Application of optical-fiber sensing to concrete support and continuous wall strain monitoring

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Abstract. Optical-fiber sensing technologies are being theoretically and practically researched. These technologies, possessing linear and real-time properties, realize the sectional analysis of strain and temperature and improve point monitoring methods in deep foundation pit supporting systems. In this paper, a field experimental model of the deep foundation pit supporting system was designed in the subway station in Suzhou, China, which utilizes optical-fiber sensing technology. In this field experiment, conventional monitoring methods, namely steel-bar meters, inclinometer, and water-level observation hole were firstly employed for comparative study. Distributed optical-fiber sensors (DOFS) were employed at the same time based on Brillouin optical time-domain analysis (BOTDA). The experimental results show that the DOFS can more comprehensively monitor the pit support system than the conventional methods. The fiber sensors data reflect the positive and negative strain distribution of the walls in a linear section and detect a leakage by analyzing abnormal data. The fiber sensors data response a linear increase of the axial strain with excavation depth, and a bending phenomenon is discovered by the data curves because of the excavation depth difference of the testing support. With temperature compensation, the fiber monitoring data are more accurate to the excavation result than the steel-bar does. Thus, the sensors can get a combined action function of steel-bar which used for testing axial force and temperature, inclinometer which used for testing wall horizontal displacement, and water-level observation holes with accurately monitoring data.

1. Introduction

Monitoring supporting systems of deep foundation pits are crucial in engineering, such as metro stations, tunnel shafts, and multilayer basements. Additional monitoring methods mainly adopt point measurement techniques [1]. But detecting and locating abnormality through these techniques are difficult because of their low monitoring accuracy and limited measuring points. In particular, steel-bar meters which are used for monitoring axial forces of concrete supports, are unreliable because their alarms can be triggered easily [2].

To supports, the alarm value of axial force is calculated on the basis of earth pressure, which is dependent on the hydrogeological and engineering geological conditions and the forecasted loads. After the supporting system parameters (e.g., insert ratio of continuous wall, wall thickness, steel ratio, and support quantity, etc.) are given, the design value of axial force and the minimum section size of the supports can be computed [3]. In general, 70% axial force value of the design is set as the controlling alarm value.
However, research and practical experience have shown that many factors influence the monitoring value, including the calculation methods of earth pressure and axial force, amplification coefficient, installing accuracy of the steel-bar meter, shrinkage and creep of concrete, tensile crack, and atmospheric temperature [2]. The conventional measurement techniques cannot eliminate these influences.

The deformation and stress state of a continuous wall are conventionally measured by an inclinometer. However, it is not a real-time and whole-section monitoring, and can’t detect defects and leakage points before excavation. Studies have explored the principles of optical-fiber sensing [4–8] and have compared it with point measurement techniques [9]. Because of the distributed and real-time properties, optical-fiber sensing is widely applied in the monitoring of concrete structures such as bridges and high-rise buildings [10-11]. In addition, monitoring studies of tunnels [12-13], slopes [14–15], deep foundations [16], soil reinforcements [17-18], and other geotechnical structures have been reported. However, existing studies paid less attention to enhance the point monitoring assessment reliability of the supporting force.

In this paper, a series of field tests were set using distributed optical-fiber sensors (DOFSs) to monitor the concrete supporting system at Suzhou’s subway station. The objective of the experiments is to enhance the conventional monitoring method of monitoring the concrete supporting system and test a technique with reliable alarm value. In this field test, the conventional methods, namely the steel-bar meter (for measuring axial force) and the inclinometer (for measuring wall deformation), and the DOFSs (for measuring temperature, and strain) were designed in the test plan. The comparison of the two methods reveals that the DOFSs are more comprehensive and accurate in measuring the strain which can be converted into the stress by multiplying elasticity modulus.

2. Methods

2.1. Site description

The DOFS along with the conventional monitoring instruments of axial force, wall displacement, and water level were installed at a metro station construction in Line 4 of Suzhou rail transit in China in Figure 1. During excavation, monitoring data were collected to analyze the strain of the entire supporting system.

