Reuse of existing bored piles for high-rise building foundation

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ABSTRACT

The Ochanomizu Sola City building is one of the largest redevelopments in which existing bored cast-in-place piles have been used in combination with new bored piles for the foundation of a new high-rise building in Japan. The building, completed in 2013, is a 110-m high-rise office building supported by 169 existing bored piles and 99 new bored piles. In addition to the existing piles, the existing foundation slab and pile caps were also reused. During the demolition of the old building, which was constructed in 1983, several types of investigations of the existing piles, including two pile load tests, were conducted to assess their integrity and performance. In the design stage, the safety of the mixed foundation system subjected to vertical and horizontal loads was verified using detailed analytical methods. It was also estimated that approximately 4,000 tons of CO2 were saved by reusing the existing piles. The measured settlements and vertical sharing loads of the existing piles were found to be in reasonable agreement with the predicted results.

Keywords: reuse, existing pile, pile load test, settlement prediction, field monitoring, CO2 emissions

1. INTRODUCTION

In recent years, reuse of existing foundations has become increasingly popular with designers and developers in major cities. Reusing existing foundations, particularly existing bored cast-in-place piles, has beneficial impacts on the cost, construction time, and CO2 emissions. This paper presents a practical example of reusing existing bored cast-in-place piles in the foundation for a new high-rise building.

2. OUTLINE OF BUILDING AND SITE CONDITIONS

Ochanomizu Sola City is a 110-m high-rise office building in front of the JR Ochanomizu Station in Tokyo, as shown in Fig. 1 and Fig. 2. The building construction over two existing subway lines, the Chiyoda line and the Marunouchi line, as shown in Fig. 3, was completed in 2013, after a previous 30-year-old, 78-m high-rise office building was demolished. The new building is supported by 169 existing bored piles and 99 new bored piles. The outline of the piles is shown in Table 1. The main motivation for reuse of the existing piles was that there was no place for additional piles around the Chiyoda line just below the planned high-rise block.

A typical soil profile, standard penetration test

Fig. 1. View of Ochanomizu Sola City

Fig. 2. Cross-sectional view with field monitoring locations

Fig. 3. Layout of existing and new piles and monitoring locations

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INVESTIGATIONS OF EXISTING PILES

As the project progressed, comprehensive investigations of the existing piles were conducted, as summarized in Table 2, to obtain sufficient information for design. In the primary stage before the demolition, the locations and sizes of the existing piles were checked in existing design documents and piling reports. Settlement measurement of the old building confirmed that there was little differential settlement and no serious cracking caused by differential settlement.

The Stage 1 investigation of two unreused existing piles was conducted in the excavated pit under the old building during demolition. The Stage 2 investigation of 169 reused existing piles was carried out after the superstructure of the old building was demolished. Investigations of physical damage, material deterioration, material strength, and bearing capacity were conducted. Visual inspections of the existing pile heads indicated that the pile surface conditions and the reinforcing steel bars were very good, as shown in Fig. 5. Integrity tests of all the reused piles showed that there was no serious damage to the piles and that the measured pile lengths corresponded approximately to those indicated in the existing piling records. It was also verified that neutralization had not made much progress and that the measured material strengths were greater than the original design strengths (21.0 N/mm²), as shown in Fig. 6. The bearing capacities determined from the results of two pile loading tests were greater than 28.5 MN, as shown in Fig. 7, and much higher than the original design ultimate capacities (approximately 12 MN and 16 MN).

The results of comprehensive investigations showed the existing piles were serviceable and had sufficient bearing capacities. The existing foundation slabs and pile caps were also reusable, based on the results of tests of the materials, such as the concrete and steel.

SETTLEMENT PREDICTION

It was estimated that the new loads of the 110-m high-rise building were higher than those previously applied. To supplement the capacity of the existing piles, 99 new piles were installed. In such a mixed foundation, differential settlement could occur because of the different stiffnesses of the pre-loaded existing piles and the new piles. Therefore, settlement analyses were conducted to predict the differential settlements and the load sharing of the existing piles.

The hybrid analytical approach developed by Nagao et al. 2, illustrated in Fig. 8, was used for the nonlinear analyses. Pile–soil–pile interactions were taken into account in the analyses.
account by means of Mindlin's first solution. The nonlinear behavior of the soil surrounding the piles was modeled using nonlinear soil springs. The validity of the method has been examined through comparisons with the results of other numerical models and the results of field monitoring\(^3\).

The load–settlement behavior of the two tested existing piles was back-analyzed using the hybrid approach to calibrate realistic values for each input parameter and for the soil interaction. The back-analyzed results were found to be in good agreement with the test results, as shown in Fig. 7. The input parameters used for settlement prediction are summarized in Table 3.

The calculated settlement distribution of the foundation slab is shown in Fig. 9. The predicted maximum settlement and deflection were approximately 25 mm and 1/1500, respectively, which satisfied the design criteria. The load sharing of the existing piles was calculated to be approximately 40%. As a result, the sharing loads of the existing and new piles were less than the respective allowable bearing capacities.

