Field Test Study on Deformation Monitoring of Antifloating Anchor Using Optic Fiber Sensor

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The antifloating anchors have been widely used in the antifloating problem of underground engineering recently. Due to the complexity of the anchor force in the geotechnical material and the limitations of traditional monitoring methods, it is impossible to grasp the deformation characteristics of the anchor comprehensively. The pullout test of the antifloating anchor on-site is carried out in this paper based on the housing construction project. The Optical Frequency Domain Reflectometry (OFDR) technology is used, the strain distributions are obtained, and the distribution law of axial force is analyzed. The test results show that the strain of the antifloating anchor gradually decreases when anchoring depth increases and eventually tends to zero. The anchoring section is divided into main stressed section and unstressed section. The results show that the OFDR technology can be used to effectively monitor the antifloating anchor in the pullout test; it will help to grasp the deformation of antifloating anchor.

1. Introduction

The antifloating problem is one of the difficult problems of underground engineering. At present, the main antifloating methods used are antifloating anchor method, blind trench drainage method, counterweight method, antifloating pile method, sand washing method, etc. The antifloating anchor method has been widely used in the project because of its easy construction, short construction period, low cost, and good antifloating effect. For the deformation and force of the antifloating anchor, the traditional strain sensors such as vibrating string type and resistance type are mostly used to monitor the deformation of anchor. However, these traditional sensing methods have the shortcomings of point measurement and low survival rate; it is difficult to accurately grasp the force and deformation law of anchor rod during the pullout test.

The distributed optical fiber sensing technology is a new type of sensing technology for sensing and transmitting external information [1, 2]. The optical fiber sensor has the advantages of corrosion resistance, high temperature resistance, light weight, and high sensitivity; it has been used in the field of geotechnical engineering [3–10]. For the floating anchor deformation monitoring, Zhang et al. [11] conducted the field pullout test on floating anchors and used Fiber Bragg Grating sensors to monitor the distribution of axial force along the depth. Kou et al. [12] used Fiber Bragg Grating sensors to monitor the stress-strain distribution of GFRP floating anchors. Bai et al. [13] used Fiber Bragg Grating sensors to monitor the strain variation of anchor rods during the field pullout test of GFPR antifloating anchor rods. Weiwei et al. [14] conducted the field pullout test study on GFRP floating anchor rods using conventional strain gauges and Fiber Bragg Grating sensors, respectively. The axial force, shear stress, and displacement variation laws of the conventional steel anchors and GFRP antifloating anchors under load condition were analyzed. Kuang et al. [15] studied the force characteristics of GFRP floating anchor rods in weathered rock foundation with Fiber Bragg Grating sensors. Sui et al. [16] used the Brillouin optical time domain...
reflectometry (BOTDR) for the pullout test of slope anchors; it shows that the optic fiber technology can be used for long-term monitoring of slope anchors.

Optical Frequency Domain Reflectometry (OFDR) distributed optic fiber sensing technology is the measurement technology based on the principle of Rayleigh scattering technology. The sensing measurement accuracy reaches ±0.1°C and ±1με with the measurement length within 100 m; it has the advantages of high spatial resolution, high accuracy, and high measurement sensitivity; it can monitor temperature and strain in real time. Gao et al. [17, 18] applied OFDR technology to measure the strain of PCC pile. Jiang et al. [19] used the OFDR technology to measure the strain of the pipeline. Kwon et al. [20] used OFDR technology to monitor the stress of anchors of soil slope.

In summary, the study on the deformation of antifloating anchors is little. The deformation characteristics of antifloating anchor rods cannot be fully investigated. In order to accurately grasp the deformation characteristics of antifloating anchors, the field test of antifloating anchor rod deformation based on OFDR optical fiber sensing technology was carried out in this paper. The deformation characteristics of antifloating anchors were obtained. It will provide the reference basis for the design and construction of antifloating anchors in the future.

2. Engineering Background

The test is based on the foundation pit antifloating project of the housing construction project in Nanjing, Jiangsu Province, China. The project area is 7684 square meters, and the design service life is 50 years. The strata revealed in the test site are miscellaneous fill layer, clay layer, and weathered conglomerate layer. The type of groundwater is mainly bedrock fracture water, which is stored in the weathered rock. In the engineering investigation, the depth of water level was found from 0.3 to 1.8 m. According to the regional hydro-geological data of the area, the water level varies seasonally. The annual variation of groundwater level is about 1.0 m.

The length of the antifloating anchor used in this test is 15 m, the diameter of the hole is 200 mm, and the strength of the concrete is C35. The internal reinforcing steel of the anchor is HRB400, which is formed by spot welding with reinforcement, and there are three reinforcing steel. Figure 1 shows the antifloating anchor and optical fiber sensors.

