Experimental behaviour of prefabricated pile-cap foundation under seismic loading

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Abstract. Precast building has attracted more and more interest of both researchers and engineers due to fast constructional speed and lower labour cost. In the past, the precast structure was generally used in the superstructure, such as load bearing frame, however, it is seldom applied in the substructure such as foundation. The paper thus proposed a type of pile-cap connection to fabricate the foundation of a substation. A series of tests on the prefabricated pile-cap connection using these connections were carried out under seismic loading. The failure mode and lateral load versus lateral displacement response of the tested specimens were experimentally investigated. The seismic behaviour of the precast foundation was compared with the behaviour of the corresponding cast-in-place foundation.

1. Introduction

Recently, prefabricated structures have been increasingly used worldwide mainly due to the environmental and sustainable benefits. Compared with the cast-in-place structures, the prefabricated structure is characterised by the improved construction quality, faster construction speed, less environmental pollution and reduced energy consumption [1]. In China, many substation building are built in remote area, where concrete is difficult to be transported and cast on site. In this case, the application of precast structures, which the structural members is fully manufactured in a factory and then assembled on site, is expected to be very favourable to the substation building. In the past, the behaviour of precast superstructures, such as precast beam-to-column connections, column-to-column connections and bearing frames, have been comprehensively studied [2-8]. However, research on prefabricated foundation is still very limited due to the lack of suitable pile-cap connections.

This paper thus proposes a type of pile-cap connection for the prefabricated foundation, where the bolt flange connection is adopted to connect the pile and cap, as shown in Figure 1. Two steel flanges are connected with a steel tube via welding. Several steel bars are embedded in concrete cap and concrete pile respectively when they are cast in the factory. The screw thread is manufactured at end of these steel bars. After the cap and pile are transported to the constructional site, several bolts are employed to connect the cap to the top flange, and then the pile to the bottom flange. A series of tests, including a prefabricated foundation and a cast-in-place foundation under constant axial compressive load and cyclically lateral loading, were carried out to examine the feasibility of using the proposed pile-cap connection. The failure mode, ultimate strength, load versus displacement hysteretic response,
and deformation ability of the precast foundation was experimentally analysed and compared with the control cast-in-place specimen.

![Figure 1. Schematic view of precast pile-cap foundation.](image)

### 2. Experimental program

In this research, two pile-cap foundation models, the prefabricated specimen and the reference cast-in-place specimen, were tested, where the combined actions of constant axial compressive load and cyclically lateral load were imposed to investigate the seismic behavior of them.

#### 2.1. Specimen preparation

The concrete of pile was reinforced by five longitudinal steel bars with the diameter of 18 mm (Φ18) and a serial of hoops with diameter of 6 mm (Φ6). The longitudinal bars of pile extended to the concrete of cap for anchoring. The cap was reinforced by Φ14@150 steel bars, whilst four Φ20 bars were also arranged to enhance the anchorage of the pile. For the prefabricated specimen, a set of high strength bolts were adopted to connect the steel flange and the steel plate that was pre-embedded in the concrete cap.

#### 2.2. Material properties

Table 1 presents the measured average yield stress ($f_y$), tensile strength ($f_u$), Poisson's ratio ($\nu$), Young's modulus ($E$) and elongation ($\delta$) of the steel components used in this test via steel coupon tests.

| Steel type | t or d (mm) | $f_y$ (MPa) | $f_u$ (MPa) | $\nu$ | $E$ (GPa) | $\delta$ (%) |
|------------|-------------|-------------|-------------|------|-----------|-------------|
| Tube       | 16.0        | 509.4       | 600.9       | 20923.3 | 0.316     | 17.01       |
| Flange     | 18.0        | 395.22      | 552.4       | 21678.5 | 0.289     | 17.97       |
| 6mm bar    | 8.1         | 507.035     | 721.8       | 24208.2 | 0.265     | 23.02       |
| 14mm bar   | 13.7        | 492.89      | 684.6       | 23083.7 | 0.320     | 25.00       |
| 18mm bar   | 17.9        | 530.27      | 686.9       | 21911.1 | 0.284     | 19.44       |
| 20mm bar   | 20.2        | 455.01      | 649.6       | 24541.0 | 0.302     | 16.50       |

The cube strength ($f_{cu}$) of the concrete is 59.4 MPa and 79.5 MPa for the pile and the cap at the time of testing, respectively.

