Mechanical Behavior of Pile Head Joint Disconnected Pile Head Rebars from Foundation for Earthquake Resistance

ABSTRACT: In this study, a new simplified pile head joint is proposed; this joint has not only excellent earthquake resistance but also high productivity. The joint has no anchor rebar, which connects the pile head to the foundation. This study aims to clarify the mechanical behavior of the joint via structural experiments and theoretical studies. We perform structural experiments for cast-in-place piles and steel composite concrete piles. It is clear that the deformation capacity of the joint is very high and the damage to the pile head is small. We create a formula for the theoretical prediction of the relation between the bending moment and rotational angle of the pile head. It is confirmed that the formula coincide well with experimental results. We also suggest a design method that includes the formula.

1. INTRODUCTION

In Japan, currently, because of the existence of excellent seismic design code, there are only few cases where the super structure of a building is damaged owing to frequent earthquakes. On the other hand, there are some cases where a building is tilted owing to the destruction of pile heads, for example, as in the case of the 2011 off the Pacific coast of Tohoku Earthquake.

There are several methods for protecting piles from such earthquake damage. If the rotational boundary condition of the pile head is close to free, the bending
moment around the pile head decreases, as shown in Fig. 1 (Sugimura et al. 1986). Based on this theory, the development of new joints with high earthquake resistance has been ongoing since the 1980s. These new joints can be classified into two categories: one involves the installation of a device that can be rotated and the other uses the elastic deformation of the pile cap (foundation) and the separation between the pile head and pile cap for rotation (Aoshima et al. 2006), (Aoshima et al. 2010), (Hirade et al. 2004).

We propose a simple joint, which the main reinforcements of the pile head are disconnected from the pile cap (Hamada et al. 2006). Fig. 2 shows the newly developed joint and conventional joint. When a large lateral force is applied to the developed joint, the edge of the pile head separates and it causes the rotation of the pile head and a decrease in the bending moment. The problem is that the joint exhibits complicated behaviors in such a situation.

This study aims to develop a new joint, which the pile head is not connected to the foundation. First, via structural experiments, we prove the excellent seismic performance of the joint under axial and lateral forces. Then, we clarify the abovementioned complicated behaviors via theoretical studies and discuss the simple seismic design method.

**FIG. 1. Bending moment under different pile head joint conditions**
2. CYCLIC LOAD TEST

List of experimental cases is shown in Table 1. The test setup of a cast-in-place pile and the details of the specimen are illustrated in Figs. 3 and 4. Cyclic lateral loading tests under a constant vertical load were conducted. Experimental variables are the type of pile, the axial load, and the depth of pile head embedment. The types of piles are cast-in-place piles and steel composite concrete piles. For the experiment, specimens were placed upturned, that is, the pile heads were bottom side.

### Table 1. Experimental cases

<table>
<thead>
<tr>
<th>Type of pile</th>
<th>Case name</th>
<th>Axial load (kN)</th>
<th>pile head embedding (mm)</th>
<th>pile diameter (mm)</th>
<th>Fc (MPa)</th>
<th>Main reinforcement</th>
<th>Shear reinforcement</th>
<th>Internal diameter (mm)</th>
<th>Thickness of steel pipe (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast-in-place pile</td>
<td>S-2</td>
<td>1000</td>
<td>0</td>
<td>550</td>
<td>27</td>
<td>deformed bar 45-96</td>
<td>round bar 3.2mm @ 40</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>S-4</td>
<td>2000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Steel composite concrete</td>
<td>Case 1</td>
<td>2500</td>
<td>100</td>
<td>400</td>
<td>105</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>1250</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Case 3</td>
<td>2500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

2-1 Cast-in-place pile (S-2, S-4)

Two test cases were performed with axial loads of 1000 kN (S-2) and 2000 kN (S-4) for a cast-in-place pile. Tables 2 and 3 show the properties of concrete and steel for the cast-in-place pile.

Fig. 5 shows the relation between the rotational angle and bending moment at the pile head. Fig. 6 shows the positions of displacement gauges for measuring the inclination of the pile and the inclination distribution results for S-2.