3. Optical Fiber Sensor Installation

3.1. Selection of Optical Fiber Sensor. This test took the single-cycle tension test with the single anchor pullout time of 1 hour. Because of the short time and the small effect of temperature change on the monitoring results, the temperature compensation of optical fiber sensor is not considered. Zhang et al. [11] proved that when the time of the antifloating anchor pullout test is short, the influence of temperature changes on the test results can be ignored, and the temperature compensation is not required. Combined with the site construction conditions and the survival rate of optical fiber sensor, the optical fiber sensor was finally selected as the high transmission tightly wrapped sheath strain sensing optical fiber cable. The optical fiber sensor is laid in the steel reinforcement body of the antifloating anchor. This type of optical fiber sensor is convenient for groove implantation due to its higher strength and smaller diameter.

3.2. Installation of Optical Fiber Sensor. Figure 2 shows the optical fiber sensor field installation. Firstly, the slot is cut in the reinforcement as shown in Figure 2(a), and the depth of the slot is controlled as small as possible. Then the optical fiber sensor is placed in the slot, the certain external force is applied to make the optical fiber sensor in the taut state, and the optical fiber sensor can be closely bonded to the anchor rod. At the same time, the 502 glue is used to fix the sensor as shown in Figure 2(b). The epoxy resin is used to encapsulate as shown in Figure 2(c). After the optical fiber sensor is placed, the optical fiber sensor at the bottom of the anchor rod is protected with metal hoops, 502 glue, and adhesive tape. This protects the optical fiber sensor from the reinforcement during the process of anchor rod transportation and lowering. The specific protection is shown in Figure 2(d). The optical fiber sensor at the top of the anchor rod was protected with the sleeve during the anchor rod lowering and later testing.

4. Field Test Process

According to the CECS 22:2005 Technical Specification for Geotechnical Anchor Rods (Ropes) of China [21] and the GB 50086-2015 Technical Specification for Geotechnical Anchor Rods and Shotcrete Support Engineering of China [22], the field pullout test of the antifloating anchor rod was carried out in the single-cycle tension test according the field test conditions. The design value of axial bearing capacity is 250kN. According to the specification test, the maximum test load is 1.2 times of the design value of axial bearing capacity of the anchor, and the number of load levels should be greater than 4 levels. Combined with the actual situation on site, the field pullout test of antifloating anchor is divided into 6 levels of loading, 25kN, 100kN, 150kN, 200kN, 250kN, and 300kN, respectively.

The antifloating anchor field pullout test device consists of antifloating anchor, mat, rigid mat, piercing steel plate, jack, anchor device, manual pressurization device, and other
components. Firstly, two layers of matting blocks are placed on the ground around the antifloating anchor as the bottom, and then the rigid matting plate is placed on the matting blocks. Next, the piercing steel plate is placed, and the piercing jack is installed. After that, the piercing steel plate is placed again, and the rebar is welded to the upper part of the piercing steel plate as the anchor device by electric welding. After the test device was installed, the manual pressurization device was connected to the jack. Figure 3 shows the pullout test of the antifloating anchor, Figure 3(a) shows the schematic diagram, and Figure 3(b) shows the field photo. The monitoring equipment used is the OFDR distributed optical fiber sensing instrument developed by the Hong Kong Dong Long Technology Company; it supports four channels of measurement, with the single channel measuring range of 100 m, the spatial resolution of 1 mm, the temperature resolution of 0.1°C, and the strain accuracy of 1.0με. The spatial resolution of this field test was set at 5 mm. The optical fiber sensors is high transmission tightly sheathed strain relief optical fiber cable. The fiber type is SMG.625b, number of fiber cores is 1, inner diameter is Φ0.9 mm, outer diameter is Φ2.0 mm, and optical fiber cable weight is 1 kg/km.

5. Analysis of Results

5.1. Monitoring Results. Figure 4 shows the original strain of the antifloating anchors. The strain data obtained from the monitoring is divided into loading data and unloading data. The data of anchor rod selected for this test is selected from 2 m to 14 m, because the protection of the optical fiber sensor and the anchor is made by the two 12-m and 3-m steel bars connected with bolts.

From the monitoring results, it can be seen that the overall force of the anchor rod remains stable when the load is applied to 300kN, and no damage of anchor is observed in the field. The antifloating anchor can withstand 300kN, which is 1.2 times of the design value of axial tension, and the antifloating anchor meets the engineering design requirements.

