A Study on Seismic Evaluation for Pile-Supported Building with Reusing Existing Piles

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SUMMARY
Reusing existing piles has advantages, but it is uncommon to replace a building with reusing the piles because of difficulties in seismic evaluation. Seismic response of the building may be significantly affected by the reuse methods of the piles. When the rigidity of existing pile heads are smaller than the rigidity assumed in seismic design because of construction method of pile head connection, new piles may be excessively loaded laterally. By setting the appropriate rigidity of new pile heads instead of increasing the number of piles, both new and existing piles are loaded reasonably. When it is difficult to connect existing piles directly to a raft because of piles arrangement and architectural planning, the piles are efficiently reused by improving the soil shallowly between the piles and the raft. This paper presents the findings about the appropriate strength and depth of improved soil under the reuse condition.

Keywords: Existing pile, Seismic evaluation, Finite element method, Rigidity of pile head, Improved Soil

1. INTRODUCTION

When replacing a building, reusing existing piles left in the soil is required in urban areas. Reusing the piles has advantages as shortening construction periods and reducing construction costs. In addition, it leads to reduction of construction waste and contributes to global environment conservation. In fact, it is uncommon to reuse the piles because of difficulties in non-destructive integrity evaluation for the piles and seismic evaluation for the building. Seismic response of the building may be significantly affected by the reuse methods of the piles. The purpose of this study is to investigate the effect of the methods on the behavior of the building and pile stresses under earthquakes.

Reuse methods of existing piles are divided into 3 classes (Fig. 1). When the piles have the same horizontal bearing capacity as new piles, both piles are connected to a mat slab directly (Fig. 1a). When the capacity is less than the capacity of new piles, the piles are connected to a raft with some kind of pile head connection (Fig. 1b). In Fig. 1a, both new and existing pile head conditions are assumed to be fixed in seismic design. In fact, when connecting existing piles, it is difficult to choose the same construction method of pile head connection as new piles because of the piles arrangement and the horizontal gap between the superstructure column and the pile. Thus, there is a strong presumption that the rigidity of existing pile head decreases. Figure 2 shows the summary of previous studies on the rigidity of pile head by construction methods. The rigidity increases with axial force increasing by seismic overturning moment, but is less than 1. At first, seismic response analyses were conducted to investigate the effect of the decrease of rigidity of existing pile head on seismic response.

It can be difficult to connect existing piles directly to a raft because of piles arrangement and architectural planning. One of the authors presented, by lateral loading tests, that the piles are efficiently reused by improving the soil shallowly between the piles and the raft (Fig. 1c). Secondary, seismic response analyses were conducted to investigate the appropriate strength and depth of improved soil under the reuse condition.
2. EFFECT OF RIGIDITY OF PILE HEAD ON SEISMIC RESPONSE

2.1. Analytical method

Analyses were conducted under the condition that cast-in-place concrete piles were left in the soil, where old 5-stories building was pulled down and replaced by new 10-stories building. Finite element models are shown in Figs. 3, 4. Analysis cases are shown in Table 1. As shown in Fig. 3a, existing piles were ignored. 24 new piles (φ1500) were driven into the ground and arranged in a square 4x6. As shown in Fig. 3b, 24 existing piles (φ1100) were reused and arranged in a square 4x6. 12 new piles (φ1500) were driven into the ground to increase the vertical bearing capacity of pile foundation, and arranged in a square 3x4 between the existing piles. The distance between piles was 6 m and the depth of embedment was 2 m. Viscous boundaries were set at the sides and bottom of the model.

Superstructure was modelled as a lumped mass system with nonlinear shear spring elements. The material properties of superstructure are summarized in Table 2. The initial shear stiffness \( k_i \) was calculated from the following equations, and \( T \) was 0.8 sec.

\[
k_i = k_n A_i \frac{(n - i + 1)}{A_n} \tag{2.1}
\]

\[
A_i = 1 + \left( \frac{1}{\sqrt{\alpha_i}} - \alpha_i \right) \times \frac{2T}{1 + 3T}, \quad \alpha_i = \frac{w(n - i + 1)}{wn} \tag{2.2}
\]
where $A_i$=the distribution of seismic shear force coefficient along the height of building, $T$=the first natural period of building (sec), $w$=the floor weight (t), $n$=the number of stories. The damping of superstructure was proportional to the initial stiffness, and the damping factor $\nu$ was 3 percent for the first natural period.

