ANALYSIS OF DYNAMIC RESPONSES OF AN EXTENDED PILE UNDER CENTRIFUGE SHAKING TABLE TESTING

J.S. Chiou¹, W.Y. Hung², Y.T. Lee³ and Z.H. Young⁴

ABSTRACT

This study uses SAP2000 to simulate the dynamic responses of an extended pile-soil model under centrifuge shaking table tests. The centrifuge models consisted of a pile partially embedded in dry sand under 80g centrifuge acceleration. The pile in the prototype was 35.44 m. The thickness of sand in the prototype was 25.4 m with relative density of about 80%. In the simulation, both the inertia effect from the structure mass and the kinematic effect of ground on the pile are considered. A pile-soil model connected to a shear beam model is established to account for both effects at the same time. The soil parameters used in the analyses, such as shear-wave velocity and damping ratio, are determined via transfer function analysis of preshaking tests prior to the formal events. Preliminary analyses show that the combined model can reasonably simulate structure acceleration and pile bending responses.

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Analysis of Dynamic Responses of an Extended Pile under Centrifuge Shaking Table Testing

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This study uses SAP2000 to simulate the dynamic responses of an extended pile-soil model under centrifuge shaking table tests. The centrifuge models consisted of a pile partially embedded in dry sand under 80g centrifuge acceleration. The pile in the prototype was 35.44 m. The thickness of sand in the prototype was 25.4 m with relative density of about 80%. In the simulation, both the inertia effect from the structure mass and the kinematic effect of ground on the pile are considered. A pile-soil model connected to a shear beam model is established to account for both effects at the same time. The soil parameters used in the analyses, such as shear-wave velocity and damping ratio, are determined via transfer function analysis of preshaking tests prior to the formal events. Preliminary analyses show that the combined model can reasonably simulate structure acceleration and pile bending responses.

Introduction

When a pile supported structure is subjected to earthquakes, the pile foundation will undergo the inertial force transmitted from the superstructure and the action of ground movement \([1]\). Dynamic time history analysis can directly simulate the above complicated behavior of soil-pile-structure interaction. Beam on Winkler foundation approach is commonly used in practice. In applying this method, a structure-pile-soil model is built to be excited by seismic motions from the endpoints of soil springs \([2,3]\). The process is a little tedious since a soil model is needed to perform ground response analysis first for retrieving the ground motions at every depth of soil, and then applying them as the input to the structural-pile-soil model. Besides, some structural analysis programs cannot deal with the above multiple input problem. To implement the method in general structural analysis software, on the platform of SAP2000, this study attempts to build a single-input model which combines the structure-pile-soil model and ground response analysis model together. To verify the model, this study utilizes a series of centrifuge tests conducted on an expended model pile.

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Centrifuge Shaking Table Tests

Centrifuge tests were performed using the 1-D servo-hydraulically controlled shaking table on the 3-m-radius centrifuge at the National Central University (NCU) in Taiwan. Models were tested in a laminar container at a centrifugal acceleration of 80g. The laminar container has inside dimensions of 711 mm×356 mm×353 mm (L×W×H) and consists of 9 light-weight stacked aluminum alloy rings. The shaking table has maximum shaking force 53.4 kN with maximum table displacement of ±6.4 mm under 80 g centrifugal acceleration. The nominal operating frequency range is 0-250 Hz.

Fig. 1 shows the arrangement for the test model. The soil profile consisted of dry fine quartz sand with thickness of 317 mm in model scale. The sand was uniformly graded, with mean particle size of 0.19 mm, specific gravity of 2.65, maximum dry unit weight of 16.6 kN/m³ and minimum dry unit weight of 13.8 kN/m³. In the tests, a dense specimen with a relative density of about 80% was prepared by air pluviation. The length of the model pile was 443 mm. Table 1 summarizes the model and prototype properties. In the tests, a mass (weight of 2.55 kN) was attached to the top of the pile to simulate the superstructure.

The events adopted in the centrifuge tests were sinusoidal waves with frequencies of 0.5, 1.0 and 1.5 Hz, and amplitude of about 0.06 g. In order to determine the dynamic properties of soil and the mass-pile-soil system, a preshaking test was performed prior each formal event. Because of the dense soil condition, the transfer function analyses of the preshaking tests indicated that the predominant frequencies of the mass-pile-soil system and soil layer changed less before and after each formal event, about 0.62 Hz and 1.99 Hz, respectively.

![Extended pile model](image-url)

Figure 1. Instrumentations of centrifuge shaking table tests.
Numerical model

In this study, we apply SAP2000 to build a combined model which links a mass-pile-soil system with a shear beam model to simultaneously consider the effects of inertia loading and kinematic ground movement. First, the shear beam model composed of a series of shear springs is built to simulate the dynamical responses of a soil layer under excitations as shown in Fig. 2. To determine the stiffness of the shear springs, the format of Seed’s formula [4] as shown in Eq. (1) is applied to estimate the shear modulus of the soil. \( k \) in Eq. (1) is calibrated by matching the predominant frequency of the shear beam model with that of the soil layer identified from the preshaking test. Then, Eq. (2) is applied to calculate the spring stiffness based on the set spring spacing and soil column size. The soil damping is also determined via the transfer function of the preshaking test.

\[
G = 1000k (\sigma'_m)^{0.5} \\
K = \frac{GA}{s}
\]

where \( G \) is the shear modulus, \( k \) is an empirical constant, \( \sigma'_m \) is the effective confining pressure, \( K \) is the shear spring stiffness, \( s \) is the spacing of the shear springs and \( A \) is the cross-section area of the soil column in the shear beam model.

