

**T/CECS 622—2019**

**Code of China Association for Engineering Construction Standardization**

**Technical specification for pile distributed fiber optic testing**

**（征求意见稿）**

March 1, 2020

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**Chief Development Organization:**

China Ordnance Industry Survey and Geotechnical Institute Co., Ltd

Nanjing University

**Approval Organization:**

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**Notice**

**This standard is written in Chinese and English. The Chinese text shall be taken as the ruling one in the event of any inconsistency between the Chinese text and the English text.**

Announcement of China Association for Engineering Construction Standardization

No.487,2019

Announcement on Publishing “Technical Specification for Pile Distributed Fiber Optic Testing”

According to the requirements of Document Jian Biao Xie Zi [2017] NO. 014 issued by China Association for Engineering Construction Standardization - “Notice on Printing the Development and Revision Plan of the first batch of association standardization for engineering construction in 2017”. After the examination of the branch of investigation and surveying, CECS, the code of “Technical Specification for Pile Distributed Fiber Optic Testing” drafted by China Ordnance Industry Survey and Geotechnical Institute Co., Ltd., Nanjing University, etc, has been approved with a serial number of T/CECS 622 – 2019, and will be implemented on March 1, 2020.

**China Association for Engineering Construction Standardization**

**September 10, 2019**

**Foreword**

According to the requirements of Document Jian Biao Xie Zi [2017] NO. 014 issued by China Association for Engineering Construction Standardization - “Notice on Printing the Development and Revision Plan of the first batch of association standardization for engineering construction in 2017”. The drafting group completed this code by carrying out investigation and researches extensively, summing up practical experience carefully, and soliciting opinions broadly.

The code comprises 7 chapters and 5 appendices with the main contents as follows: general provisions, terms and symbols, general requirements, instrument, and optical sensing cable, installation of optical sensing cable, field test, data processing, and test report, etc.

Branch of investigation and surveying, China Association for Engineering Construction Standardization is in charge of the administration of this code. China Ordnance Industry Survey and Geotechnical Institute Co., Ltd (Address: No.79, Xibianmennei Street, Xicheng District, Beijing, 100053) is responsible for the explanation of specific technical contents. All relevant organizations are kindly requested to sum up and accumulate your experiences in actual practices during the process of implementing this code. The relevant opinions and advice, whenever necessary, can be posted or passed on to the organization responsible for the explanation.

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Contents

1 General Provisions 1

2 Terms and Symbols 2

2.1 Terms 2

2.2 Symbols 3

3 Basic Requirements 5

3.1 Testing Contents 5

3.2 Testing Preparation 5

3.3 Testing Conditions and Quantity 6

4 Instrument and Optical Sensing Cable 8

4.1 Instrument 8

4.2 Optical Sensing Cable 9

5 Installation of Optical Sensing Cable 10

6 Field Testing 11

7 Data Processing and Testing Report 12

Appendix A Checklist of Optical Sensing Cable 17

Appendix B Installation Technology of Optical Sensing Cable 18

Appendix C Record Table for Installation of Optical Sensing Cable  [28](#_Toc472941503)

Appendix D Record Table for Distributed fiber optic testing 29

Appendix E Record Table for Long Term Distributed Fiber Optical testing 30

Explanation of wording in this specification 38

Addition: Explanation of provisions 39

**1 General Provisions**

**1.0.1** This specification is formulated to uniform the distributed fiber optic testing and data analysis of piles, ensure the technical advancement, safety and usability, economy and rationality, as well as the construction quality.

**1.0.2** This specification is applicable to the distributed fiber optic testing of piles.

**1.0.3** Distributed fiber optic testing of piles shall comply with not only the requirements stipulated in this specification but also those in the current relevant standards of the nation.

**2 Terms and Symbols**

**2.1 Terms**

**2.1.1** optical fiber

An optical fiber is made of silica glass or plastic to transmit light.

**2.1.2** optical sensing cable

One or more optical fibers are encapsulated in specific ways and used as sensing and transmission medium to realize strain and temperature sensing.

**2.1.3**  distributed fiber optic testing

A technology to implement continuous testing of the multi-physical parameters in one dimension of the piles with the installed optical sensing cables.

**2.1.4** optical time domain reflectometry(OTDR)

Based on the backscattering of Rayleigh scattering and Fresnel reflection in optical fiber, optical time domain demodulation technology is utilized to test the fiber length, transmission attenuation, connector attenuation, and fault location.

**2.1.5** Brillouin optical time domain reflectometry(BOTDR)

Based on the principle of spontaneous Brillouin scattering, optical time domain demodulation technology is utilized to test the distributed temperature or strain of the piles by using optical sensing cables.

**2.1.6** Brillouin optical time domain analysis(BOTDA)

Based on the principle of stimulated Brillouin scattering, optical time domain demodulation technology is utilized to test the distributed temperature or strain of the piles by using optical sensing cables.

**2.1.7**  Brillouin optical frequency-domain analysis(BOFDA)

Based on the principle of stimulated Brillouin scattering, optical frequency-domain demodulation technology is utilized to test the distributed temperature or strain of the piles by using optical sensing cables.

**2.1.8** length of strain isolation

A performance index of the strain optical sensing cable refers to the length where the cable strain drops to 5%.

**2.1.9** strain uniformity

An index expressed by double mean square deviation characterizes the uniformity of initial strain distribution for a certain length of optical sensing cable.

**2.1.10** full width at half maximum

The width of the Brillouin spectrum at half of the peak amplitude.

**2.2 Symbols**

**2.2.1** Resistance and material properties

E - Modulus of elasticity of pile

I - Cross-sectional moment of inertia of the pile

**2.2.2**  Actions and action effects

M(z) - Bending moment of pile at depth z

Q(z) - Axial force of pile at depth z

qs(z) - Shaft resistance value of pile at depth z

qp - Toe resistance value of pile

S - Displacement of pile top

SS - Concrete compression of pile

Sb - Soil compression at pile tip

S(z) - Relative displacement between pile and soil at depth z

 - Deflection of pile at depth z

ε - Strain tested by optical fiber

**2.2.3** Geometric parameters

A - Cross-sectional area of pile

D - Spacing of the symmetrically laid optic sensing cables

L - Pile length

u - Pile circumference

z - Depth of the data points tested by optical fiber

**2.2.4**  Calculation coefficients

CS - Ratio between the frequency shift of Brillouin backscattered light and the strain

CT - Ratio between the frequency shift of Brillouin backscattered light and the fiber temperature

**3 Basic Requirements**

**3.1 Testing Contents**

**3.1.1** The distributed fiber optic testing of pile can be used for vertical compressive static load testing, vertical uplift static load testing, and horizontal static load testing of a single pile. The testing content shall meet the requirements in Table 3.1.1.

