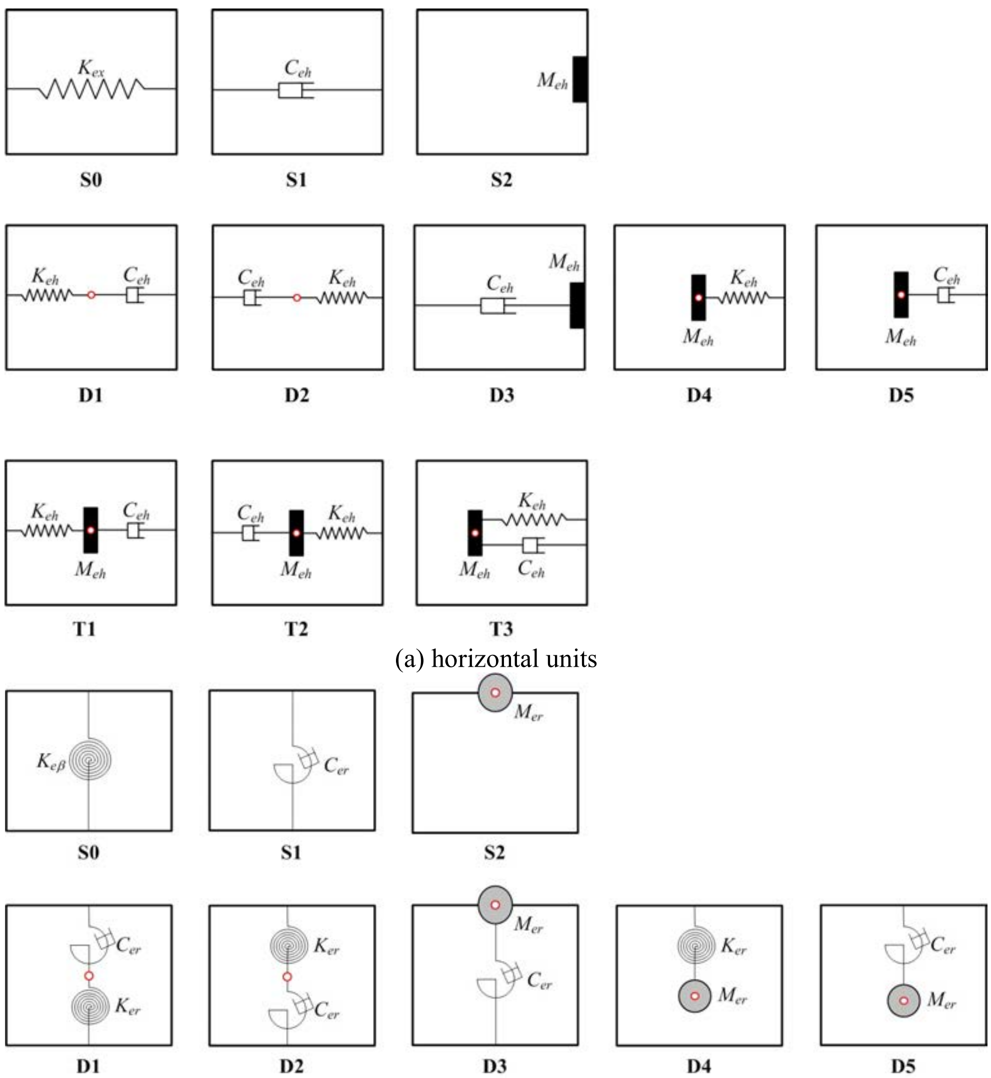
$$b_s = M_b / \rho R^3; \qquad r_{sx} = K_b / K_{sx} \tag{4}$$

where b_s is the story mass ratio; r_{sx} is the story stiffness ratio; M_b is the story mass; K_b is the lateral story stiffness; K_{sx} is the static foundation stiffness in the horizontal direction. This study uses Eq. (3) to analyze the transfer function of the building system with pile foundations subjected to horizontal excitations. The theoretical impedance function is used to calculate the actual system response. The approximate impedance function of the simplified model is also applied to calculate the system response for further comparisons. The results will demonstrate the effectiveness of the simplified model applied in the dynamic SPSI analysis.



(a) soil-pile system (b) simplified model

Figure 1:Dynamic soil-pile interaction models.



(a) horizontal units

(b) rotational units

Figure 2: Modulized unit for simplified models (adapted from Ref. [19]).

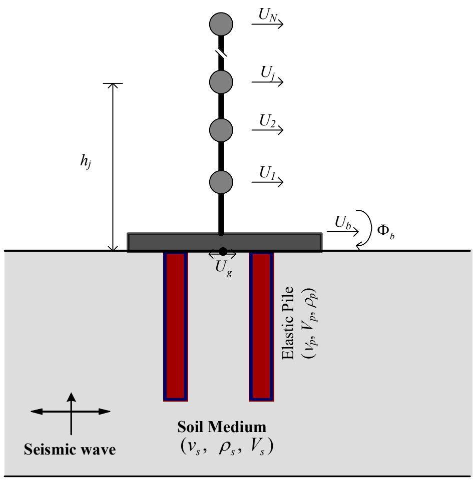


Figure 3: Building system with dynamic SPSI.