Rotational angles were obtained from Eqs. (1) and (2). The pile head inclined...
from initial loading, i.e., the pile head was not completely constrained. This rotation results from the elastic deformation of the pile cap.

$$\theta_1 = (DL_1 - DR_1)/\ell,$$

$$\theta_i = (DL_i - DR_i)/\ell + \theta_{i-1}, \quad (i = 2-9).$$

Maximum bending moments were 256 kN·m (S-2) and 447 kN·m (S-4); they were larger in proportion to axial loads. Because the main reinforcements of the pile were disconnected from the pile cap, tensile stress does not act on the joint; only compressive stress acts to resist rotation. Consequently, the generation of the bending moment reached a plateau, damage to the pile was small, and deformation capacity was very high. However, the slope of the curve following the peak of S-4 was greater than that of S-2 because the collapsed area of the joint of S-4 in large deformation was wider.

Table 2. Properties of concrete used in cast-in-place pile experiments

<table>
<thead>
<tr>
<th></th>
<th>Compressive strength (MPa)</th>
<th>Young's modulus (GPa)</th>
<th>Strain at the maximum stress (µ)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pile</td>
<td>33.0</td>
<td>31.5</td>
<td>1803</td>
<td>0.194</td>
</tr>
<tr>
<td>Pile Cap</td>
<td>35.0</td>
<td>29.7</td>
<td>1868</td>
<td>0.197</td>
</tr>
<tr>
<td>S-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pile</td>
<td>33.0</td>
<td>30.1</td>
<td>1809</td>
<td>0.176</td>
</tr>
<tr>
<td>Pile Cap</td>
<td>35.0</td>
<td>30.5</td>
<td>1821</td>
<td>0.201</td>
</tr>
</tbody>
</table>

Table 3. Properties of steel used in cast-in-place pile experiments

<table>
<thead>
<tr>
<th>Steel type</th>
<th>Yield stress (MPa)</th>
<th>Yield strain (%)</th>
<th>Tensile strength (MPa)</th>
<th>Yield ratio</th>
<th>Dilation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>main reinforcement</td>
<td>D6 SD345</td>
<td>368</td>
<td>1794</td>
<td>478</td>
<td>0.77</td>
</tr>
<tr>
<td>shear reinforcement</td>
<td>φ3.2 SS400</td>
<td>569</td>
<td>2777</td>
<td>615</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Fig. 5. Relation between bending moment and rotational angle

Fig. 6. Angle of inclination (S-2)

2-2 Steel composite concrete pile (Case 1–3)

Three cases were tested with axial loads of 2500 kN (Cases 1 and 3) and 1250 kN (Case 2). Cases 1 and 3 had 100mm embedment. Fig. 7 shows the specimen details. This type of pile has a steel pipe on the circumference and a void at the center. A cruciform plate was installed between the pile head and pile cap. Tables 4 and 5 show the properties of concrete and steel for the steel composite concrete pile.

Fig. 8 shows the relation between the rotational angle and bending moment at the
pile head. The tendency of the maximum bending moment and deformation capacity was similar to that of cast-in-place piles. However, the gradient decrease following the peak of steel composite piles was smaller than that of cast-in-place piles because of their high cross-sectional performance.

Fig. 9 shows compressive strain distribution around the pile head for Case 1. Here, a minus value indicates compression. The strain in the compression side of the pile head was approximately 2000µ at a distortion angle of +15/1000 rad, which was equivalent to a rotational angle of 0.015 rad. This means that the stress of concrete reached the compressive strength.

Table 4. Properties of steel used in steel composite concrete pile experiments

<table>
<thead>
<tr>
<th>Steel thickness (mm)</th>
<th>Steel type</th>
<th>Yield stress (MPa)</th>
<th>Yield strain (%)</th>
<th>Tensile strength (MPa)</th>
<th>Yield ratio</th>
<th>Elastic strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>STK400</td>
<td>446</td>
<td>2176</td>
<td>585</td>
<td>0.76</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 5. Properties of concrete used in steel composite concrete pile experiments

<table>
<thead>
<tr>
<th></th>
<th>Compressive strength (MPa)</th>
<th>Young’s modulus (GPa)</th>
<th>Strain at the maximum strength (%)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile</td>
<td>110</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pile Cap</td>
<td>25.5</td>
<td>31.6</td>
<td>1500</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 7. Specimen details (Case 1, Case 3)