![Figure 1. Plan of the fiber sensors (red lines) and traditional sensors layout.](image)

Figures 1, 2 depict the plan and cross-sectional view of the sensors, respectively. The optical-fiber sensors for monitoring strain and temperature are set in the supporting structure along the entire length of the continuous walls with fiber number JX-01, JX-02, and the concrete supports with fiber number JX-03 where the excavation depth difference is 3-4 meters. The steel meters are fixed on supports ZL-04-01 and ZL-05-01; the water level is observed in holes SW-07 and SW-08; the inclinometers test is in holes CX-07, 08; and the wall displacement-meters test equipment is in holes ZQS-07, 08, 19 and 20.

Firstly, the optical-fiber sensors which are protected by jacket and metal matrix, and bound along with the steel by beams which are more easier than the steel-bar meters sealed with the steel, and the
inclinometer-pipes which are set across the steel cages, are set in the continuous wall and supports. Secondly, concrete is poured into the mounds around the steel cages to form the reinforced concrete walls and supports and the sensors are sealed into the structures.

![Figure 2. Cross-sectional view of the fiber sensors layout (red lines).](image)

The fiber sensors are leading out of the structures directly to the safe area which is isolated with construction area by wire netting so that the sensors and analyzers are protected well and the data collection is easier. They are detailed in Figure 2.

Installation of the optical-fiber sensors in the wall and supports is illustrated in Figure 3.

![Figure 3. Installation of the optical-fiber sensors (red lines) in the steel cages of the wall and support.](image)

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2.2. DOFS technology
Pulse-prepump-BOTDA (PPP-BOTDA) sensing is based on stimulated Brillouin backscattering [19–22]. The pulse laser (pump laser) and the probe continuous wave are injected into the optic fiber from its two ends. When the frequency difference between the two lasers equals the Brillouin frequency shift, Brillouin backscattering is stimulated and energy transfer occurs between the lasers [19]. Kishida et al. introduced a new method in which a prepump pulse is placed in front of a conventional laser pulse to enhance accuracy and spatial resolution in Figure 4[22].
According to the linear relationship between the Brillouin frequency shift and strain (or temperature), the strain (or temperature) can be measured by detecting the frequency change in the stimulated Brillouin scattering (SBS):

\[ V_B(T, \varepsilon) = C_\varepsilon \varepsilon + C_T T \]  

(1)

where \( C_\varepsilon \) and \( C_T \) are the strain and temperature coefficients, respectively, and \( V_B \) is the Brillouin frequency shift. The subscripts \( \varepsilon \) and \( T \) are the strain and temperature variations, respectively.

Thus, continuous temperature and strain distributions along the fibers can be obtained through time-domain analysis by measuring the propagation times for the light pulses travelling in the fiber.

With continuous walls bending deformation, the strain and the rotation angle relation are as following:

\[ \omega(z) = \varepsilon_{\text{outer}}(z) \]  

(2)

\[ \frac{d\omega(z)}{dz} = \theta(z) \]  

(3)

\[ \omega(z) \text{- Bending deformation,} \] \[ \theta(z) \text{- rotation angle,} \] \[ \varepsilon_{\text{outer}}(z) \text{- strain of outside of the continuous wall (connection with soil),} \] \[ \varepsilon_{\text{inner}}(z) \text{- strain of inside of the wall (pit side),} \] \[ D \text{- continuous walls width.} \]

In consideration of temperature compensation, the strain includes two parts:

\[ \varepsilon(z) = \varepsilon(T) + \varepsilon(D) \]  

(4)

\( \varepsilon(T) \) - Temperature strain, \( \varepsilon(D) \) - Deformation strain

According to Figure 5, the temperature strain is little and the temperature strain of the two sides of the wall is considered equal on the whole, so temperature compensation cannot be considered in the continuous walls data analysis. In the same time, when calculating the walls flexural strain, the formulas are as following:

\[ \varepsilon_{\text{outer}}(z) - \varepsilon_{\text{inner}}(z) = [\varepsilon_{\text{outer}}(T) + \varepsilon_{\text{outer}}(D)] - [\varepsilon_{\text{inner}}(T) + \varepsilon_{\text{inner}}(D)] = \varepsilon_{\text{outer}}(D) - \varepsilon_{\text{inner}}(D) \]  