**Table 3.1.1** Contents of pile distributed fiber optic testing

|  |  |
| --- | --- |
| Testing methods | Testing contents |
| Vertical compressive static load testing | deformation of pile, axial force of pile, shaft resistance of pile and toe resistance of pile |
| Vertical uplift static load testing | deformation of pile, axial force of pile and shaft resistance of pile |
| Horizontal static load testing | Bending moment of pile and deflection of pile |

**3.1.2** The distributed fiber optic testing technology may be used for long-term monitoring of the internal forces and deformation process of piles.

**3.2 Testing Preparation**

**3.2.1** The following work should be carried out before testing:

**1** Clarify the requirements of the client;

**2** Collect the geotechnical investigation report, design drawings of piles, construction plan, and static load testing plan;

**3** Collect the construction records of piles to understand the construction technology and the abnormalities during construction;

**4** Conduct site investigation;

**5** Evaluate the feasibility of installing fiber test on project sites;

**6** Draft the test plan, including project overview, geotechnical conditions, overview of pile design, distributed optical fiber testing methods and standards, selection and installation plan of optical cables, testing equipment, testing period, content of testing report, measures of quality, safety and environmental protection, required machinery or manual cooperation.

**3.2.2** The installation of the optical sensing cables shall be in accordance with the following requirements:

**1** The optical sensing cables shall be installed on the reinforcement cage for cast-in-place piles. After protection, the optical sensing cables will be lowered into the borehole together with the reinforcement cage to form a pile by concrete pouring.

**2** The optical sensing cables may be installed in the manufacture of the precast piles. The spot welding and bonding methods may be used to install the optical sensing cables for the cured precast piles and steel piles. The piles are driven after the adhesive cured.

**3.2.3** The performance of the optical interrogator shall be checked and debugged before the distributed fiber optic testing of piles.

**3.3 Testing Conditions and Quantity**

**3.3.1** When there are requirements in the design or one of the following requirements are met, the distributed fiber optic testing of piles shall be carried out:

**1** The piles locate in the sites with complex geotechnical conditions, special construction environment, or have low reliability of construction quality;

**2** New pile types or new piling technology;

**3** Piles with long-term monitoring requirements.

**3.3.2** For the same static load testing, the number of pile distributed fiber optic testing shall not be less than 2.

**3.3.3** The number of optical sensing cables shall be in accordance with the following requirements:

**1** The cast-in-place piles with a diameter less than or equal to 600mm shall be symmetrically installed with no less than 2 optical sensing cables. If the diameter of the cast-in-place piles is more than 600mm, no less than 4 optical sensing cables shall be installed symmetrically. The optical sensing cables should be a U-bend loop.

**2** The precast piles with a diameter less than or equal to 800mm shall be symmetrically installed with no less than 2 optical sensing cables. If the diameter of the precast piles is more than 800mm, no less than 4 optical sensing cables shall be installed symmetrically. The optical sensing cables should be a U-bend loop.

**3** The steel pile shall be symmetrically installed with no less than 2 optical sensing cables. The optical sensing cables should be a U-bend loop.

**4 Instrument and Optical Sensing Cable**

**4.1 Instrument**

**4.1.1** An optical interrogator with features of distributed optical fiber strain and temperature testing shall be selected. The optical interrogator shall have functions of data acquisition, display, and storage. The main performance shall be in accordance with the following requirements:

**1** The operating ambient temperature shall be -10℃ ~ 50℃. The ambient humidity shall be 0 ~ 95%. The sampling time shall be less than or equal to 15min. The strain testing range shall be within ± 15000με. The positioning error shall be less than or equal to 50cm. The sampling resolution shall be less than or equal to 10cm.

**2** When both ends of the optical sensing cable are accessed for testing, the strain error shall be less than or equal to 10με, the repeatability shall be less than or equal to 20με, and the spatial resolution shall be less than or equal to 50cm. When one end of the optical sensing cable is accessed for testing, the strain error shall be less than or equal to 35με, the repeatability shall be less than or equal to 50με, and the spatial resolution shall be less than or equal to 100cm.

**4.1.2** The pile should be tested using the same optical interrogator. The testing parameters shall be consistent when different optical interrogators are used.

**4.1.3** The optical interrogators shall be selected in accordance with the following requirements:

**1** When the sensing cable forms a loop, optical interrogators based on Brillouin optical time domain analysis (BOTDA) and Brillouin optical frequency-domain analysis (BOFDA) shall be used.

**2** When the sensing cable does not form a loop or the fiber loss is greater than 10dB, optical interrogators based on Brillouin optical time domain reflectometry(BOTDR) shall be used.

**4.2 Optical Sensing Cable**

**4.2.1** Optical sensing cable shall have distributed strain and temperature sensing performance. The mechanical strength shall meet the requirements of site construction conditions and testing environment.

**4.2.2** The fiber core with large backscattering attenuation shall be chosen for the optical sensing cable. The parameters of the optical sensing cable should be selected according to those set out in Table 4.2.2.

**Table 4.2.2** Parameters of optical sensing cables

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Installation technology | Types of optical sensing cable | Axial tensile strength(N) | Lateral compressive strength(N/m) | Length of strain isolation(cm) | Strain uniformity(μɛ) | Full width at half maximum(MHz) | Operating temperature(℃) | Applicable pile type |
| bundling | metal-based cord strain sensing cable, high strength strain sensing cable | ≥800 | ≥1300 | ≤80 | ≤2500 | ≤120 | -20～80 | cast-in-place pile, precast pile (implanted in advance) |
| bonding | strain sensing cable with diameter of 0.25mm ~ 2mm | ≥15 | ≥500 | ≤20 | ≤500 | ≤85 | -20～80 | steel pile, precast pile |
| bonding in shallow grooves | precast pile |
| spot welding | metal-based belt sensing cable | ≥500 | ≥5000(consolidation) | ≤20 | ≤500 | ≤85 | -20～80 | steel pile |

Note: A special optical cable should be used when the temperature exceeds the specified range in the table.

**4.2.3** The cable for temperature compensation shall meet the following requirements:

**1** The fiber core of the cable for temperature compensation may be single-mode or multi-mode fiber.

**2** A loose tube structure shall be adopted for the cable for temperature compensation, of which the fiber core shall not be affected by the strain of pile.

**5 Installation of Optical Sensing Cable**

**5.0.1** The optical sensing cables should be inspected according to the requirements of appendix A before installation.