Fig. 9. Axial strain of pile (Case 1)
3. METHOD FOR ESTIMATING BENDING MOMENT

3-1 BENDING MOMENT CHARACTERISTICS

3-1-1 Initial rotational stiffness

Our experiments revealed that the initial rotational stiffness of the joint is not fixed by pile cap deformation. This rotational stiffness is expressed as Eq. (3), which is derived from the rocking stiffness of a circular disc on a homogeneous half-space.

\[ K_{00} = \frac{\pi E D^3}{32(1-\nu^2)}, \]  

where  
\[ E \] : Young’s modulus of the pile cap  
\[ D \] : Pile diameter  
\[ \nu \] : Poisson’s ratio of the pile cap  
\[ \pi \] : Circle ratio (pi)

The rotational stiffness of an annular cross-section (e.g. steel composite concrete piles) is smaller than that of the circular cross-section (e.g. cast-in-place piles). However, the difference is negligibly small. Therefore, Eq. (3) can be applied for both sections.

3-1-2 Bending moment at separation time

When the pile head separates from the pile cap on the tension side, the rotational stiffness starts to decrease. After this point, the relation between the bending moment and rotational angle shows nonlinearity. The bending moment of \( M_{sp} \) occurs when compressive stress at the pile head edge becomes zero, in accordance with Eq. (4). \( M_{sp} \) is defined by Eqs. (5) and (6).

\[ \sigma = \frac{N}{A} - \frac{M}{Z} = 0. \]  

Substitution of the section modulus of the pile head in Eq. (4) yields Eqs. (5) and (6).

\[ M_{sp} = \frac{ND}{8} \quad \text{for a circular cross-section}, \]  
\[ M_{sp} = \frac{N(D_1^2 + D_2^2)}{8D_1} \quad \text{for an annular cross-section}, \]

where  
\[ N \] : Axial force at pile head  
\[ D \] : Pile diameter  
\[ D_1 \] : Pile outer diameter  
\[ D_2 \] : Pile inner diameter

3-1-3 Maximum bending moment

Fig. 10 shows the diagram of forces at the pile head. \( R(x) \) represents compressive stress distribution. The bending moment at the pile head is obtained from Eq. (7) from the force diagram. Eq. (7) converges to Eq. (8) when only the edge of the pile head
contacts the pile cap.

\[ M = QL = \frac{ND}{2} - \int_0^D R(x) \cdot x, \quad \text{(7)} \]

\[ M_{\max} = \frac{ND}{2} \quad \text{(8)} \]

\[ \text{Fig. 10. Diagram of forces at pile head} \]

If the pile head is embedded in the pile cap, Eq. (9) is substituted for Eq. (8). Increase in the maximum bending moment \( M_{em} \) is calculated as follows (Yamamoto et al. 2007):

\[ M_{\max} = \frac{ND}{2} + M_{em}, \quad \text{(9)} \]

where \( M_{em} = (M_c + M_s) \): Bending moment resistance of pile head embedment

\( M_c = 0.41 F_c D \times \ell^2 \): Effect of ultimate strength of compressive failure

\( M_s \) (ignored): Effect of ultimate strength of punching shear failure

\( F_c \): Compressive strength of pile cap concrete

\( \ell \): Depth of pile head embedment

3-2 Estimation formula

We initially use the linear model, Eq. (10), until the pile head separates and then use the hyperbolic curve model, Eq.(11), which asymptotically approaches the maximum bending moment \( M_{max} \) from \( M_{sp} \).

\[ M = K_{\theta_0} \cdot \theta \quad (\theta \leq \theta_{sp}), \quad \text{(10)} \]

\[ M = \frac{M_{\max} - M_{sp}}{1 + \frac{M_{\max} - M_{sp}}{K_{\theta_0} (\theta - \theta_{sp})}} + M_{sp} \quad (\theta > \theta_{sp}), \quad \text{(11)} \]

where \( \theta \): Rotational angle of the joint

\( \theta_{sp} \): Rotational angle of the joint at separation time \( \left( M_{sp} / K_{\theta_0} \right) \)

Fig. 11 shows the maximum values of the experiments and the line predicted by Eqs. (10) and (11). The maximum values for Case 2 and S-2 with low axial loads agreed well with the predicted line. On the other hand, the predicted line was higher than the maximum values for Cases 1 and S-4 with higher axial loads. We hypothesize that the cause of this difference is that the compressive strength of the
pile head joint was not sufficiently high for Eq. (8) to apply.

