EVALUATION OF SEISMIC BEHAVIOR OF A BUILDING WITH INSULATED PILE FOUNDATION BASED ON THE SHAKING TABLE TEST

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ABSTRACT

The objective of this study is to examine the seismic behavior of a building with an insulated pile foundation which consists of a raft foundation and a set of piles installed in a ground without being connected to the raft. The authors conducted a shaking table test using a scaled model and a simulation analysis of its behavior by a three-dimensional finite element method in order to investigate the effects of input motions on dynamic characteristics of the building with the insulated pile foundation.

The study demonstrated that the insulated pile foundation can reduce the building response and the stress exerted on the piles near their heads during an earthquake. It was also revealed that the behavior of the piles during strong shaking varies from place to place due to a difference in amplitude of the input motion. The building response is also dependent on the amplitude of the input motion. The study further elucidated that the influence of the rocking motion on the response of a superstructure with the insulated pile foundation is not conservative when the amplitude of the input motion is large.

Keywords: Soil-foundation-structure interaction; Insulated pile foundation; Shaking table test; Three-dimensional finite element analysis

1. INTRODUCTION

In the case of common pile foundations, a stress exerted on the piles by a seismic inertia force in a superstructure is concentrated on their heads during an earthquake, because of a rigid connection between the pile heads and the pile caps. Recent surveys have reported that a number of pile foundations have been damaged during the 2011 Great East Japan Earthquake (e. g. Nakai et al. 2014; Nakai 2015). Some damages were serious in that the superstructure was so much tilted, causing health disturbance to its residents.

In order to overcome this problem, one of the authors has been exploring the feasibility of a special type of foundation, named an insulated pile foundation (IPF), which consists of a raft foundation and a set of piles installed in a ground without being connected to the raft. The previous studies have demonstrated two findings based on a centrifuge test and on a scaled experiment at a site (Jang et al. 2010; Sekiguchi et al. 2015; Yamamoto et al. 2015). One of the findings is that the response acceleration of the superstructure with the IPF was reduced. The other is that it also significantly reduced the stress exerted on the piles near their heads. However, the previous studies have been limited from the viewpoint of the input motion and/or the number of piles.

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amplitude of the input motion is large. The authors conducted a shaking table test using a scaled model and a simulation analysis of its behavior by a three-dimensional finite element method in order to investigate the effects of the input motions on the dynamic characteristics of a building with the IPF.

2. SHAKING TABLE TEST

2.1 Outline of the Shaking Table Test

Figure 1 shows a schematic diagram of an experimental apparatus including a shear box. The size of the shear box used in this study is 2 m \((L) \times 1\) m \((W) \times 0.96\) m \((D)\). The shear box was filled with Toyoura sand (e.g. Iwasaki et al. 1978) to 0.96 m in depth. As can be known from Figure 1, two scaled models are placed in the shear box. One of the models is the pile foundation (PF) structure, and another is the IPF structure. Each of these structures has 16 hollow aluminum piles, and the lateral distance left between the structures is 0.9 m.

The specifications of the superstructure and the pile are shown in Table 1. Figure 2 shows a detailed drawing of the pile head. As can be known from the right diagram of Figure 2, Toyoura sand was filled in the space between the raft and the pile top for the IPF. In order to add friction, a sandpaper was attached to the bottom of the raft. On the other hand, an aluminum plate and the pile tops were rigidly connected together for the PF as shown in the left diagram of Figure 2.

The shaking table provides one-dimensional in-plane motions in the lateral direction. The similarity rule for length was considered as 25 in this study. Figure 3 shows the examples of input motions. The amplitude characteristics of the input motions were basically specified according to the design response spectrum stipulated in the Building Standard Law in Japan, while the peak amplitudes were changed between 25\% and 200\% (6 amplitude levels) of the design response spectrum. Three types of phase characteristics were considered, which are called JMA Kobe, Random, and Hachinohe, respectively. In a series of experiments, the amplitudes of input motions were gradually increased. To suppress changes in ground conditions due to continuous vibration excitation, the ground was made so that the relative density might be 80\%. According to the measurements of the depths from the tops of the shear box to the ground surface, the relative density of the ground was approximately 80\% before the vibration excitation being started.
Table 1. Specification of scaled model

<table>
<thead>
<tr>
<th>Superstructure</th>
<th>Pile (hollow aluminum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>Diameter (mm)</td>
</tr>
<tr>
<td>Natural frequency (Hz)</td>
<td>Length (mm)</td>
</tr>
<tr>
<td>Upper part: 128</td>
<td>30</td>
</tr>
<tr>
<td>Base part: 57</td>
<td>IPF: 940</td>
</tr>
<tr>
<td>12</td>
<td>130</td>
</tr>
</tbody>
</table>

Figure 3. Examples of the input motions used in the experiment. (Left) acceleration time history and (right) response spectrum. Similarity rule is considered.

