Distributed monitoring of deformation of PCC pile under horizontal load using OFDR technology

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Abstract. To study the horizontal bearing behavior of cast-in-place concrete (PCC) pipes, a horizontal static load model test is conducted based on the optical frequency domain reflectometry (OFDR) technology. The deformation distribution in the pile is studied. Results show that the pile moment increases with the horizontal load, whereas the position of the maximum point of moment is roughly unchanged. Moreover, the calculated and measured values of horizontal displacement at the pile top are compared; results show that the values are in agreement, which demonstrates that the deformation of a PCC pile can be successfully measured using the OFDR technology.

Key words: PCC pile; horizontal displacement; OFDR; bending moment

1. Introduction

Compared with conventional piles, such as cement mixing piles, cast-in-place concrete (PCC) pipes are more rapidly constructed and economical in cost; moreover, their quality can be easily checked[1]. Abundant research has been conducted on PCC piles, including their deformation mechanism, bearing behavior, and other parameters[2-5]. The deformation characteristics of PCC piles are crucial for design and construction. However, the pile strain is obtained mainly by using electronic gauges, which are difficult to apply and have a low survival rate and low precision. Moreover, pile strain cannot be measured comprehensively by using electronic gauges; therefore, new technology should be used to study deformation in PCC piles.

To monitor geotechnical and geological engineering projects, distributed optical fiber sensor (DOFS) technology has been developed[6-20] in which the entire length of optical fiber can be used to measure deformation. DOFS technology includes methods such as fiber Bragg grating, optical frequency domain reflectometer (OFDR), Brillouin optical time domain analysis, Brillouin optical time domain...
reflectometer (BOTDR), and Brillouin optical frequency domain analysis. Compared with other frequently used DOFS methods, OFDR offers superior qualities including short measuring time and high precision and is widely used in power and structural engineering applications\[^{[21-23]}\]. However, its application in geotechnical engineering, particularly for pile foundations, has not been extensively reported.

The deformation of PCC piles under the horizontal load is a crucial factor in superstructures. To obtain this value, OFDR is used to monitor the deformation in the piles. In this study, a model test of a single pile is conducted under the horizontal load. The strain of the PCC pile is measured using the OFDR technology, and the method and process used for the optical fiber sensor placement, horizontal load application, and data analysis are presented. Moreover, the strain curves are analyzed according to the experimental conditions, and the bending moment and horizontal displacement curves are obtained. Finally, the reliability of OFDR applied to PCC piles is discussed.

2. Principle of OFDR technology
When a light wave enters an optical fiber, the Rayleigh, Raman, and Brillouin scattering light are simultaneously obtained at the backward reflecting end (Figure 1). The Rayleigh scattering light belongs to the elastic scattering light, and the frequency will not drift during the scattering process. OFDR used optical fiber sensing technology based on the Rayleigh scattering light.

![Figure 1. Scattered light in the optical fiber\[^{[21]}\).](image)

Rayleigh scattering is caused by random changes in the refractive index of an optical fiber. When the strain in the fiber changes, the spectrum of back-scattering signals will drift in terms of frequency. The amount of drift is proportional to the strain generated by the optical fiber. Through relevant calculation of the measured and initial signals, the drift value can be obtained. Then, the strain value can be calculated from equation (1). The distributed strain information of the entire optical fiber can be obtained by scanning.

\[
\Delta \nu = C_\varepsilon \cdot \Delta \varepsilon. 
\] (1)

In this equation, \(\Delta \nu\) is the value of the frequency drift of the Rayleigh spectrum, \(\Delta \varepsilon\) is the change of strain in the optical fiber relative to the initial value, and \(C_\varepsilon\) is the strain proportional coefficient of the optical fiber.

3. Calculation of bending moment and horizontal displacement of pile under horizontal loading
Under horizontal loading, the pile produces horizontal deformation. The formula of bending moment and horizontal displacement of the pile under horizontal loading is calculated according to the strain measured by the optical fiber sensor based on the OFDR distributed optical fiber sensing technology. The strain at the axis of the pile is assumed to remain unchanged. One side of the optical fiber is pulled, and the other is compressed. In equation (2), $\varepsilon_1(z)$ and $\varepsilon_2(z)$ are the strain values of the two points on the symmetrically distributed optical fiber at the depth of $z$ m, $\varepsilon_1(z)$ is the test value of tension side, and $\varepsilon_2(z)$ is the test value of compression side. Then, the bending strain $\varepsilon_m(z)$ is

$$
\varepsilon_m(z) = \frac{(\varepsilon_1(z) - \varepsilon_2(z))}{2}.
$$

(2)

![Diagram of pile deformation under horizontal loading.](image)

Figure 2. Diagram of pile deformation under horizontal loading.