(5)

\[ \frac{d\omega(z)}{dz} = \frac{\varepsilon_{\text{outer}}(z) - \varepsilon_{\text{inner}}(z)}{D} = \frac{\varepsilon_{\text{outer}}(z) - \varepsilon_{\text{inner}}(z)}{D} \]  

(6)

\( \varepsilon_{\text{outer}}(z) \text{- strain of outside of the continuous wall (connection with soil),} \) \( \varepsilon_{\text{inner}}(z) \text{- strain of inside of the wall (pit side)} \)

So the temperature influence is eliminated.

And we can get the horizontal displacement in depth of the continuous walls by formula as following:

\[ \omega(z) = \int_0^z \theta(z) dz + a = \int_0^z \frac{\varepsilon_{\text{outer}}(z) - \varepsilon_{\text{inner}}(z)}{D} dz dz + az + b \]  

(7)
3. Analysis of the data through the conventional methods

3.1. Steel-bar meter
The steel-bar meter establishes a relationship between vibration frequency and strain/stress. Changes in the internal strain can be determined according to changes in the vibration frequency caused by stress in the steel. The stress in the concrete support is calculated by assuming the following: (1) the elastic deformation of the reinforcement and concrete is synchronized and (2) the reinforced concrete supports satisfy the flat section assumption.

Data of the steel-bar meters are analyzed. The measuring axial force with max value 4.0MN in the concrete is higher than the designed alarm value of 1.44 MN (sectional stress design alarm value = 2.057 Mpa; maximum design value = 2.939 Mpa) and even before excavating the foundation pit, the values get to more than 1.5MN. This behavior occurs frequently, and no effective solutions have been reported.

3.2. Continuous wall displacement data
The top displacement of the continuous wall at ZQS-07, 08,19, and 20 showed that displacement increased with excavation depth (Figure 6). By the top displacement data, the leakage destruction cannot be found.

![Continuous 24-h data for the continuous wall at JX-02.](image1)

(April 27, max 25 °C at day and mix 10 °C at night)

![Horizontal displacement–time curves for the continuous wall.](image2)

Figure 5. Continuous 24-h data for the continuous wall at JX-02.  
Figure 6. Horizontal displacement–time curves for the continuous wall.

3.3. Water-level data
The water level in SW-08 is lower than that in SW-07, which is indicative of the low quality of pit supporting systems in SW-08 side. The continuous wall could not effectively prevent water from entering the foundation pit during excavation, but the position cannot be judged before excavation.

3.4. Inclinometer data
Conventional inclinometer responds to deformation of the continuous wall by measuring the change of the inclined pipes in the reinforcing cage of the wall. Such point measurement is easily affected by personal factors. Moreover, the deformation of the embedded pipes affects precision. These influences have not be cancelled well. The measured deformation curves are plotted. Still the leakage message can’t be found by the deformation curve analysis.

4. Dofs data analysis
4.1. Data pre-processing
The strain data are pre-processed by diagnosing and smoothing. The denoising mainly is a wavelet analysis, and the smoothing mainly is moving average method.
4.2. Error analysis.  
The vertical deformation of the reinforced concrete walls is not considered.

\[ \omega(z) = \int_0^z \theta(z) dz + \alpha = \int_0^z \frac{\epsilon_{\text{outer}}(z) - \epsilon_{\text{inner}}(z)}{D} dz + az + b \]  

The strain and rotation angle can be assumed as zero in the bottom of the continuous wall, so a and b is zero.

4.3. Data analysis  
Data were obtained at different stages of the excavation (Table 1). The fibers are specially designed for protection by metal matrix and protecting bush (Table 2). The fiber sensors are tied up by beam with steel cages and protected well when enclosed by concrete with the leading-out terminal directly setting in the save area which is isolated with construction area by wire netting.