Table 1. Information about the centrifuge test model.

<table>
<thead>
<tr>
<th>Property</th>
<th>Model</th>
<th>Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile diameter</td>
<td>15.9 mm</td>
<td>1.27 m</td>
</tr>
<tr>
<td>Pile length</td>
<td>443 mm</td>
<td>35.44 m</td>
</tr>
<tr>
<td>Pile EI</td>
<td>50 N-m²</td>
<td>2050 MN-m²</td>
</tr>
<tr>
<td>Size of mass</td>
<td>54.8x53.6x30.0 mm³</td>
<td>4.38x4.29x2.40 m³</td>
</tr>
<tr>
<td>Weight of mass</td>
<td>260 gram</td>
<td>133 ton</td>
</tr>
</tbody>
</table>
Before the shear beam model is linked to the pile-soil model, ground response analyses are conducted to verify the appropriateness of the shear beam model. Fig. 3 shows the recorded ground surface acceleration responses for the input acceleration of 0.06 g at different excitation frequencies of 0.5, 1.0 and 1.5 Hz (blue lines). As the excitation frequency increases, the ground surface acceleration increases. The acceleration response for the excitation frequency of 1.5 Hz is largest since the excitation frequency is close to the predominant frequency of the soil layer. Fig. 3 further compares the simulated ground surface accelerations with the recorded ones. They are in good agreement at the excitation frequencies of 0.5 and 1.0 Hz, but a larger underestimation occurs at the excitation frequency of 1.5 Hz. To improve it, a nonlinear model (Ramberg-Osgood model) is utilized to consider the possible effect of soil nonlinearity. Fig. 4 displays the simulated ground surface accelerations using the nonlinear model, which agree well with the recorded. The above comparisons imply that the underestimation of acceleration for the event of the excitation frequency of 1.5 Hz is due to the nonlinearity of soil while for the events of the excitation frequencies of 0.5 and 1.0 Hz, the nonlinear behavior of soil is less significant.
Figure 3. Ground surface acceleration responses under excitation frequencies of (a) 0.5 Hz, (b) 1.0 Hz and (c) 1.5 Hz.
Figure 4. Ground surface acceleration responses under excitation frequencies of (a) 0.5 Hz, (b) 1.0 Hz and (c) 1.5 Hz (nonlinear model).

Next, the mass-pile-soil model is established as shown in Fig. 5. The pile is modeled by beam elements and the soils are modeled by spring elements. The force ($F$)-displacement ($y$) relations of the horizontal soil-pile interaction springs is defined as follows:

$$ F = p \cdot s $$  \hspace{1cm} (3)

where $p$ is the soil reaction per unit length of pile and $s$ is the spacing of the horizontal springs.

In this study, the soil reaction $p$ is defined based on the format of the API sand p-y model [5]:
\[ p = p_u \tanh\left( \frac{E_s(z)}{p_u} y \right) \]  
\[ p_u = \min(p_{us}, p_{ud}) \]  
\[ p_{us} = (C_1 z + C_2 D) \gamma' z \]  
\[ p_{ud} = C_3 D \gamma' z \]

in which \( y \) is the pile displacement, \( E_s(z) \) is the horizontal subgrade modulus at different depths \( z \), \( p_u \) is the ultimate soil resistance, \( p_{us} \) and \( p_{ud} \) are the ultimate soil resistance of shallow and deep soils, respectively, \( \gamma' \) is the effective unit weight of soil, \( D \) is the pile diameter, and \( C_1, C_2 \) and \( C_3 \) are empirical constants, depending on the soil friction angle \( \phi' \).

In Eq. (4), the subgrade reaction modulus \( E_s \) is estimated by using \( G/(1+\nu) \), in which \( \nu \) is the Poisson’s ratio.

Through the mode analysis, the predominant frequency of the pile is about 0.7 Hz, which is close to that identified from the preshaking test.

**Results**

Fig. 6 displays the recorded acceleration histories of the mass at the top of the pile at different excitation frequencies (blue lines). Different from the soil response, when the excitation frequency is 1.5 Hz, the acceleration of the mass is largest since the excitation frequency is close to the predominant frequency of the mass-pile-soil system. Compared with the simulated results (red lines in Fig. 6), it is shown that the simulated accelerations agree well with the measured. Further, Figs. 7-9 show the simulated and measured moment time histories under excitation frequencies of 0.5, 1.0 and 1.5 Hz. They are in good agreement. In the figure, it is found that
moment is largest at the shallow depth of soil and decays with depth. For the excitation frequency of 0.5 Hz, the moment response is largest due to larger acceleration of the mass.

Figure 6. Pile acceleration responses under excitation frequencies of (a) 0.5 Hz, (b) 1.0 Hz and (c) 1.5 Hz.
Figure 7. Pile moment time histories under excitation frequencies of (a) 0.5 Hz, (b) 1.0 Hz and (c) 1.5 Hz.

Conclusions

This study develops a structure-pile-soil interaction dynamic analysis model on the platform of SAP2000. The model simultaneously considers the effects of inertial loading transmitted from the superstructure and kinematic ground movement. Centrifuge shaking table tests on an extended model pile are used to verify the model. The analysis parameters of the structure-pile-soil model and the shear beam model are determined using the transfer function analysis of the preshaking test prior to each formal test. The comparison between the simulation results and the test data show that the model can appropriately capture the acceleration of the mass and the moments in the pile. Due to the single pile-soil condition used in this study, more validation is needed to examine the applicability of the model to other pile/soil conditions.

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References