Figure 2 shows the pile deformation under horizontal loading. The horizontal displacement curve m–n of the pile changes to m′–n under the load. A micro-segment $O_1O_2$ on the neutral axis of the pile is selected, where the curvature radius is $\rho(z)$ and the length is $dz$. If the central angle corresponding to the micro-segment is $d\theta$, the bending strain of the micro-segment at $y(z)$ from the neutral axis is

$$
\varepsilon_m(z) = \frac{y(z)d\theta}{dz}.
$$

(3)

The curvature of the micro-segment is

$$
\frac{1}{\rho(z)} = \frac{d\theta}{dz}.
$$

(4)

Equation (4) is substituted into equation (3) to obtain the bending strain at different distances from the neutral axis:

$$
\varepsilon_m(z) = \frac{y(z)}{\rho(z)}.
$$

(5)

When the pile is bent, the relationship between the curvature and bending moment is

$$
\frac{1}{\rho(z)} = \frac{M(z)}{EI},
$$

(6)

where $EI$ is the bending rigidity of the pile in units of kN·m², and $M(z)$ is the bending moment of the pile at depth of $z$ m in units of kN·m.
Equation (5) is substituted into equation (6) to obtain

$$M(z) = E \cdot I \cdot \frac{ε_m(z)}{y(z)}.$$  \hspace{1cm} (7)

The curvature of a curve in the plane can be shown as

$$\frac{1}{ρ(z)} = \pm \frac{d^2ω}{dz^2} \left[ 1 + \left(\frac{dω}{dz}\right)^2 \right]^{-\frac{3}{2}}.$$  \hspace{1cm} (8)

In actual engineering, the horizontal displacement curve of a pile is very gentle. \((dω/dz)^2\) is very small and negligible compared with 1, which belongs to the case of small deformation. Thus, the above formula can be simplified as

$$\frac{1}{ρ(z)} = \pm \frac{d^2ω}{dz^2}.$$  \hspace{1cm} (9)

Combining equation (5) with equation (9) yields

$$\frac{d^2ω}{dz^2} = \frac{ε_m(z)}{y(z)}.$$  \hspace{1cm} (10)

The bending strain is then integrated to obtain

$$ν(z) = \sum\sum \frac{ε_m(z)}{R} \Delta z \Delta z.$$  \hspace{1cm} (11)

The strain data is processed according to equations (2)–(11), and the bending moment and horizontal displacement can be obtained to examine the working behavior of the pile.

4. Model test

To measure the horizontal deformation of the PCC pile, a horizontal static load test system was designed with the layout shown in Figure 3(a). The external diameter and height of the pile were 0.11 m × 1.65 m, respectively, and the wall thickness was 3 cm. A jack was used to exert horizontal force on the pile; a load sensor was used to record the load; and a displacement gauge was used to measure the horizontal displacement of the pile top. An optical fiber was placed into the grooves in a U-shape, as shown in Figure 3(b). The load was applied at three levels of 62, 187, and 436 N, in which the successive load were applied after the displacement in the previous load became stable.
Figure 3. Schematic showing (a) the cross-section of the horizontal static load test and (b) the U-shaped layout diagram of the optical fiber. Figures 4(a) and 4(b) show photographs of the model test and the PCC pile. Figure 4(c) shows the OSI-C-D optical fiber strain demodulator used for OFDR monitoring, which has a measurement accuracy of ±8 με and a spatial resolution of 10.24 mm.

Figure 4. Images of the horizontal static load test materials. (a) Horizontal static load test; (b) PCC pile; (c) OSI-C-D optical fiber strain demodulator.
The physico-mechanical parameters of the concrete and soils tested are shown in Table 1.