Before excavation, the first testing data are the zero measurement. The difference value of the test data of each excavation and the zero value are the strain values or converted stress value with elasticity modulus 30GPa.

| Table 1. Excavation timeline. |
|-----------------------------|
|                            | 12-13 shaft (ZL-04-1) | 16 shaft (ZL-05-1 and CX-07) | 14 shaft (optical fiber) |
| Dig depth 3 meters          | On April 12            | On March 22                   | On April 10               |
| Dig depth 4 meters          | On May 27              | On May 20                     | On May 23                 |
| Dig depth 7 meters          | On June 3              | On June 8                     | On June 8                 |
| Design depth of the floor   |                          |                                |                            |

| Table 2. Specifications of fiber. |
|-----------------------------------|
| Single mode fiber                | Metal matrix            |
| cross section size (mm)          | Ø5.0                    |
| weight (kg/km)                   | 38                      |

According to Table 3, the pulse length is 10ns, the space resolution is 1m, and the space sampling interval is 0.05m.

Stress data errors, which converted from strain data with elasticity modulus value 30GPa of the concrete support, are larger, because the temperature compensation s is lack. But we can realize the temperature compensation in bending moment analysis by the strain value subtraction which the east data subtract the west data. The data curves clearly reveal the section strain of the entire support structure.
Table 3. Specifications of N8511 strain analyzer.

| Specifications                  | optional parameters |
|--------------------------------|---------------------|
| pulse length (ns)              | 1  | 2  | 3  | 4  | 5  |
| space resolution (m)           | 1  | 2  | 5  | 11 | 22 |
| Strain measurement accuracy    | ±0.004% (40με)      | ±0.004% (40με) |
| repeatability                  | <0.04%              | <0.02%          |
| Measurement range (km)         | 1, 2, 5, 10, 20, 40 |
| Space sampling interval (m)    | 1.00, 0.50, 0.20, 0.10, 0.05 |
| Positioning accuracy (m)       | ±(2.0×10⁻⁵×measurement range (m) + 0.2m + 2×sampling interval (m)) |
| Strain measurement range       | −1.5%~1.5%(15,000με) |

With no temperature compensation, the stress value of curves for the east side of the support is clearly larger than those for the west side. This difference is related to the excavation sequence. The stratified excavation was executed from the west to the east and therefore the excavation depth of the west side was always 3–4 m deeper than that of the east side, as shown in Table 1. Moreover, the continuous walls are disconnected near the sensors position (the east were drilled piles because of field conditions). The stiffness of the continuous wall is higher than that of the piles, but the soil mass in the piles side is frozen to prevent water leakage when excavation. The relatively larger active soil pressure on the west induces a tensile tendency in the east side of the support structure, and a bending trend is on the support (Figure 7) which is not reflected by the steel-bar meter data.

Figure 7. Bending moment curves for the concrete support.

Figure 6 presents the 24-h data for wall JX-02 with no further excavation. The change of stress is within the measured accuracy of the optical-fiber sensing technology and there is less variable value because of temperature.

Figure 7 shows that the strain in the concrete support declines when pit excavation is complete at the depth of 16.9m in 13th June, because a reinforced concrete plate is constructed at the bottom of the pit.

With no temperature compensation, on the west side, the stress was stable at 2.5 MPa, lower than the maximum design value of 2.939 MPa and higher than the design alarm value of 2.057 MPa. Therefore, the data on the west side confirm an ideal security-monitoring function. But we cannot make sure of a good substitution for the steel-bar meters with value curves about 3.5MPa for the above reason. Yet generally, we read the data in the morning with smooth temperature difference.

\[ M = \frac{EI(e_e - e_w)}{d}, \quad EI = 1280, d = 0.7m \]

In Kunming metro station pit, another new fiber sensing test with temperature compensation had been designed and finished from 24/09/2018 to 29/11/2018, as shown in Figure 8. From the data curves, a more accurate result can be found with max axial force 3.6Mpa which lower than the maximum design value of 4.0 Mpa, and the steel-bar meters with value curves more than 4.5MPa, but the pit has no problem. So the fiber sensing is more accurate than the steel-bar meters.
No temperature compensation  
With temperature compensation