**5.0.2** The leads of optical cables shall be drawn from the pile side. The outlet position should be 0.5m below the elevation of the pile top. The cable leads on the pile top shall be fixed and protected temporarily during the pouring of casting the cast-in-place pile and before driving the precast pile and steel pile.

**5.0.3** During the installation of the sensing cables, the quality control of the installation process shall be strengthened to avoid the damage and breakage of the optical sensing cable. The installation technology for different pile types should comply with Appendix B.

**5.0.4** Optical time domain reflectometry (OTDR), red light pen, and other technologies shall be used to check the optical integrity of the sensing cable after the installation of the sensing cable. To find out reasons, take measures and retest shall be done if the abnormal data is detected or the signal-to-noise ratio of the optical signal is low.

**5.0.5** For the long-term monitoring of the internal force and deformation of the piles, the strain sensing cables and the temperature sensing cables used for the temperature compensation shall be both installed in the piles.

**5.0.6** The installation of the optical sensing cables should be recorded according to those set out in Appendix C.

**6 Field Testing**

**6.0.1** The testing site shall have a stable power supply. The testing shall be carried out in a non-interference environment.

**6.0.2** The pile distributed fiber optic testing shall be carried out after the pile integrity testing.

**6.0.3** Before the formal testing, the reasonable test parameters of the optical interrogator shall be determined based on the Brillouin spectrum, fiber loss, and strain obtained in the testing.

**6.0.4** Before starting a pile static load test, the valid strain data shall be collected 3 times. The average value shall be taken as the initial reading.

**6.0.5** The data collection shall be carried out before applying the next load. Data inspection should be carried out after the data collection of each load. If the abnormal data is detected or the signal-to-noise ratio of the test signal is low, the optical path and the testing parameters of the interrogator shall be checked to find out reasons and retest.

**6.0.6** For the field testing, the testing parameters, testing number, testing time, data anomaly, and field problems or failures of the optical interrogator should be recorded according to Appendix D.

**6.0.7** For long-term monitoring, protective measures shall be taken for the leads of optical cable. The testing parameters of the interrogator shall be kept consistent. The field testing conditions should be recorded according to Appendix E.

**6.0.8** For the long-term monitoring of the internal force and deformation of the piles, the temperature data of the pile shall be collected as the basis for the temperature compensation of the corresponding strain data.

**7 Data Processing and Testing Report**

**7.0.1** Data preprocessing shall be carried out according to the following steps:

**1** Data verification: Check the original record data according to the field record data;

**2** Data standardization: Unify the discrete spacing of the testing data by using methods of data interpolation, extraction, etc.;

**3** Data alignment: The spatial position of each testing data shall be aligned if the length of the optical connection line changes during the testing;

**4** Data locating: Determine the locations of pile top and pile toe on the strain distribution curve, and match the curve of testing data with the location of the testing points on the pile;

**5** Data segmentation and interception: Intercept the strain distribution curve corresponding to the target segments according to data locating;

**6** Data smoothing: Smooth the data by using multi-point averaging and other mathematical methods.

**7.0.2** The axial force of the pile shall be calculated according to the following formulae:

  (7.0.2-1)

  (7.0.2-2)

 (7.0.2-3)

where  - Initial Brillouin frequency shift of the i-th optical fiber at depth z (MHz);

 - Brillouin frequency shift of the i-th optical fiber at depth z under loading (MHz);

 - Pile strain measured by the i-th optical fiber at depth z under loading;

*Q*(z) - Axial force of pile at depth z (kN);

*E*(z) - Elastic modulus of pile at depth z (kPa);

*Cs*- Strain coefficient of the Brillouin frequency shift (MHz / με), which may be provided by the supplier of the optical cables or determined by the calibration test of the optical cables;

*CT* - Temperature coefficient of the Brillouin frequency shift (MHz / ℃), which may be provided by the supplier of the optical cables or determined by the calibration test of the optical cables;

- Temperature changes of the i-th fiber at depth z;

 - Average strain of N optical fibers at depth z under loading;

*A*(z) - Cross-sectional area of pile at depth z (m2).

**7.0.3** The shaft resistance and toe resistance of the pile shall be calculated according to the following formulae:

 (7.0.3-1)

 (7.0.3-2)

where *Q*(z) - Axial force of pile at depth z (kN);

*qs*(z) - Shaft resistance of pile at depth z (kPa);

*qp*-Toe resistance of pile (kPa);

 - Perimeter of pile (m);

 - Average strain of pile toe;

Ep - Elastic modulus of pile toe (kPa).

**7.0.4** The axial deformation of the pile shall be calculated in accordance with the following requirements:

**1** The displacement *S* of the pile top is composed of the compression *Ss* of the pile concrete and the compression *Sb* of the soil near pile toe under the action of vertical loads (Figure7.0.4);

**2** The compression of concrete shall be calculated according to Eq. (7.0.4-1). The compression of the soil near the pile toe shall be calculated according to Eq. (7.0.4-2). The relative displacement *S(z)* between pile and soil at depth z shall be calculated according to Eq. (7.0.4-3).



Figure 7.0.4 The compression distribution along the pile

  (7.0.4-1)

  (7.0.4-2)

  (7.0.4-3)

where *S* - Displacement of pile top (m);

*Ss* - Compression of pile concrete (m);

*Sb* - Compression of the soil near pile toe (m);

*S*(z) - Relative displacement between pile and soil at depth z (m);

*z* - Depth of the testing point along the optical fiber (m);

**7.0.5** The bending moment *M(z)* and deflection ω(z) of the pile at different depths *z* under the horizontal load shall be calculated according to the following formulae.



Figure7.0.5 The deformation of pile under horizontal load

 (7.0.5-1)

 (7.0.5-2)

where *M*(z) - Bending moment of pile at depth *z* (kN·m);

 - Pile strain tested by the optical fiber along direction *a* at depth *z* under the action of external force *H.* Tensile strain is positive;

 - Pile strain tested by the optical fiber along direction *b* (symmetry direction of *a*) at depth *z* under the action of external force *H.* The compressive strain is negative;

 - Deflection of the pile at depth z (m);

*D* - Distance between the symmetrically installed optical cables (m);

z - Depth of the testing point along the optical fiber (m);

*I*(z) - Inertia moment of the pile section at depth *z* (m4).