3 RESULTS

The study considers dynamic interactions between piles and soils to establish the simplified model for dynamic SPSI analysis through the systematic method described in Section 2. This section uses the simplified model to calculate the dynamic response of the building structure with pile foundations subjected to horizontal excitations. In the complete SPSI system, suppose an elastic pile has a radius R, a length H = 15R, and a pile cap with a height h = 2R, buried in the homogeneous soil layer. The other parameters for the soil-pile system investigated include a Poission's ratio of soil ν = 0.5, a material damping ratio of soil ξ_s = 0.02, a ratio of the density of the pile to that of soil ρ_p/ρ_s = 0.6, a ratio of the shear-wave velocity of soil to the compression-wave velocity of the pile V_s/V_p = 0.01. In addition, the pile tip is simulated as a fixed end and a simply-supported end, respectively, to analyze the influence of boundary conditions on the dynamic response of the SPSI system. For the superstructure structure, the contribution of lateral story stiffness, story mass, and story damping to the dynamic response of the SPSI system is analyzed by using a lumped-parameter model. In this section, the pile impedance function developed by Novak and Nogami [21] is used to calculate the optimal simplified model for simulating the dynamic soil behavior. Eq. (3) is used to calculate the dynamic magnification factor, defined as a norm of the transfer function, at the floors for the SPSI system under horizontal excitations. Note that the theoretical frequency-dependent impedances are used to compute the response of a complete SPSI system, and the approximate impedances of the simplified model with frequency-independent parameters are applied to calculate the response of a simplified SPSI system. Further comparisons are performed for the analyzed results.

The horizontal magnification factor at the top floor in a ten-story building structure is shown in Figures 4-6. In Figure 4, the story mass ratio, b_s = 0.5, and story stiffness ratio, r_{sx} =0.5, are typical parametric values. In addition, Figure 5 shows the analyzed results regarding two times the typical parametric values. Figure 6 analyzes a specific condition when the story mass ratio and the story stiffness ratio are four times the typical parametric values. The results show that the dynamic magnification factor by the simplified model agrees well with the analytical solution. This agreement is also observed at the peak response of the SPSI system in the low-frequency region. However, the dynamic magnification factor by the simplified model is slightly higher than the analytical solution in the high-frequency region. The observed discrepancy shows that the simplified model may underestimate the soil damping in the high-frequency region. However, the discrepancy at the high frequencies does not magnify significantly with the increase of story mass ratios and story stiffness ratios. In addition, when the pile tip is simply supported, and the story mass ratio and the story stiffness ratio are two times the typical parametric values, the dynamic magnification factor at the high frequencies changes gently with the exciting frequency. These results indicate that the high-frequency excitations will significantly affect the ten-story building system under this condition. However, when the story mass ratio and the story stiffness ratio are four times the typical parametric values, the response at the top floor in the high-frequency region will decrease with the increase of the exciting frequency. These results show that soil radiation damping can effectively reduce the system response in this case.

In brief, the analyzed results prove that the newly-developed simplified model may effectively simulate the dynamic soil-pile interaction and accurately simulate the peak response of the SPSI system in the low-frequency region. If the pile tip is fixed, the simplified model may accurately provide the magnification factors within the analyzed frequency range. If the pile tip is simply supported, the simplified model will slightly overestimate the system response at high frequencies because the simplified model may underestimate the contribution of soil radiation damping in such a case. The overestimation of the system response will not be aggravated if the story mass ratio and story stiffness ratio are increased.

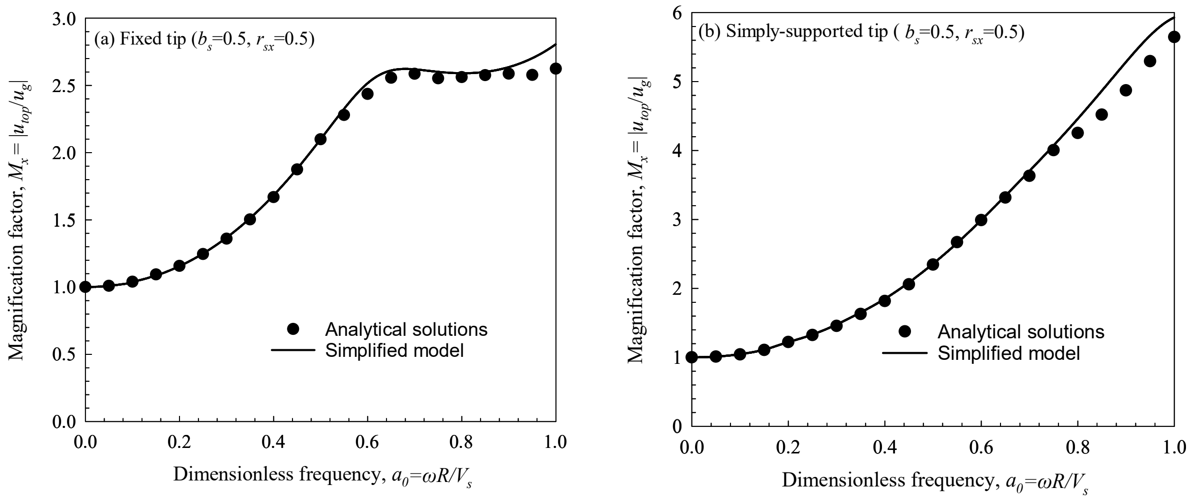


Figure 4: Magnifcaitor factors at the top floor in the SPSI system with typical parametric values.