![Figure 3. 2-dimensional finite element model](image)

![Figure 4. 3-dimensional finite element model](image)

<table>
<thead>
<tr>
<th>Table 1. Analysis cases</th>
<th>Table 2. Material properties of superstructure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case</strong></td>
<td>(a) Only new piles</td>
</tr>
<tr>
<td><strong>New Pile</strong></td>
<td></td>
</tr>
<tr>
<td>Pile type</td>
<td>Cast-in-place concrete pile $\phi$ 1500x24</td>
</tr>
<tr>
<td>Pile head condition</td>
<td>Fixed</td>
</tr>
<tr>
<td><strong>Existing pile</strong></td>
<td></td>
</tr>
<tr>
<td>Pile type</td>
<td>-</td>
</tr>
<tr>
<td>Pile head condition</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha_c$</td>
<td>0.25, $\alpha_s=0.01$</td>
</tr>
<tr>
<td>$Q_i$ Yield load</td>
<td>3</td>
</tr>
<tr>
<td>Deformation angle at yield point</td>
<td>1/200</td>
</tr>
</tbody>
</table>
Soil was modelled as linear plane strain element for 2-D, as linear solid element for 3-D. The material properties of soil are summarized in Table 3. As shown in Fig. 5, the dynamic deformation properties of soil was expressed as following R-O model.

\[
\frac{G}{G_0} \left( 1 + \alpha \left( \frac{G}{G_0} \gamma \right)^{\beta-1} \right) = 1
\]

(2.3)

\[
\alpha = 2^{\beta-1}
\]

(2.4)

\[
\beta = \frac{2 + \pi h_{\text{max}}}{2 - \pi h_{\text{max}}}
\]

(2.5)

\[
h = h_{\text{max}} \left( 1 - \frac{G}{G_0} \right)
\]

(2.6)

where \(G_0\) is the initial shear modulus of soil, \(\gamma_{\text{ref}}\) is the reference strain (\(G/G_0=0.5\)), \(h_{\text{max}}\) is maximum damping factor. The initial shear wave velocity of soil \(V_s\) was proportional to the one-fourth power of confining pressure, and the minimum value of \(V_s\) was 80 m/s. The equivalent shear wave velocity of soil \(V_{se}\) was determined from the nonlinear analysis for free field by using \(V_s\) and the preceding R-O model. The damping of soil was proportional to the linear combination of the mass and the equivalent stiffness, and the equivalent damping factor \(h_e\) was the value shown in Table 3 for the first and second natural periods of soil.

<table>
<thead>
<tr>
<th>GL (m)</th>
<th>(\rho) (t/m³)</th>
<th>(V_s) (m/s)</th>
<th>(V_{se}) (m/s)</th>
<th>(h_e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~-4</td>
<td>1.6</td>
<td>56</td>
<td>0.163</td>
<td></td>
</tr>
<tr>
<td>~-8</td>
<td>1.6</td>
<td>65</td>
<td>0.187</td>
<td></td>
</tr>
<tr>
<td>~-12</td>
<td></td>
<td>78</td>
<td>0.180</td>
<td></td>
</tr>
<tr>
<td>~-16</td>
<td></td>
<td>94</td>
<td>0.167</td>
<td></td>
</tr>
<tr>
<td>~-20</td>
<td></td>
<td>108</td>
<td>0.155</td>
<td></td>
</tr>
<tr>
<td>-20-~</td>
<td>1.8</td>
<td>350</td>
<td>350</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Figure 5. Dynamic deformation properties of soil

Piles were modelled as linear beam elements. The Young’s modulus and the unit weight of piles were 24700000 kN/m², 2.5 t/m³. Top of the pile beam element was connected to the footing element by using the rotational spring. Rotational rigidity of the spring \(K_{\theta}\) was calculated from the following equations suggested by ‘Recommendation for the Design of Building Foundations’.

\[
\alpha = K_{\theta} / (E l \beta + K_{\theta})
\]

(2.7)

\[
\beta = \left[ k_h B / (4 E l) \right]^{1/4}
\]

(2.8)

where \(\alpha\) is the rigidity of pile head, \(E\) is the Young’s modulus of pile (kN/m²), \(l\) is the moment of inertia of pile (m⁴), \(k_h\) is the coefficient of horizontal subgrade reaction (kN/m²), \(B\) is pile diameter (m).
Footing was modelled as linear beam element for 2-D, as linear shell element for 3-D. The Young’s modulus of footing was excessively larger than the modulus of other element. Figure 6 shows the input earthquake motion that occurs extremely rarely. The acceleration response spectrum of the motion conformed to a value stipulated in the notification No. 1461 of the Ministry of Construction.

![Input earthquake motion](image)

Figure 6. Input earthquake motion

2.2. Decrease of rigidity of existing pile head

Bending moment distributions along each pile are shown in Fig. 7, 8. $M_{u}$ is the ultimate bending moment of pile. In case of $\alpha=1.0$, the bending moment of new pile was almost equal to the moment for the case of only new piles, and was smaller than $M_{u}$. With $\alpha$ decreasing, the bending moment of new pile head increased and became larger than $M_{u}$. This result suggests that when the rigidity of existing pile head is smaller than the rigidity assumed in seismic design, new pile may be excessively loaded laterally.