**7.0.6** The testing report shall contain the followings:

**1** Project profile, testing purpose, testing basis, testing quantity, testing date;

**2** Geotechnical conditions;

**3** Types of testing piles, pile number, pile parameters, and related construction conditions;

**4** Testing methods, testing equipment, testing process;

**5** Testing data, curves, and tables;

**6** Conclusions and suggestions.

 **Appendix A Checklist of Optical Sensing Cable**

**Table A Checklist of optical sensing cable**

|  |  |  |
| --- | --- | --- |
| Inspection items | Inspection methods | Inspection requirements |
| Product name and manufacturer | Manual inspection | The words of sensing, measuring or testing shall be clearly included in the product name to prevent misusing communication optical cables. |
| Appearance inspection | Manual inspection | The package of the optical cables shall be intact and no significantly squeezed. The jacket of the optical cables shall be no peeling damages. The optical cables shall have a regular shape. The color of the optical cables should be consistent with outgoing quality control. |
| Types of fiber core | Manual inspection | The optical fiber of low water peak and multimode should not be suitable for strain testing. G.652B fibers should be used. |
| Length inspection | Optical time domain reflectometry (OTDR) | The length of the optical cables may be inspected using the equipment having a function of optical time domain reflectometry (OTDR). The jump of the reflection peak may be used for judging the integrity of the optical cable by slightly bending the cable end. The length shall be verified with outgoing quality control and the meter markings on the optical cables. |
| Fiber loss inspection | Optical time domain reflectometry (OTDR) | The average loss of the optical cable and the loss at a certain location may be inspected using the equipment having a function of optical time domain reflectometry (OTDR). |
| Strength inspection | Methods based on tensile testing machines | Sampling inspection and rechecking may be used for the tensile strength of the optical cable. |
| Initial strain distribution | Testing methods of Brillouin light scattering | The initial strain of the optical fiber is checked by using Brillouin scattering light testing equipment. If the initial strain is larger than 10000 με or the strain differences are too large to meet the monitoring requirements, the corresponding segments of the optical cable should be replaced. |

**Appendix B Installation** **Technology of Optical Sensing Cable**

**B.1 Installation technology by bundling**

**B.1.1** Installation technology by bundling is applicable to the installation of optical cables into cast-in-place piles, precast piles, and mixing piles. The optical sensing cables shall be implanted into precast piles in advance.

**B.1.2** For cast-in-place piles, the optical cables should be bundled on the reinforcement cages before testing. The reinforcement cage is lowered into the hole, and then the concrete is poured into the hole.

**B.1.3** The metal-based cord strain sensing cable with high strength should be used for the installation.

**B.1.4** The installation procedure of the optical cables should comply with the follows:

**1** Locating and wiring: The optical sensing cables shall be bundled along the symmetrical main rebars of the reinforcement cage. The optical sensing cable should be located inside the reinforcement cage to avoid contact with surrounding rock or soil and the pouring equipment during the construction process.

**2** Bundling point by point: The optical sensing cables shall be pre-tensioned to be straight. The optical sensing cables should be bundled to the main rebars at an interval of 1.0 ~ 2.0m. The bundling interval should be shortened if the optical sensing cables are curvedly installed or cross the main stirrups. Loose tubes shall be used to protect the optical sensing cables at the U-bend of the pile toe, the bending of the optical cable, and the outlet on the pile top (Figure B.1.4-1a). The bend radius of the optical cable shall meet the requirements.



(a) Bundling and protection at the U-bend (b) Protection at the outlet

Figure B.1.4-1 Bundling and protection of optical sensing cables

1 - Optical sensing cable; 2 - Main rebar; 3 - Cable tie; 4 - Protective tube

**3** Cable protection: When the pile top needs to be demolished and reconstructed, the optical cable shall be protected with a high strength PU tube, bellows, etc. (Figure B.1.4-1b). The protected depth must be greater than the designed demolition depth. During the static load testing of piles, the testing optical cables need to be led out from the side of the pile top to avoid the loading devices. For the long-term monitoring of piles, the exposed optical cables should be protected by steel protective tubes, iron boxes, etc. according to the site operating conditions. There should be identifying and warning signs.

**4** Installation of optical sensing cables for multi-section reinforcement cages: For the lowering of multi-section reinforcement cages, the optical sensing cable should be bundled on the bottom section in advance. The rest optical cables can be installed simultaneously on the upper reinforcement cages by being pulled with ropes (Figure B.1.4-2).



Figure B.1.4-2 Installation of optical sensing cables for multi-section reinforcement cages

1 - Pulley; 2 - Pulling rope; 3 - Cable tie; 4 - Optic sensing cable

**5** Testing: After the loading devices are installed, the leads of the optical cable are unwinded, fusion spliced with the fiber optic patch cords, and connected to the optical interrogator for testing.

**6** Special types of pile foundations: For mixing piles, the optical sensing cables may be bundled on rebar or a steel strand for installation. For precast piles, the optical sensing cables may be installed at the stage of pile manufacturing. The optical sensing cable shall be bundled on a reinforcement cage, which is then cast in the mold. The construction process is the same as the above statement. The optical sensing cable at the stage of pile manufacturing shall withstand the curing temperature of the precast pile.

**B.2 Installation technology by bonding in shallow grooves**

**B.2.1** Installation technology by bonding in shallow grooves is applicable to the installation of optical cables on concrete precast piles.

**B.2.2** The optical sensing cables shall be bonded in the cutting grooves on the pile surface with adhesives of epoxy resin and so on.

**B.2.3** The strain optical sensing cables with a diameter of 0.25 mm ~ 2.00 mm should be selected for installation.

**B.2.4** The installation procedure should comply with the follows:

**1** Marking the installation path: Optical cable shall be installed symmetrically. A U-bend connection near the pile toe should be used for the cable installation. Markers or ink fountain should be used to mark the installation location of the optical cables.

**2** Grooving: A concrete cutter is used to groove along with the marked installation path. The groove width should be 2.0mm～4.0mm, and the groove depth should be 5.0mm～8.0mm. The optical sensing cables should be fully bonded in the groove. The optical cables may be connected with a U-bend 50cm above the bottom of the pile. The bend radius should be larger than 100mm (Figure B.2.4-1). To facilitate the installation of the optical cable, the groove for U-bend section may be cut wider and deeper.



Figure B.2.4-1 Installation of optical sensing cables

1 - Groove; 2 - Optical sensing cable;

**3** Groove cleaning: The grooves should be clean by using air blowers, brushes, rags, and other tools after cutting. The uneven parts in the grooves should be worn down.

**4** Installation of optical sensing cables: The optical sensing cables are installed along the grooves and bonded point by point with quick-dry adhesive after the optical cables are pre-stretched (Figure B.2.4-2a). The whole cables are covered with adhesives of epoxy resin and so on. A hot air gun is used to repair and smooth the adhesives and to remove bubbles in the adhesive (Figure B.2.4-2b). The optical cable of the U-bend section should be protected with a PU tube.