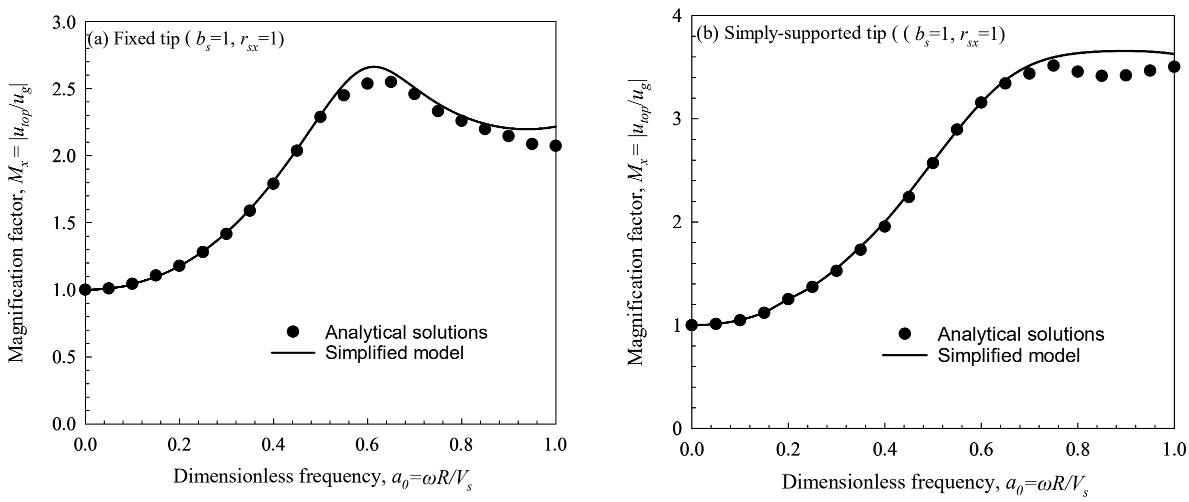


Figure 5: Magnifcaitor factors at the top floor in the SPSI system with two times typical parametric values.

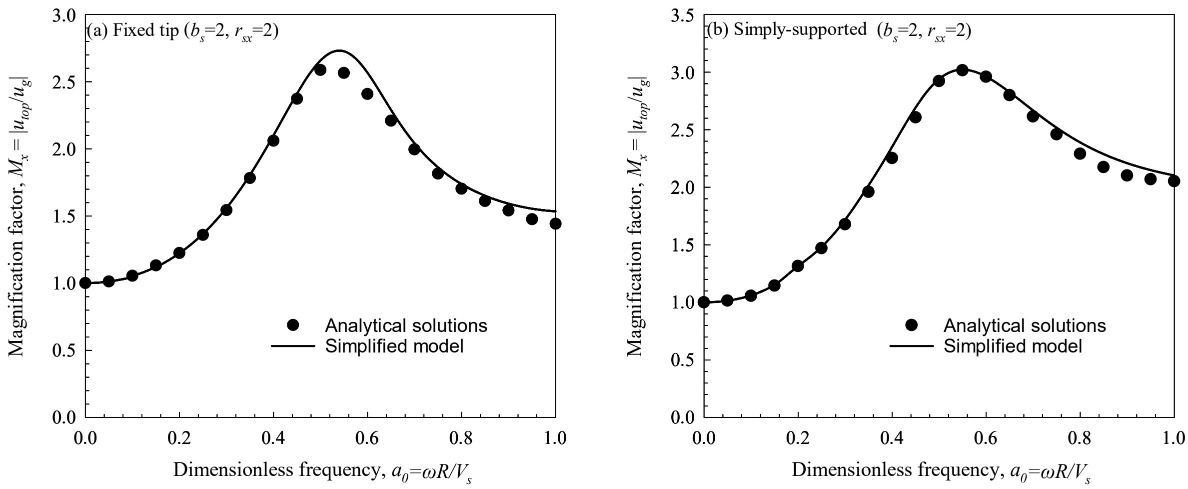


Figure 6: Magnifcaitor factors at the top floor in the SPSI system with four times typical parametric values.

4 CONCLUSIONS

- This study shows the newly-developed simplified model may effectively simulate the dynamic soil-pile interaction for building structures subjected to horizontal excitations.
- The simplified model is found to accurately simulate the peak response of the SPSI system in the low-frequency region when the pile tip is fixed or simply supported.
- The simplified model will slightly overestimate the system response at high frequencies when the pile tip is simply supported on the rigid base.
- The overestimation of the system response caused by the simplified model is not found to be aggravated when the story mass ratio and story stiffness ratio increase.

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