**Figure 8.** Support axial force curves.

Bending moment data curves are shown in Figure 7. Strain data curves along the direction of the wall depth are shown in Figure 9, 10. The data comparison of the finite element, the inclinometer and the measured strain are shown in Figure 11. The value is the highest near the ground, and the strain increases with excavation depth. Because of the identical geological conditions and construction methods on either side of the foundation pit, there is an abnormality at 7.5m depth at JX-01 in Figure 9, 10. In this area, a leakage was found at 10m depth and 6m distance from the optical-fiber sensors by excavation discovering. The leakage accident was only reflected in the water-level monitoring data and not reflected by other conventional methods. So the accident position could not be located by conventional methods. The abnormal point can be discovered in the stress–depth curves at JX-01, and no abnormal point can be observed in the stress–depth curves at JX-02 (on the other side of the pit). The water leakage causes a slight frequency drift in the fiber sensors, and the stress–depth curves react to this change.

At each excavation stage, as mapped in Figure 10, the positive strain distribution of the active earth pressure area and the negative strain distribution of the passive earth pressure area can be obtained easily.

**Figure 9.** Strain-depth curves of walls (pit and soil side).

**Figure 10.** Flexural strain-depth curves.

**Figure 11.** Data comparison of inclinometer and measured and finite element displacement.
5. Finite element
One finite element model was built to simulate the test with model of horizontal length 100m, pit center as axis of symmetry, depth 52.3m, pit width 21.4, and width 16m. The pit bottom soil is silt.

Soils condition from surface to deep, are fill 2.8m, muddy clay 10.2m, silty clay 2.4m, silt 9.1m, silty clay 5.5m, silt with silty clay 10.1m, and silty clay 12.2m respectively.

Continuous wall is modeled with plate element, wall depth 33.3m, width 800 mm, flexural rigidity \( EI = 1280 \text{MN.m}^2/\text{m} \).

The first is reinforced concrete support, with size 700 mm *1000 mm and axial stiffness 350MN/m, muddled as support. And steel supports are from the second to the fourth, with size 609 mm *16mm, and axial stiffness 166.9MN/m, muddled with anchor rod. The supports interval is 6m.

The finite element analysis of bending moment of concrete support and displacement of walls has the same trend with the test curves in Figure 7 & 11.

6. Result analysis
The test data analysis shows that the optical-fiber sensors monitoring system does well in the continuous walls and concrete supports. Optical-fiber sensing is more advantageous compared with conventional measurement technologies such as the steel-bar meter and inclinometer:

1) Because of its linear properties and compact size, optical-fiber sensing is ideal for the wall and support system. The compact size of the device substantially reduces the influence of embedded pipes of inclinometers on the measuring accuracy. Furthermore, the sensors directly respond to the deformation of the walls and supports.

2) Optical-fiber sensing replaces the function of several conventional meters such as water-level observations which only giving point data of water level, inclinometers which only giving point data of the wall displacement, and steel-bar meters which only giving point data of the support axial force. The fiber sensors reflect the construction quality and locate the leakage positions more accurately by analysis of the abnormal data curves.

3) In each excavation stage, optical-fiber sensors can comprehensively monitor the distribution of the positive strain within the active earth pressure area and the negative strain within the passive earth pressure area. Soil pressure is extremely sensitive to water press change and this relationship is exploited to locate a water leakage point more accurately and timely, but the water level point data in the observation hole can only indicate the leakage question and cannot locate the position.

4) The axial forces in the concrete support increase linearly with excavation depth and can response bending curves to excavation depth difference on two directions which cannot be given in the data analysis of the steel-bar meters. And the fibers sensing data with max force 3.6Mpa are more accurate than the steel-bar meters with max force more than 4.5Mpa when no pit question is found.

7. Conclusions
It is easier to bind the fiber sensors in the support steel than sealing the steel-bar meters, and the fiber sensors can give linear data to locate leakage positon and show the bending phenomena of the support because of excavation depth difference in both side.

The fiber sensing data with temperature compensation are more accurate in monitoring the pit excavation with max observing data of 2.9Mpa which are lower than the max design value of 3.5Mpa and in line with excavation result.

Fiber sensing monitoring is a good substitution of steel-bar meter, inclinometer and water level observation.

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