Table 1. Physico-mechanical parameters of concrete and soils.

| Material | Soil distribution | Density $\rho$ (kg/m$^3$) | Young’s modulus $E$ (MPa) | Poisson’s ratio $\nu$ | Internal friction angle $\phi$ (°) | Cohesion $c$ (kPa) |
|----------|-------------------|-----------------------------|---------------------------|----------------------|-----------------------------------|------------------|
| Concrete | /                 | 2300                        | 30300                     | 0.2                  | /                                 | /                |
| Clay     | 0.00–0.85         | 1930                        | 15                        | 0.3                  | 23.1                              | 28.6             |
| Sand     | 0.85–2.20         | 1700                        | 15                        | 0.3                  | 29.7                              | 0                |

In addition, a Corning G652 Φ250 μm bare optical fiber was used. The layout process of optical fiber is described below.

The surface of the pile was cleaned, and the optical fiber was effectively coupled with the pile beneath the horizontal load. To protect the optical fiber, two grooves about 2 mm in depth were cut symmetrically on the surface of pile. The dust in the grooves was cleaned, and the optical fiber was placed. The optical fiber was attached tightly to the pile by using epoxy resin. A certain amount of prestress should be applied during the attachment because the optical fiber can deform in coordination with the pile when the load is applied.

The strain distribution on the tension and compression sides of pile was measured simultaneously. To eliminate the influence of temperature on the calculation result, the layout of the temperature compensation optical fiber is used. In OFDR technology data need to be collected only from a single end, which greatly reduces the difficulty of the optical fiber layout and improves the survival rate of the fiber.

5. Result

Figure 5 shows the distributed strain curves of the left and right sides of pile measured by OFDR under horizontal loading. The depth is taken as 0 at the soil surface height, positive above the surface, negative below the surface, 0.1 m at the pile top, and −1.55 m at the pile bottom. Figure 5 shows that the tension and compression strains of the pile under horizontal loading are symmetrically distributed along the pile and increase with an increase in load.
Figure 5. Distributed strain curves for two sides of the pile.

Figure 6 shows the horizontal displacement curve obtained from the distributed strain curve of the pile. The displacement of the pile top gradually increases with the load, and the maximum displacement of the pile top reaches 1.51 mm. The horizontal displacement curve is a smooth curve, and the curvature continuously increases. The horizontal displacement of the pile gradually decreases with increasing depth. When the depth reaches $-1.20$ m, the horizontal displacement decreases to 0 and remains unchanged until the pile bottom is reached.

Figure 6. Curves of (a) horizontal displacement and (b) bending moment.

The bending moment curve of the pile is shown in Figure 6(b). The bending moment was distributed mainly in the depth range of 0.1 to $-1.45$ m. In general, the bending moment increased first and then decreased. With an increase in the horizontal load, the bending moment increased nonlinearly.
position of the maximum bending moment was −0.53 m below the ground, and the maximum bending moment was 524 N·m. With an increase in the horizontal load, the maximum bending moment position remained essentially stable at a depth of 0.53 m below the ground.

To verify the reliability of the optical fiber test results, a displacement gauge was placed on the top of the pile. The measured horizontal displacement under all load levels was 0.17, 0.65, and 1.55 mm. Table 2 and Figure 7 show comparisons between the horizontal displacement in the pile top calculated by optical fiber strain and the measured value of displacement gauge. The absolute and relative errors of the optical fiber calculated value were relative to the measured results.

| Load/N | Calculated value (mm) | Absolute error (mm) | Relative error (%) |
|--------|-----------------------|---------------------|--------------------|
| 62     | 0.19                  | 0.02                | 11.8               |
| 187    | 0.77                  | 0.12                | 18.5               |
| 436    | 1.51                  | −0.04               | 2.6                |

*Table 2. Comparison of displacement test results*

Figure 7 shows that the results of optical fiber calculation were close to measured values with a maximum relative error of 18.5%. This indicates that OFDR technology is reliable for detecting distributed damage in pile foundations under horizontal loading.

6. Conclusions

Based on the above experiments, the following conclusions were obtained:

(1) A new test system for PCC piles is developed using the OFDR technology. The horizontal displacement and bending moment of the PCC pile is obtained under different loads.

(2) The calculated results of the optical fiber are compared with the measured results using a displacement gauge. The calculated values agree with the measured values, and the maximum error under the load is 18.5%. The reliability of OFDR technology in calculating horizontal displacement and bending moment is verified.
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