2.2 Result of the Shaking Table Test

First, the response of the superstructure is discussed. Figure 4 shows the relation of the peak accelerations at the top and at the base of each superstructure between the PF and IPF for the 18 input motions. As can be known from the figure, the peak response accelerations at the bases of the IPF and PF, indicated by open circles (○), are roughly similar to each other, while those at the top of the IPF, represented by red open circles (○), are lower than those at the top of the PF. Figure 5 shows the relation of the peak relative displacements of the superstructure between the PF and IPF for the 18 input motions. It is also found that the responses of the superstructure with the IPF are lower than those with the PF when the amplitude of the input motion is large.
In order to investigate a difference in response between the PF and IPF, the transfer function of the superstructure was obtained based on a single degree of freedom (SDOF) model with a flexible base shown in Figure 6. The upper diagrams of Figure 7 show Fourier spectral ratios of the tops to that of the bases (\(Z_i/Z_0\)), or the ratios of the tops to that of the ground surface (\(Z_i/Y_{FF}\)), respectively, for the input motions shown in Figure 3. In addition to those spectral ratios, the transfer function for the base-fixed condition, \(Z_i/(Z_0 + H\theta_0)\), was also obtained using the vertical acceleration records of the base for evaluation of rocking motion \(H\theta_0\). As known from the upper diagrams of Figure 7, the peak frequency of \(Z_i/Y_{FF}\), i.e. interactive system with the ground, is lower than sway-fixed \((Z_i/Z_0)\) and base-fixed \((Z_i/(Z_0 + H\theta_0))\) peak frequencies of the superstructure. The sway-fixed and base-fixed peak frequencies are roughly similar to those of the PF. On the contrary, it can be seen that a difference in peak frequency between the sway-fixed and base-fixed modes varies with the amplitude of the input motion for the IPF. The lower diagrams of Figure 7 compare the estimated ratios of sway, rocking and elastic deformation to total motion. These ratios are expressed as follows:

Sway ratio = \(Z_0 / Z_i\), Rocking ratio = \(H\theta_0 / Z_i\), Elastic deformation = \((Z_i - Z_0 - H\theta_0) / Z_i\)

(It is noted that the ratio may exceed 100% due to a phase difference of each motion.)

As can been known from the lower diagrams of Figure 7, the sway motion is dominant in the low frequency range and the elastic deformation is dominant in the vicinity of the natural frequency of the superstructure. The rocking ratio for the IPF is larger than that for the PF. It is also found that the rocking ratio for the IPF increases when the amplitude of the input motion is large. Thus, as known from the experiment result, the influence of the rocking motion on the transfer function of the IPF may not be conservative when the amplitude of the input motion is large.

![Figure 7](image)

(a) Input: JMA Kobe with 25% amplitude  (b) Input: JMA Kobe with 100% amplitude

Figure 7. (Upper) Observed transfer functions of the superstructure and (lower) the estimated ratios of sway, rocking and elastic deformation to the total motion.

Next, the stress exerted on the piles during an earthquake is discussed. Figure 8 shows the distributions of peak bending moments in depth, for the input motions of JMA Kobe with the amplitudes of 25% and of 100%, respectively. From the figure, it is confirmed that bending moments at the pile heads of the IPF are lower than those of the PF regardless of the amplitude of the input motion. It is also found that the bending moments at the pile heads of the IPF vary with the amplitude of the input motion. The
Figure 8. Distributions of observed peak bending moments of piles

Figure 9. Relation between the observed bending moment and the axial force at the pile heads.
bending moment is relatively large at the pile located on the inner side with the small amplitude of the input motion, while it is relatively small at the pile located on the inner side with the large amplitude of the input motion. This implies that the behavior of the IPF may change complicatedly due to the amplitude of the input motion.

Figure 9 illustrates the relation between the bending moment and axial force at the pile heads of the PF and IPF. In the figure, a positive axial force indicates a tensile one. As can be known from the figure, the bending moment is negative when the axial force is negative (i.e. compression) for the PF. On the other hand, the bending moment is positive when the compressional axial force is applied to the IPF. Therefore, it was also revealed that the characteristics of the inertial force of the superstructure acting on the pile heads are different depending on the pile head conditions.