3.3 Maximum bending moment considering plasticity of the pile head

We precisely estimated the maximum bending moment by assuming stress profiles illustrated in Fig. 12. We assume triangular and rectangular stress profiles to obtain the relation between the maximum bending moment and axial load. The triangular stress profile linearly increases from zero at the separated area and reaches the concrete strength at the edge of the pile head, which indicates the state immediately prior to yielding. The rectangular stress profile is zero at the separated area and reaches the concrete strength at the contact area, which indicates an almost completely plastic state. These equations obtained from this assumption are very simple. An example of the equations is provided in the Appendix. The compressive stresses of the main reinforcement of a cast-in-place pile and that of a steel pipe of a steel composite concrete pile are given as stresses calculated by assuming a strain of 1800 $\mu$ with a Young’s Modulus of 205 GPa; this is because strain at the maximum strength of concrete is around 1800 $\mu$.

Fig. 13 shows calculated values for conditions illustrated in Fig. 12 and experimental values which are reduced by $M_{cm}$ in Eq.(9). The values calculated by the triangular stress profile were lower than the experimental values and the values calculated by the rectangular stress profile were almost equal to the experimental values.

Fig. 14 shows a recalculation of the values of Figs. 11 (b) and (d) by substituting the value of the rectangular stress profile for ND/2 in Eq. (9). The prediction precision of Fig. 14 is more improved than that of Fig. 13.
3-4 Allowable value for design

The Japanese seismic design for a building is performed in two steps. At Level 1, the performance objective is “buildings are not damaged by seismic loads due to around 50 years return period earthquake.” At Level 2, the performance objective is “buildings do not collapse owing to seismic loads generated by 500 years return period earthquake.”

An example of the procedure for setting the design allowance value in accordance
with the Japanese seismic code is presented. The Level 1 criterion is that the sectional force at the joint exists in the curve depicting the relation of the bending moment to axial load assumed in the triangular stress profile because the damage to the joint is expected to be slight. Fig. 15 shows allowable rotational angle for the cast-in-place pile, using Fig. 13 and Eq. (11). When the axial load becomes greater, the allowable rotational angle generally becomes smaller. Moreover, the sharply decrease of the allowable rotational angle in very small axial load is effect of disappearance of contact area of pile main reinforcements.

We could not confirm the ultimate strength because of the high deformation capability of piles. Considering safety margins and the maximum rotational angle confirmed by the experiments, 0.02 rad is given as the Level 2 criterion within the scope of the axial load ratio of the experiments.

![Fig. 15. Relation between axial load and allowable rotational angle](image-url)
4. CONCLUSIONS

We proposed a new, simple pile head joint, which the main reinforcements of the pile head are not connected to the pile cap. We performed structural experiments on cast-in-place piles and steel composite concrete piles and confirmed the performance of the joint via theoretical and experimental studies. The following conclusions were obtained.

1) The joint has a high deformation capability.
2) The initial rotational stiffness of the joint can be evaluated by assuming the rotational stiffness of a circular disc on a homogeneous half-space.
3) Maximum bending moment at pile head depends on the compressive strength of pile head joint.
4) If the compressive strength of the pile head joint is sufficiently high, the maximum bending moment is only given by the axial load and pile diameter.
5) The hyperbolic curve model agrees well with the experiments because the bending moment asymptotically approaches the maximum bending moment after the pile head joint separates.
6) An example of the procedure for setting the design allowance value is presented.

REFERENCES

APPENDIX

Relation between bending moment and axial load assumed triangular stress condition.

For circular section

\[ N = \int_{A} \sigma(y) dA \]

\[ = \int_{A} \frac{\sigma}{2r-x} (r \sin \theta + r - x) \cdot (2r \cos \theta \cdot r \sin \theta) \]

\[ = \frac{2 \pi r^2 \sigma}{2r-x} \int_{0}^{\pi/2} \sin^2 \theta \cdot (r \sin \theta + r - x) d\theta \]

For ring section

\[ M = \int_{A} y \sigma(y) dA \]

\[ = \int_{A} \frac{\sigma}{2r-x} (r \sin \theta + r - x) \cdot (2r \cos \theta \cdot r \sin \theta) \]

\[ = \frac{2 \pi r \sigma}{2r-x} \int_{0}^{\pi/2} \sin \theta (r \sin \theta + r - x) d\theta \]

where \( \sigma \): stress at edge, \( r \): radius, \( x \): length of separated area, \( t \): thickness