5.2. Data Processing Methods. Due to the high testing accuracy of OFDR sensing instrument and the selected sensing spatial resolution of 5 mm in this test, the data measured by optical fiber sensors were mixed with certain noise information. From the strain curves of the antifloating anchor under the loading and unloading, it can be seen that the
raw data has certain fluctuation, which is difficult to judge and analyze the deformation of the antifloating anchor visually. It is necessary to further process the raw strain data obtained from the test in order to analyze the deformation characteristics of the antifloating anchor. In this paper, the wavelet transform is used to reduce the noise of original data of the antifloating anchor. The wavelet functions commonly used are Daubechies (DB), Haar, Biorthogonal (Bior), and so on. The signal of optical fiber monitoring during the test is often contaminated by white noise, and the original data includes effective signal and invalid noise. There is a big difference in the nature of the signal and noise; the signal has the higher smoothness and lower singularity, while the noise has the higher singularity. The wavelet transform performs noise reduction according to this difference. The wavelet transform uses its own strong decorrelation to make the energy of the noise distributed throughout the wavelet domain. After the wavelet decomposition, the amplitude of the wavelet coefficients of the signal is greater than the amplitude of the noise coefficients. The wavelet coefficients with larger thresholds are dominated by the noise, and the coefficients with smaller amplitudes are generally dominated by the signal. The use of thresholding allows the signal coefficients to be retained while reducing most of the noise coefficients to zero. For the wavelet coefficients with high resolution at each scale, the wavelet coefficients of the observed signal data are processed by setting the threshold and threshold function, and the processed wavelet coefficients are subjected to inverse wavelet transform to obtain the reconstructed signal for the purpose of denoising [23–27].

The DB wavelet function was chosen for this noise reduction process. The expansion model is a periodic model, and a custom threshold type is chosen, with the threshold taken as 200% each time. A total of four noise reductions were performed. Since the strain data after noise reduction still has certain volatility, this paper uses the adjacent averaging method to smooth the noise reduction strain data further. No boundary conditions were set for this smoothing process, and the number of window points was set to 100.

Figure 5 shows the strain treatment for antifloating anchors under loading conditions. No. 1 and No. 2 antifloating anchors showed good and consistent regularity after noise reduction and smoothing. The strain of the antifloating anchor increases as the load increases step by step during the pullout test. The strain of the antifloating anchor rod tends to be consistent with the depth direction under the action of each load level. The load transfer depth was in the range of 9.5 m. In this range, with the increase of anchorage depth, the strain of antifloating anchor rod gradually decreases and finally tends to zero. The strain is zero at the end of the antifloating anchor.

Figure 6 shows the strain treatment for antifloating anchors under unloading conditions. The second stage load of the No. 1 antifloating anchor is 80 kN and the No. 2 antifloating anchor is 90 kN. There is some deviation due to the manual unloading method. According to the unloading strain curve of the antifloating anchor, the unloading strain change law of the two antifloating anchors is more consistent. As the load decreases step by step, the strain of the antifloating anchor decreases. The load transfer depth during unloading was still within the range of 9.5 m. In this range, the strain of the antifloating anchor rod gradually decreases with the increase of anchorage depth and finally tends to zero.

5.3 Monitoring Axial Force Analysis of Antifloating Anchors. The optical fiber sensor is laid in the steel body recess of the anchor rod; the optical fiber is deformed in coordination with the steel body of the antifloating anchor rod under the test tension. It can be considered that the tensile strain of the antifloating anchor is consistent with the axial tensile strain of the optical fiber. The tensile strain of the antifloating anchor bar is \( \varepsilon(Z) \), and then the tensile stress of the
Figure 4: Continued.
The anti-floating anchor bar $\sigma(Z)$ is

$$\sigma(Z) = \varepsilon(Z) \cdot E_c.$$  

(1)

In the equation, $E_c$ is the modulus of elasticity of the reinforcement body within the float-resistant anchor. The axial force of the buoyancy-resistant anchor $Q(Z)$ is

$$Q(Z) = \sigma(Z) \cdot A.$$  

(2)
In the equation, $A$ is the cross-sectional area of the buoyancy-resistant anchor. Equation (1) is substituted into equation (2) to obtain the relationship between the axial force of the antifloating anchor rod body and the strain data measured by the optical fiber sensor:

$$Q(Z) = \varepsilon(Z) \cdot E_c \cdot A.$$ 
(3)
The floating anchor reinforcement body used in this test was formed by three steel bars with 25 mm and reinforcement spot welded. The rest of the open hole is maintained with slurry pouring. The two are well cemented; the calculation can be simplified. The cross-section of the anti-floating anchor in tension is converted to a circular cross-section with the same material and diameter $R$ according to the principle of equal stiffness.