(a) Bonded point by point



(b) Covered with epoxy resin

Figure B.2.4-2 Optical sensing cable bonded and covered with epoxy resin

1 - Quick dry adhesive; 2 - Bonding points; 3 - Groove; 4 - Optical sensing cable; 5 - Hot air gun;

6 - Brush; 7 - Adhesive

**5** Adhesive curing: The curing time should be determined by referring to the table of adhesive curing rate after the optical cable is bonded with adhesives of epoxy resin and so on. The pile may be driven only if the strength of the adhesive reaches more than 70% of the design strength or hardening strength. In cold weather, heaters may be used to speed up the adhesive curing.

**6** Protection of the cable lead: After optical sensing cables are installed on the pile, the lead optical cables on the pile top should be protected by rigid bellows, steel tubes, and other tubes to avoid being damaged during transport and pile driving.

**7** Processing of pile connection: For closed-ended piles and open-ended piles where the length of the soil plug is smaller than the length of the bottom pile section, the outlets of the optical cable may be close to the connection of piles. The optical sensing cables on the upper and lower piles are led into the hollow center by passing through the outlets and are fuse spliced inside the pile (Figure B.2.4-3a). For solid piles and open-ended piles where the length of the soil plug is larger than the length of the bottom pile section, fusion splicing outside the pile should be adopted. The sensing optical cables may be bonded on the surface of the pile at the pile connection and protected with glass fiber geotextiles or covered with steel plates to prevent the sensing optical cable from being damaged during the pile driving (Figure B.2.4-3b).

 

 (a) (b)

Figure B.2.4-3 Installation of optical sensing cables during pile connecting

1 - Optical sensing cable; 2 - Fusion splicing; 3 - Protection layer; 4 - Pile joint; 5 - Outlet of optical cable

**B.3 Installation Technology by Spot Welding**

**B.3.1** Installation technology by spot welding is applicable to steel pipe piles, sheet piles, SMW steel piles, etc.

**B.3.2** Welding machines and other tools may be used to weld the optical sensing cables on the pile.

**B.3.3** The metal-based belt sensing cables should be selected for installation.

**B.3.4** The installation procedure should comply with the follows:

**1** Polish and dust removal: Polishing, rust removal, and smoothing of the welding joints shall be conducted along the installation path of optical sensing cables (Figure B.3.4-1). The installation path shall be flat and clean.



Figure B.3.4-1 Polishing along the installation path of optical sensing cables

1 - Welding joint; 2 - Path of optical sensing cables; 3 - Grinding machine

**2** Fixing by welding: The metal-based optical sensing cable shall be laid horizontally on the installation path and fixed by an electric welding machine (Figure B.3.4-2). To prevent the optical cables from being damaged by high-temperature welding, dense spot welding should be adopted.



Figure B.3.4-2 Installation of optical sensing cables by spot welding

1 - Welding joint; 2 - Path of optical sensing cables; 3 - Electric welding machine; 4 - Optical sensing cable

**3** Optical cable protection: Adhesive of epoxy resin should be used to bond the optical sensing cable along the installation path to ensure a full coupling between the optical cables and the metal matrix.

**4** Surface protection: After the adhesive is cured, a layer of fireproof material (Figure B.3.4-3) shall be bonded on the adhesive surface, such as gold foil paper, asbestos, etc., to prevent the optical cable from being burned by the welding slag during the subsequent welding of protective channel steel. If there is no protective channel steel, this step is not required.



Figure B.3.4-3 Surface protection of optical sensing cables

1- Welding joint; 2- Path of optical sensing cables; 3-Fireproof layer; 4- Optical sensing cable

**5** Welding channel steel: A channel steel shall be welded at the bottom of the pile to protect the optical sensing cables (Figure b.3.4-4). The length of the channel steel shall not be less than 5.0m. The bottom of the channel steel shall be sealed at a tilt angle. For the soil containing coarse particles, the whole optical cables shall be covered with channel steel to avoid being damaged during the pile driving. To prevent the cables from being burned by welding, the width of channel steel should not be less than 8.0 cm.



Figure B.3.4-4 Protection by channel steel

1 - Welding joint; 2 - Protective channel steel; 3 - Optical sensing cable

**6** Protection of the lead cable: The leads of the optical cable shall be protected by tube sleeves. The optical cables shall be fixed by welding a stud or a hook to avoid the dispersion or damage of the lead cable during pile driving (Figure B.3.4-5).



Figure B.3.4-5 Lead protection of optical sensing cable

1 - Welding joint; 2 - Protective channel steel; 3 - Protective sleeve; 4 - Fixing stud

**B.4 Installation Technology by Full Bonding**

**B.4.1** Installation technology by full bonding is applicable to steel pipe piles, sheet piles, SMW steel piles, concrete precast piles, etc.

**B.4.2** The belt optical sensing cables may be fully bonded with adhesive on the pile surface.

**B.4.3** The fiber-based belt sensing cables should be adopted for installation.

**B.4.4** The installation procedure should comply with the follows:

**1** Polish and dust removal: The piles shall be polished along the axial symmetrical lines. Rust removal and smoothing of the welding joints shall be conducted for metal piles. The stains on the pile surface should be cleaned for concrete piles.

**2** Painting bottom adhesive: The bottom adhesive is painted on the installation path of optical sensing cables to improve the bonding degree between the optical cable and the pile (Figure B.4.4-1).



Figure B.4.4-1 Painting bottom adhesive along the installation path of optical sensing cables

1 - Brush; 2 - Bottom adhesive; 3 - Installation path of optical sensing cables

**3** Installation of optical sensing cables: The optical sensing cables shall be installed on the bottom adhesive (Figure B.4.4-2). Another covering adhesive shall be painted on the optical sensing cables to ensure a full coupling of the optical cables and the pile.



Figure B.4.4-2 Painting covering adhesive along the installation path of optical sensing cables

1 - Brush; 2 - Covering adhesive; 3 - Optical sensing cables

**4** Surface protection: After the curing strength of the covering adhesive reaches more than 50%, a layer of fireproof material shall be bonded on the adhesive surface, such as gold foil paper, asbestos, etc., to prevent the optical cable from being burned by the welding slag.