Figure 2 shows the test set-up. In the testing program, the axial compressive load was first imposed on the specimen by the 1000kN jack, where the applied axial load was allowed to move with the specimen through the rolling support. Then, a hydraulic actuator was employed to apply cyclically lateral load at the specimen, as shown in Figure 2. A series of displacement sensors were installed to record the deflections along the pile.
3.  Experimental results

3.1.  Failure modes

The testing program was proceeding in a smooth way, and both cast-in-place specimen and prefabricated specimen showed a ductile failure mode.

For the cast-in-place pile-cap foundation, as the displacements reached 36 mm, first crack was found on the surface of reinforced concrete cap with the direction perpendicular to the perimeter of pile. Then, the flexural crack appeared near the end of concrete pile, as shown in Figure 4(a). With more imposed cycles, both pile and cap showed several new cracks extending and propagating as the displacement attaining 56 mm, as shown in Figure 4(b). As the lateral displacement rose, it was observed that the width of cracks began to increase significantly and the propagation of cracks developed dramatically. At the displacement of 66 mm, the surface of concrete cap exhibited several main cracks with big crack widths, whilst concrete spalling was also seen at the cap, shown in Figure 4(c). Figure 4(d) shows the failure appearance of the tested specimen, where the severe spalling of concrete was also observed in the connective zone of pile and cap.
For the prefabricated specimen, when the controlled displacements attained 45 mm, first crack was observed on the reinforced concrete cap in the pile-cap connective zone, as shown in Figure 4(a). Then with the increasing lateral load, the top surface of concrete cap tended to show more cracks around the steel flange, shown in Figure 4(b). At the lateral displacement of 99 mm, the steel bar of the pile at the bottom end was found to be yielding, shown in Figure 4(c). Soon after that, the specimen attained failure. It can be seen from Figure 4(d) that, the prefabricated pile-cap foundation failed mainly due to the failure of connection between steel flange and concrete cap.

**Figure 3.** Failure mode of the tested cast-in-place specimen.

**Figure 4.** Failure mode of the tested precast specimen.
3.2. Lateral load \((P)\) versus lateral deflection \((\Delta)\) responses

The recorded lateral load \((P)\) versus lateral deflection \((\Delta)\) hysteretic curves of the specimens in this test are illustrated in Figure 5. It can be seen that, the shape of \(P-\Delta\) hysteretic curves are generally similar for both cast-in-place specimen and precast specimen. Significant pinching effect was found in \(P-\Delta\) hysteretic curves mainly due to the cracking of concrete and the slip between reinforcing bars and concrete. Residual displacements were found after the concrete cracking, and then the successive yielding of steel bars lead to more significant nonlinear feature of the \(P-\Delta\) hysteretic response. After the peak load was reached, the load decreased gradually while the curve tended to show more sliding feature. In general, the \(P-\Delta\) hysteretic hoops of the prefabricated specimen are slightly plumper than those of the cast-in-place specimen, indicating a better energy dissipated mechanism of the precast foundation. This is mainly since the connection of the precast specimen was made from steel components, which is supposed be better than the concrete in terms of ductility and energy dissipated ability.

![Lateral load (P) versus lateral deflection (Δ) responses.](image)

Figure 5. Lateral load \((P)\) versus lateral displacement \((\Delta)\) responses.

3.3. \(P-\Delta\) envelope curves

Figure 6 compares the \(P-\Delta\) envelope curves of the prefabricated specimen and cast-in-place specimen. It is obvious that the ultimate strength of the prefabricated specimen is lower than that of the reference cast-in-place one. It seems that additional enhancement is needed to enhance the connection between the steel flange and the concrete of cap. It also can be seen that, the displacement at peak load of the prefabricated foundation is nearly twice of that of the cast-in-place foundation, indicating the significantly improved deformation ability.

![Comparison of P-Δ envelope curves.](image)

Figure 6. Comparison of \(P-\Delta\) envelope curves.

4. Conclusion

This paper proposed a type of prefabricated pile-cap foundation, and the cyclic test was performed to investigate the behaviour of the connection. The failure mode, ultimate strength, lateral load versus lateral deflection response, and deformation ability of the prefabricated specimen was compared to
those of the reference cast-in-place foundation. It was found that the shape of $P$-$\Delta$ hysteretic curve of the prefabricated connection is generally close to that of the cast-in-place one, where the ultimate strength of the former is lower than that of the latter. However, the prefabricated foundation exhibited more favourable deformation ability. It seems that further research needed to be conducted to enhance the connection between the steel flange and the concrete of cap.

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