3. SIMULATION ANALYSIS

3.1 Analysis Method

In this study, analysis was done basically by a three-dimensional frequency domain finite element method (FEM) with an equivalent linear approach to consider soil nonlinearity, hence soil plasticity is not considered. In order to obtain the time history at each nodal point from the analysis, the authors utilized the interpolation technique of the transfer functions and the inverse Fourier transform method (e.g., Ghiocel 2011). In order to consider soil nonlinearity by the equivalent linear approach, it is necessarily to evaluate an effective shear strain for shear modulus reduction (\(G-\gamma\)) and damping (\(h-\gamma\)) curves. Therefore, the authors evaluated an effective shear strain from the three-dimensional analysis result following the steps listed below:

- Shear strains (i.e., \(\gamma_{xy}, \gamma_{yz}\) and \(\gamma_{zx}\)) were computed at Gauss points of an element using nodal displacements.
- By averaging for each of shear strains over the Gauss points of the element, the averaged shear strains were obtained for the element.
- The maximum shear strain was obtained from the individual averaged shear strains by the square root of sum of squares.
- The value 0.65, commonly used in SHAKE (Schnabel et al. 1972), was used as a frequency-independent coefficient to evaluate the effective shear strain.

It is noted that the shear modulus reduction was considered in the analysis according to the above procedure; however, the complex bulk modulus was assumed to be constant regardless of the shear strain amplitude. (Sato and Kanatani 2006)

3.2 Analysis Model

Figure 10 shows a finite element mesh layout used in the analysis for the IPF structure. Three-dimensional symmetrical half-part model was used. Lateral roller conditions were applied to the side boundaries of the FEM model except the symmetry plane and forced vibrations were applied to the bottom boundary of the model.

The initial shear wave velocity of the ground was modeled based on the results of the bender element, confining pressure and transfer function between the ground surface and the bottom of the ground. For the IPF, the initial shear wave velocity was increased in the zone A, taking into account increased confining pressure due to existence of the superstructure. The shear modulus reduction and damping curves based on the result by Iwasaki et al. (1978) were used.

Piles were modeled as solid elements with Timoshenko beam elements. In order to improve the calculation accuracy of the bending deformation of the pile, rigid beam elements were inserted in the cross-sectional direction of the pile as shown in Figure 11.
The superstructure was modeled so that the natural frequency (12Hz, base-fixed condition) might roughly correspond to the model. In addition, in order to consider the interaction of the bending term with the column, the base and upper parts, rigid beam elements were also inserted in the horizontal direction relative to the solid elements of the base and upper parts.

### 3.3 Result of the Analysis

Figure 12 illustrates the analysis result of the transfer functions of the superstructure and the estimated ratios of sway, rocking and elastic deformation to the total motion. As known from the upper diagram

(a) Input: JMA Kobe with 25% amplitude

(b) Input: JMA Kobe with 100% amplitude

Figure 12. (Upper) Computed transfer function of the superstructure and (lower) estimated ratios of sway, rocking and elastic deformation to total motion.
Figure 13. Distribution of computed and observed peak bending moments of the pile

Figure 14. Relation between the computed bending moment and axial force at the pile head.
of the figure, the peak frequency of the interactive system \((Z_1/Y_{FF})\) is lower than that in the base-fixed condition \((Z_1/(Z_0+H\theta_0))\). A difference in peak frequency is larger for the IPF than that for the PF. Looking at the case of the IPF, the peak frequency of the interactive system is different depending on the amplitude of the input motion, and it is lower when the amplitude of the input motion is large. The overall tendency of the peak frequency of the transfer function corresponds to the experiment result as shown in Figure 7. However, the effect of rocking motion on the transfer function, which was discussed above, cannot be expressed completely. A detailed study on the evaluation of the rocking motion is the subject of a future study.

Figure 13 shows the analysis result of the distribution of peak bending moments in depth. Comparing the experiment result with the analysis result, it can be seen that there is a difference in bending moment around the depth of 0.3 m for the PF, but all the tendencies are quite similar. Therefore, it is confirmed that the bending moments at the pile heads of the IPF are lower than those of the PF regardless of the amplitude of the input motion.

Figure 14 illustrates the relation between the bending moment and axial force at the pile head for each of IPF and PF from the analysis result. As with the experiment result shown in Figure 8, the bending moment is negative when the axial force represents negative (i.e. compression) for the PF. On the other hand, for the IPF, the relation between the bending moment and axial force changed compared to that of PF. Although it is not clear when compared to the experiment result, the tendency of the inertial force acting on the pile head is roughly similar. Thus, the characteristics of the inertial force of the superstructure acting on the pile head may be different depending on the pile head conditions.

4. CONCLUSIONS

The authors conducted the shaking table test using a scaled model and its simulation analysis by three-dimensional finite element method in order to investigate the effect of the input motions on the dynamic characteristics of the building with the IPF. From the study, following conclusions can be attained:

・ It was confirmed from the study that the IPF could reduce the building response and the stress exerted on the piles near their heads during the earthquake.

・ It was also revealed that the behavior of the piles of the IPF varies from place to place depending on the amplitude of the input motion.

・ The response of the building is also dependent on the amplitude of the input motion. Thus, the influence of the rocking motion on the responses of the IPF is not conservative when the amplitude of the input motion is large.

5. ACKNOWLEDGMENTS

The authors use GMT (Wessel and Smith, 1998) to draw some figures.

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