**5** Welding channel steel: It may comply with item 5 in B.3.4 of this specification.

**6** Protection of the lead cable: It may comply with item 6 in B.3.4 of this specification.

**Appendix C Record Table for Installation of Optical Sensing Cables**

**Table C Record Table for Installation of Optical Sensing Cables**

|  |  |  |  |
| --- | --- | --- | --- |
| Project Title |  | Pile No. |   |
| Project address |  | Client |  |
| Cable types |  | Cable length |  |
| Cable parameters | Diameter: Factory light loss: Strength: Length of strain isolation:  |
| Installation plan |  | (To draw the sketch) |
| Sensing line No. | Position | Top scale | Bottom scale | Lead identification |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |
|  Process record |
| Time | Steps completed | Optical inspection | Comments(Construction photos) |
| 1 |  |  |  |
| 2 |  |  |  |
| 3 |  |  |  |
| 4 |  |  |  |
| … |  |  |  |
| Completion record |
| Sensing line |   |  |  |  |  |
| Length |  |  |  |  |  |
| Integrity |  |  |  |  |  |
| Lead identification |  |  |  |  |  |
| Comments: |

Tester: Checker:

**Appendix D Record Table for Distributed Fiber Optic Testing**

**Table D Record Table for Distributed Fiber Optic Testing**

|  |  |  |  |
| --- | --- | --- | --- |
| Project Title |  | Pile No. |   |
| Equipment name and No. |  | Sensing line No. |  |
| Line length |  | Line sequence |  |
| Loading level |  | Design load |  |
| Parameters | Test distance: Spatial resolution: Sampling resolution:Start frequency: Stop frequency: Frequency scanning step:  |
| No. | Load (No.) | Test time | Filename | Comments(settlement, abnormality, emergency) |
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| Comments: |

Tester: Checker:

**Appendix E** **Record Table for Long Term Distributed Fiber Optic testing**

**Table E Record Table for Long Term Distributed Fiber Optic testing**

|  |  |  |  |
| --- | --- | --- | --- |
| Project Title |  | Pile No. |   |
| Equipment name and No. |  | Sensing line No. |  |
| Line length |  | Line sequence |  |
| Parameters | Test distance: Spatial resolution: Sampling resolution:Start frequency: Stop frequency: Frequency scanning step:  |
| No. | Date & time | Filename | Ambient temperature | Tester | Checker | Comments(working condition and abnormality) |
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| Comments: |

**Explanation of Wording in This Specification**

**1** Words used for different degrees of strictness are explained as follows in order to mark the differences in executing the requirements in this code.

**1**) Words denoting a very strict or mandatory requirement:

“Must” is used for affirmation; “must not” for negation.

**2**) Words denoting a strict requirement under normal conditions:

“Shall” is used for affirmation; “shall not” for negation.

**3**) Words denoting a permission of a slight choice or an indication of the most suitable choice when conditions permit:

“Should” is used for affirmation; “should not” for negation.

**4**) “May” is used to express the option available, sometimes with the conditional permit.

**2** “Shall comply with…”or “Shall meet the requirements of…”is used in this code to indicate that it is necessary to comply with the requirements stipulated in other relative standards and codes.

**Code of China Association for Engineering Construction Standardization**

**Technical specification for pile distributed fiber optic testing**

**T/CECS 622 – 2019**

**Explanation of provisions**

Contents

1 General Provisions 34

3 Basic Requirements 34

3.1 Testing Contents 35

3.2 Testing Preparation 35

3.3 Testing Conditions and Quantity 36

4 Instrument and Optical Sensing Cable 38

4.1 Instrument 38

4.2 Optical Sensing Cable 39

5 Installation of Optical Sensing Cable 42

6 Field Testing 44

7 Data Processing and Testing Report 46

**1 General Provisions**

1.0.1 The distributed fiber optic testing of piles has been applied in engineering construction，which provides technical support for the quality evaluation and design optimization of piles. However, there is not a technical specification for pile distributed fiber optic testing in the world at present. The purpose of the code is stipulated in this specification.

1.0.2 The scope of the specification is stipulated.

1.0.3 This specification only involves the distributed fiber optic testing of piles. The requirements related to the piles shall comply with the current relevant standards of the nation.

**3 Basic Requirments**

**3.1 Testing Contents**

3.1.1 According to the existing research and actual testing data (BOTDR Based Distributed Strain Test on Bored Pile Buried in Complicated Geological Ground, Wei Guangqing et al.; Research on the Testing of Piles Based on Distributed Optical Fiber Monitoring Sensing Technique, Yu Xiaokui, et al.; Monitoring on axial strain of huge pile by BOTDR technology, Song Jianxue, et al.; Application of distributed fiber optic sensing techniques in bored pile detection, Piao Chunde, et al.; Application of Distributed Optical Fiber Sensing to the Lateral Static Load Test on Single Pile, Chen Wenhua, et al.; Application of Fiber Bragg Grating Sensor to Lateral Load Tests of PHC Pipe Piles, Qiu Rendong, et al.), the pile distributed fiber optic testing has been applied in vertical compressive static load testing to determine the axial force, shaft resistance, toe resistance and deformation of the piles. In vertical uplift static load testing, the axial force, shaft resistance and deformation of the piles can be determined. In horizontal static load testing, the bending moment and deflection of pile can be determined. The pile distributed fiber optic testing provides the technical support for optimizing the design of piles.

3.1.2 When the optical sensing cables are installed in pile construction, the changes of pile internal force, shaft resistance in each soil layer and toe resistance of pile may be tested, which provides a basis for investigating the bearing mechanism of piles under long-term loading.

**3.2 Testing Preparation**

3.2.1 The distributed fiber optic testing is based on the commissioned content of the owner or designer. It’s necessary to fully communicate with the client to understand the purposes and requirements of the client, to propose matters that demand the cooperation of on-site personnel, etc. The tester shall collect the geotechnical survey report, pile design drawings, pile construction and static load testing plan, technique, records and abnormal conditions in pile construction. The tester shall conduct site surveys to evaluate the feasibility of fiber optic testing and to predict the possible problems in advance, based on which the fiber optic testing plan is prepared and submitted to the client. As needed, a borehole may be drilled near the testing piles to collect rock and soil samples in each layers or conduct in-situ testing. The laboratory experiments on physical and mechanical properties are conducted to determine the standard values of extreme shaft resistance and extreme toe resistance of the rock and soil according to the current national standard “Code for investigation of Geotechnical Engineering GB50021”.

3.2.2 The optical sensing cables are installed on the reinforcement cage for cast-in-place piles. After installation and necessary protection, the optical sensing cables are lowered into the borehole together with the reinforcement cage and concreted for a pile. The optical sensing cables may be installed in the manufacture of the precast piles. The optical sensing cables shall be able to withstand the curing temperature of the precast piles. For the precast piles and steel piles ready for piling, installation of optical sensing cables can follow the requirements of appendix B. When the optical sensing cables are directly bonded or bonded in the cutting grooves on the surface of the precast pile and steel pile, the pile may be driven only if the strength of the adhesive reaches more than 70% of the design strength or hardening strength according to item 5 of Appendix B.2.4.