5 DESIGN FOR HORIZONTAL LOAD

The design criteria and the analytical model subjected to horizontal loads are shown in Table 4 and Fig. 10, respectively. In the analytical model, the foundation members and the soil were modeled using beam elements and soil springs. The nonlinearity of the soil springs and the group pile effect were considered in accordance with the Recommendations for Design of Building Foundations\(^4\). The range of reduction ratio values considered for a pile group was set to 0.45 to 0.81. The pile head connections of the existing piles were assumed to have semi-rigid connections: the main reinforcement bars of the existing piles were not anchored into the new foundation slab, and rotations were allowed. In the numerical model, the rotation behavior at the pile head was represented by nonlinear rotation springs developed based on the test results and considering the effect of variation in the axial forces\(^5\).

It was confirmed from the analysis results that the stresses in the piles under each design seismic load were lower than the allowable values, as shown in Fig. 11. It was also predicted that the sharing load ratio of the existing piles subjected to the largest possible earthquake loads was 34%.

6. FIELD MONITORING

Field measurements have been conducted to confirm the validity of the settlement prediction and the quality of the foundation system during and after construction. The monitoring program consists of measurements of the foundation settlement, axial loads on the piles, the earth pressure on the foundation slab, and the pore water pressure, as shown in Fig. 2 and Fig. 3.

Table 3. Input parameters used for settlement analysis

<table>
<thead>
<tr>
<th>Depth from final level (m)</th>
<th>Soil type</th>
<th>(E_s) (MN/m(^2))</th>
<th>(v_s)</th>
<th>Ultimate shaft resistance (s_t) (MN/m(^2))</th>
<th>Ultimate base resistance (q_b) (KN/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Clay</td>
<td>155</td>
<td>0.49</td>
<td>100</td>
<td>120</td>
</tr>
<tr>
<td>20</td>
<td>Sand</td>
<td>455</td>
<td>0.30</td>
<td>165</td>
<td>165</td>
</tr>
<tr>
<td>27</td>
<td>Clay</td>
<td>365</td>
<td>0.47</td>
<td>100</td>
<td>185</td>
</tr>
<tr>
<td>30</td>
<td>Gravel</td>
<td>1111</td>
<td>0.30</td>
<td>100</td>
<td>185</td>
</tr>
<tr>
<td>120</td>
<td>Sand</td>
<td>1074</td>
<td>0.30</td>
<td>-</td>
<td>7500</td>
</tr>
</tbody>
</table>

Table 4. Design criteria for seismic horizontal loads

<table>
<thead>
<tr>
<th>Reparability limit state</th>
<th>Ultimate limit state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load for seismic design</td>
<td>Medium earthquake</td>
</tr>
<tr>
<td>Medium earthquake</td>
<td>CB = 0.11</td>
</tr>
<tr>
<td>K = 0.15</td>
<td>The largest possible earthquake</td>
</tr>
<tr>
<td>Addition to soil deformation</td>
<td>CB = 0.165, K = 0.3</td>
</tr>
<tr>
<td>Foundation members *</td>
<td>Less than allowable stress for short-term loading</td>
</tr>
<tr>
<td>Safety ratio of ultimate resistance: Axial and bending: over 1.2</td>
<td>Shear: over 1.5</td>
</tr>
</tbody>
</table>

*Pile body, foundation beam, foundation slab and pile top connection
Figure 12 shows the measured and calculated settlements of the B2F columns along the Y6 line. The maximum measured settlement and deflection on 2012/12/22 were 16 mm and 1/3600, respectively which were in good agreement with the calculated values.

The time histories of the measured load sharing of the new and the existing piles in Zone B are shown in Fig. 13, together with the calculated results. Note that the each axial force is the sum of the axial forces at the pile heads carried by the two new piles or the two existing piles in Zone B. According to Fig. 13, the load sharing of these piles increased during the construction process. After construction of the building was completed, the load sharing became almost constant but varied cyclically and increased slightly. It was thought that changes in the water pressure, as shown in Fig. 14, and concrete creep behavior may have influenced the measurement results. The measured and calculated sharing loads of the new and the existing piles at the time that construction of the building was completed are summarized in Table 5. Reasonable predictions were obtained from the calculations.

7. ESTIMATION OF CO2 EMISSIONS

Table 6 shows the results of calculation of CO2 emissions for two cases. Case A represents the reusing of existing piles in combination with the use of new piles in the foundation for this project. Case B represents the use of all new piles after removal of some existing piles. As Table 6 shows, it was estimated that approximately 4,000 tons of CO2 were saved by reuse of the existing piles.

8 CONCLUSIONS

This paper describes the foundation design for the Ochanomizu Sola City redevelopment. The new high-rise building was constructed on a foundation that included 169 existing bored cast-in-place piles and 99 new piles. The main points can be summarized as follows:

・Comprehensive investigations of the existing piles, constructed in 1980, confirmed that the piles remained serviceable and had sufficient bearing capacity.

・The settlement and vertical sharing load measurements for the existing piles were in reasonable agreement with the values predicted in the design stage.

・The safety against the largest possible earthquakes was confirmed by beam–spring modeling analyses.

・It was estimated that approximately 4,000 tons of CO2 were saved by reusing the existing piles.

REFERENCES