![Bending moment distribution](image)

(a) New pile
(b) Existing pile

Figure 7. Bending moment distributions (2-D)

![Bending moment distribution](image)

(a) New pile
(b) Existing pile

Figure 8. Bending moment distributions (3-D)

2.3. Setting appropriate rigidity of new pile head

When the rigidity of existing pile head decreases, bending moment of the pile decreases at pile head, but increases at the middle part of pile. As mentioned in section 2.2, because of a large difference of the rigidity of pile head between new piles and existing piles, new piles may be excessively loaded laterally. Therefore, it is important for the piles to be loaded reasonably by setting appropriate rigidity of the pile heads.

Analyses were conducted under the condition that the rigidity of existing pile head decreased ($\alpha_{0}=0.6$). Two kinds of measures were taken against the increase of bending moment at new pile head caused by $\alpha_{0}$ decreasing. One was to set the appropriate rigidity of new pile head ($\alpha=0.9$), and the other was to
increase the number of new piles (12 to 15). Seismic response for superstructure and piles for 3-D analyses are shown in Fig. 9, 10. There was little difference in the seismic response of superstructure. In case of increasing the number, the bending moment of new pile was less than the moment for the case of no measures, but was still larger than \( M_u \). On the other hand, by setting the appropriate rigidity, the moment was less than \( M_u \).

(a) Shear force distribution  
(b) Deformation angle distribution  
(c) Bending moment distribution  
(d) Bending moment distribution  

**Figure 9.** Seismic response for superstructure  

**Figure 10.** Bending moment distributions

### 3. EFFECT OF IMPROVED SOIL ON SEISMIC RESPONSE

#### 3.1. Analytical method

2-D finite element model is shown in Fig. 11. Analysis cases are shown in Table 4. Improved soil was modelled as linear plane strain element. The shear wave velocity of improved soil \( V_s \) was determined from the previous research by ASAKA and Katsura (2005), which presented the relation between \( V_s \) and \( q_u \) of cemented soil (Fig. 12). Considering the material non-linearity of improved soil, the equivalent shear modulus was one-half of the initial shear modulus calculated from \( V_s \). Other analytical conditions were mentioned in section 2.1.

**Figure 11.** 2-dimensional finite element model  

**Figure 12.** Relation between \( V_s \) and \( q_u \) of cemented soil  

(ASAKA & Katsura, 2005)
Table 4. Analysis cases

<table>
<thead>
<tr>
<th>New pile</th>
<th>Pile type</th>
<th>Cast-in-place concrete pile φ 1500×12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pile head condition</td>
<td>Fixed</td>
</tr>
<tr>
<td>Existing pile</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pile type</td>
<td>Cast-in-place concrete pile φ 1100×24</td>
</tr>
<tr>
<td></td>
<td>Pile head condition</td>
<td>Not connected to raft</td>
</tr>
<tr>
<td>Improved soil</td>
<td>Unconfined compressive strength $q_u$</td>
<td>$0.2, 0.5, 1.0$ N/mm$^2$ ($V_d=290, 390, 480$ m/s)</td>
</tr>
<tr>
<td></td>
<td>Depth</td>
<td>GL-2<del>3, 2</del>4, 2~5 m ($H=1, 2, 3$m)</td>
</tr>
<tr>
<td></td>
<td>Unit weight</td>
<td>$1.7$ t/m$^3$</td>
</tr>
</tbody>
</table>

3.2. Appropriate strength and depth of improved soil

At first, analyses were conducted under the condition that $H$ was 2m. Bending moment distributions along each pile are shown in Fig. 13. With the strength increasing, the bending moment of new pile decreased at pile head, but slightly increased at the middle part of pile. This result suggests that there is an appropriate strength of improved soil to obtain the uniform distribution of pile bending moment among the improved soil. Secondary, analyses were conducted under the condition that the strength was $0.5$ N/mm$^2$. Bending moment distributions along each pile are shown in Fig. 14. In case of $H=1$m, the bending moment of new pile was larger than the moment for fixed condition at pile head. This result suggests that when the soil is improved too shallowly, existing piles are slight loaded laterally.

![Bending moment distribution](image)

Figure 13. Effect of strength of improved soil

![Bending moment distribution](image)

Figure 14. Effect of depth of improved soil

4. CONCLUSION

Reusing existing piles has advantages, but it is uncommon to replace a building with reusing the piles because of difficulties in seismic evaluation. Seismic response of the building may be significantly affected by the reuse methods of the piles. When the rigidity of existing pile head is smaller than the rigidity assumed in seismic design because of construction method of pile head connection, new pile may be excessively loaded laterally. By setting appropriate rigidity of new pile heads instead of increasing the number of piles, both new and existing piles are loaded reasonably. When it is difficult to connect existing piles directly to a raft because of piles arrangement and architectural planning, the piles are efficiently reused by improving the soil shallowly between piles and the raft. This paper presents the findings about the appropriate strength and depth of improved soil under the reuse condition.
REFERENCES