**3.3 Testing Conditions and Quantity**

3.3.1 The distributed fiber optic testing of piles has the function of long-distance and continuous distribution testing with high accuracy and strong corrosion resistance. As an advanced testing technology, the distributed fiber optic testing can determine the shaft resistance, toe resistance and bearing capacity of the pile. Therefore, the distributed fiber optic testing may meet the cases of complex geotechnical conditions, special construction environment, some piles of which the construction quality is hard to be guaranteed, new pile types, new technologies, piles with special design requirements, or piles to be monitored for long-term.

3.3.2 In general, the number of pile static load testing is three. Considering the difficulty (such as testing on the sea) and costs, this specification stipulates that the number of pile distributed fiber optic testing shall not be less than 2 for the same static load testing.

3.3.3 The installation of optical sensing cables for cast-in-place piles, precast piles and steel piles is different. To facilitate the testing and data verification, the number of optical sensing cables is stipulated as follows: The cast-in-place piles with a diameter less than or equal to 600mm shall be symmetrically installed with no less than 2 optical sensing cables. If the diameter of the cast-in-place piles is more than 600mm, no less than 4 optical sensing cables shall be installed symmetrically. The precast piles with a diameter less than or equal to 800mm shall be symmetrically installed with no less than 2 optical sensing cables. If the diameter of the precast piles is more than 800mm, no less than 4 optical sensing cables shall be installed symmetrically. The steel pile shall be symmetrically installed with no less than 2 optical sensing cables. The optical sensing cables should be a U-bend loop for fiber optic testing .

**4 Instrument and Optical Sensing Cable**

**4.1 Instrument**

4.1.1 To ensure the testing accuracy of the pile strain, the positioning error δof the distributed fiber optic testing technology depends on the test distance l and the sampling resolution d of the optical interrogator, as shown in formula (1):

δ=±(0.2+2×*d*+2×10-5×*l*) (m) (1)

The term spatial resolution refers to the ability of the testing system to distinguish the nearest two adjacent event points on the optical sensing cable, which can be generally defined as the cable length corresponding to step change of the measured signal from the 10% to the 90% in the rising transition section. The spatial resolution is mainly determined by the pulse width of the probe light of the testing system. If the pulse of the probe light is rectangular with a width of τ, and the group velocity of light in the fiber is ν, the spatial resolution R may be calculated according to formula (2)：

R=ν•τ/2 (2)

The conditions for strain testing accuracy: The average times is 216; The frequency scanning range is 200MHz; The scanning interval is 5MHz.

4.1.2 The performance of the pile distributed fiber optic strain testing depends on the setting of the testing parameters. The strain distribution and variation of pile refer to the difference value between the strain under different loads and the initial strain. To facilitate the comparison and analysis of optical fiber strain measurements, the accuracy of each test shall be the same, which indicates that the testing parameters shall be consistent.

4.1.3 There are two kinds of demodulation technologies for distributed fiber optic strain：

One is the single-end testing technology represented by Brillouin optical time domain reflectometry (BOTDR), which can measure the strain and temperature of the optical fiber by detecting the spontaneous Brillouin scattering light in the fiber. During the testing, only one end of the optical sensing cable needs to be connected with the interrogator to test the strain distribution of the optical sensing cable. If the optical signal is interrupted because of the breakage of the optical sensing cable, this technology may obtain the complete data by testing from both ends of the optical sensing cable. Therefore, this technology is practical, convenient and widely used in pile optical fiber testing. The shortcoming of this technology is that when the testing precision of the pile is very high, it may not meet the test requirements.

The other is the double-end testing technology represented by Brillouin optical time domain analysis (BOTDA) and Brillouin optical frequency domain analysis (BOFDA). This technology injects pulsed pump light and CW probe light from both ends of the optical sensing cable respectively to generate stimulated Brillouin scattering light in the fiber, which enhances the intensity of the detection signal and improves the testing accuracy significantly. The shortcoming is that this kind of technology needs a detection loop and tests on both ends. Once the optical sensing cable which is installed in the rock and soil mass and the underground structures breaks and the signal is interrupted, it is hard to repair or replace the damaged cable. The whole testing system will be invalid and the testing risk is high.

Therefore, for the distributed optical fiber testing of the pile, the selection of the optical fiber sensing technology shall be determined according to the requirements of testing accuracy, geological conditions, construction environment, etc.

**4.2 Optical Sensing Cable**

4.2.1 During the testing process, if the temperature changes of the pile are greater than 2℃, the optical temperature sensing cable shall be installed together with the optical strain sensing cable to conduct temperature compensate for the strain testing results. The optical strain sensing cables are mainly single-mode optical cables, which are used to test the distribution and variation of the axial pile strain. The single-mode optical cables are suitable for the testing of sensing technologies such as Brillouin optical time domain reflection (BOTDR), Brillouin optical time domain analysis (BOTDA), Brillouin optical frequency domain analysis (BOFDA). The optical temperature sensing cables are mainly multi-mode optical cables, which are suitable for the distribution and variation measurement of the pile temperature based on a distributed temperature sensor (DTS). The test results can be used for the temperature compensation of the pile strain testing.

4.2.2 To prevent the optical sensing cables from being damaged during the transportation, installation and testing, the mechanical strength of the optical sensing cables, including axial tensile strength and lateral compressive strength shall meet the requirements of table 4.2.2. At the same time, to ensure the sensing performance of the optical strain sensing cable, the initial strain uniformity and the length of strain isolation of the optical sensing cable shall also meet the requirements of table 4.2.2.

The selection of optical sensing cable depends on the installation method. For the cast-in-place piles, the optical sensing cable is usually bound to the main rebars of the reinforcement cage by bundling. However, during the concrete pouring and vibrating, the pressure and impact on the optical cable will be relatively large. Therefore, the metal-based cord strain sensing cable with strong axial tension and lateral compressive strength shall be selected for testing. For precast piles, the optical sensing cables are generally installed by bonding, that is, the optical sensing cables are directly bonded on the pile surface or in the cutting groove by using epoxy resin and other adhesive. Therefore, the optical sensing cable with a smaller diameter shall be selected. For steel piles, the metal-based belt sensing cable can be selected and installed on the pile surface by spot welding.

The operating temperature in table 4.2.2 refers to the temperature range during the pile testing. When the optical sensing cables need to be implanted into the pile in the production process of the precast pile in the factory, the temperature of the pile will reach 200 ℃ because of the high temperature steam curing. For the steel pile, the pile temperature will increase to 120 ℃ by welding. To prevent the optical sensing cables from being damaged and the changes of the sensing performance, special optical sensing cables should be used to meet the temperature requirements during the installation and testing.