The principle of calculating equal stiffness is calculated as follows:

$$3 \times A \times E_1 + (\pi \times R_0^2 - 3 \times A)E_2 = \pi \times R^2.$$ (4)

In the equation, $A$, $E_1$, $R_0$, $E_2$, and $R$ are the cross-sectional area of 25 mm diameter reinforcement, the modulus of elasticity of 25 mm diameter reinforcement, the cross-sectional radius of the initial stress circle, the modulus of elasticity of the grouted body after the completion of maintenance, and the cross-sectional radius of the equivalent stress circle of the anti-floating anchor. The specific conversion schematic is shown in Figure 7.

The $A$ is 490.9 mm$^2$, $R_0$ is 27 mm, and the modulus of elasticity of reinforcing steel $E_1$ is taken as $2.0 \times 10^5$ MPa. The modulus of elasticity of the anchor solid is taken as $3.15 \times 10^4$ MPa [28]. The values of each parameter are substituted into equation (4), and $R$ is obtained:

$$R \approx 22.5 \text{mm}.$$ (5)

The elastic modulus of the reinforcement body with 25 mm diameter in equation (4) is about 6.4 times than the elastic modulus of the grouted body. The cross-sectional area of the grouted body present is about one-third of the cross-sectional area of the initial bearing circle. For the convenience of calculation, the elastic modulus of the equivalent bearing circle material of the anti-floating anchor is taken as the elastic modulus of the reinforcement body with 25 mm diameter $E_1$, i.e., $E_C = E_1$. By calculation, the equivalent force section of the anti-floating anchor is taken as a circular section with the diameter of 45 mm. The modulus of elasticity $E_C$ is $2.0 \times 10^5$ MPa, and the cross-sectional area $A$ is $1.6 \times 10^{-3}$ m$^2$. The axial force under the pullout test of the floating anchor can be obtained by substituting $E_C$ and $A$ into equation (3).

The strain data from optical fiber monitoring are calculated according to equations (3) and (4) to obtain the axial force distribution curves of the two anti-floating anchors. This paper focuses on the calculation of the strain data of anchor rods during the loading phase to obtain the axial force distribution curves.

Figure 8 shows the axial force distribution of the anti-floating anchor under loading conditions. It can be seen that the axial force of the two anti-floating anchors changes in the same. As the load increases step by step, the axial force of the anti-floating anchor increases. Under each level of load, the
Axial force of anchor varies in the same trend with depth direction. The axial force at the top of the antifloating anchor is the largest, and it decreases gradually with the increase of anchorage depth. In the actual project, the additional reinforcement of the antifloating anchor top should be applied. The axial force distribution curves are consistent with the available literature [11, 12].

From Figure 8, it can be seen that when the anchoring depth of the antifloating anchor reaches 9.5 m, and the axial force tends to be close to zero. According to this, the depth of axial force influence of the antifloating anchor is about 9.5 m. The section of the antifloating anchor under this test condition can be divided into two sections with 9.5 m as the dividing line. The anchorage depth above 9.5 m is the main force section, and the anchorage depth below 9.5 m is the nonforce section. This shows that increasing the anchorage depth of the antifloating anchor does not improve the floating performance of the antifloating anchor. On the contrary, it will increase the construction difficulty and waste construction materials, resulting in the increase of invalid cost. It is recommended to reduce the design length of antifloating anchor by 1 m for this project. Based on the field test results, it is necessary to measure the anchor deformation data through the anchor pullout test to determine the reasonable anchorage length and apply the antifloating anchor efficiently and reasonably.

6. Conclusion

(1) The strain and axial force distribution curves of the antifloating anchors were obtained by the field test, and the optical fiber sensing technology is used to measure the strain of the antifloating anchor. It shows that the strain of the antifloating anchor increases with the load step by step during the loading phase. In the unloading stage, the strain of the antifloating anchor decreases with the load. The strain of antifloating anchor rod body decreases gradually with the increase of anchorage depth and finally tends to zero at the end of the rod.

(2) The axial force distribution curves of the two antifloating anchors were compared. It is found that the axial force tends to zero when the anchor depth of the antifloating anchor reaches 9.5 m under all levels of load. As the anchor depth increases, there is no axial force at the end of the rod. The anchored section of the antifloating anchor is divided into two parts with 9.5 m as the dividing line. The section above the depth of axial force influence is the main stressed section, and the section below the depth of axial force influence is the nonstressed section.

(3) The optical fiber monitoring method for the deformation of antifloating anchors was designed for this test. The strain of the antifloating anchor was effectively monitored during the pullout test. It verified the feasibility of OFDR distributed optical fiber technology in the antifloating project, and it will provide the reference for similar projects.

(4) In this paper, only two antifloating anchors were studied. The sample of data obtained from the test is small. If more antifloating anchors are monitored, the conclusions of this paper can be further verified.

Data Availability

The data can be found in this paper.
Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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