The testing method for the length of strain isolation is as follows. An optical sensing cable is buried in a cement component. The embedded length shall not be less than 2m. The optical cable outside the cement component is stretched to 2000 μɛ after the cement is solidified, The strain distribution of the optical cable embedded in the cement component is measured by using Brillouin optical time domain analysis (BOTDA), an optical fiber strain interrogator with a spatial resolution higher than 5cm. The length of the optical cable with strain attenuation to 100 μɛ is defined as the length of strain isolation.

The testing method for the strain uniformity is as follows. when the optical sensing cable is in a strain-free state, the twice root-mean-square deviation of the initial strain in any 1km range within the full length of the optical cable is calculated, the maximum value of which is defined as the index to characterize the strain uniformity of the optical sensing cable.

4.2.3 The optical sensing cables are sensitive to both strain and temperature. It is necessary to conduct temperature compensate for the optical strain sensing cable when the temperature of the pile changes. The single-mode optical sensing cables with loose tube structure can be installed to test the pile temperature along with the installation of the optical strain sensing cables. However, it is necessary to ensure that the fiber core of the loose tube temperature sensing cables is not stressed during loading. The multi-mode optical cables can also be installed for temperature testing, by which the temperature distribution and changes of the piles during loading can be tested by a distributed temperature sensor (DTS) for the temperature compensation of the optical strain sensing cables. For long-term monitoring, the pile temperature usually changes. An optical temperature sensing cable should be installed along with the optical strain sensing cables for temperature compensation of pile strain testing.

**5 Installation of Optical Sensing Cable**

5.0.1 Manual inspection refers to the inspection and verification of the product name, specifications, appearance and other parameters of the optical sensing cables following the requirements of Appendix A by comparing with the original factory records to avoid mixing with the communication optical cables. The optical time domain reflectometry (OTDR) shall be used to check the length of the optical cable, and the Brillouin scattering light testing equipment shall be used to check the value and uniformity of the initial strain of the optical sensing cables. A tensile testing machine is used to conduct random inspections and rechecks on the tensile strength of the optical cables.

5.0.2 As the pile top needs to be treated and a pile cap needs to be constructed, the lead of the optical sensing cable or the optical sensing cable shall be led out from the pile side at the position of 0.5m below the elevation of the pile top with appropriate bending radius. Generally, the bending radius shall not be less than 20 times of the outer diameter of the optical cable to avoid bending the optical cable.

The temporary fixing and protection equipment of the cable leads shall be reasonably arranged according to the pile types, site construction and test layout to avoid the impact, tension and bending of the cable leads.

5.0.4 For the optical sensing cables in a U-bend loop, a red laser pen may be used to preliminarily check the integrity of the light transmission when the optical path is complete. If it is necessary to check the optical loss of the optical sensing cable or to inspect the sensing optical cable without a loop, the optical time domain reflectometry (OTDR) shall be adopted for testing.

The tested strain shall be compared with the previous and initial strain value after each test. If there is no strain data, or the strain shows a sawtooth distribution, or the signal-to-noise ratio of the Brillouin spectrum is low, it is necessary to check whether the fiber optic patch cord works normally, including appearance inspection and instrument inspection. After confirming the damage of the fiber optic patch cord, which shall be replaced and retested.

When part of optical fiber data is normal and part of optical fiber data is abnormal, the breakpoints and light loss points of the optical fiber cable shall be checked and located in combination with the layout of the sensing cable and the testing process, by using optical time domain reflectometry (OTDR) and red light pen, etc. When there is a breakpoint in the optical cable, the Brillouin optical time domain reflectometry (BOTDR) can be used to test from both ends of the optical cable. When the fiber loss of the optical cable is large, the test parameters of the interrogator may be adjusted, such as increasing the spatial resolution, and the test results are analyzed and evaluated to determine whether the data quality meets the test requirements.

When the strain of optical fiber changes greatly, the start frequency and the stop frequency of the interrogator shall be adjusted in time to obtain a complete Brillouin scattering spectrum. The strain of optical fiber shall be retested.

5.0.5 When the piles need long-term monitoring, the changes of the geothermal field shall be considered, which may affect the testing results. The strain sensing optical cables and loose tube optical cable for temperature sensing should be installed in the pile at the same time for temperature compensation.

**6 Field Testing**

6.0.1 During the pile distributed fiber optic testing, it is required that there is no interference such as construction and vibration near the testing piles. The technicians who are familiar with the operation of the test equipment are required for the entire testing process. The technicians shall be familiar with the fusion splicing and diagnosis of the optical cables, the operation of the optical fiber strain testing instruments, and the handling of common faults

The voltage of the stable power supply should match that of the equipment. The power shall be greater than the rated power of the equipment. The voltage shall be stable without fluctuations. When a temporary dynamo or a large power supply unit is used on site, the UPS equipment shall be used for voltage stabilization and power-off protection.

6.0.3 The testing of the initial value may be divided into 2 steps. Step1: The parameters of full bandwidth, large frequency scan step (20MHz～100MHz) and low average times (210～212) should be used for the initial scan. The frequency scan range should be determined after the initial scan. The frequency scan range shall cover all the Brillouin spectra of the effective testing cable, including the spectrum changes caused by the pile deformation. The spectrum changes may be estimated by 50MHz/1000με. When the optical loss of the cable is greater than 10dB, it is necessary to check the light transparency of the optical cable or to increase the probe power of the optical interrogator. Step 2: The frequency sweep step shall be set between 1 MHz to 5MHz, and the average times shall be no less than 212 times. If the signal-to-noise ratio of the spectrum cannot meet the test requirements, the parameters shall be adjusted until the test requirements are met.

6.0.4 To collect the data 3 times continuously according to the parameters set in term 6.0.3, the strain difference of each data in the effective testing cable should be less than the repeatability of the instrument. The average value of the data in 3 times is taken as the initial reading. When unexpected conditions such as an interruption in the pile loading process occur, the pile shall be unloaded and the initial stain reading shall be retested. For long-term monitoring of the piles, the initial reading shall be collected after the pile construction.

6.0.5 Data collection shall be carried out after the settlement of the pile stabilizes under each load. When the settlement of the pile is not stable, the data shall be collected several times, and the maximum strain value shall be used as the test reading. During the unloading process, data should be collected every two load levels. The data collected after the unloading has been completed for 2 hours will be taken as a reference for the analysis of the pile load testing.

6.0.6 Common problems of the testing data are shown in Table 1.

 Table 1 Common problems of the testing data

|  |  |
| --- | --- |
| Problems | Methods of inspection and handling  |
| Files are not saved or incompletely saved. | Reopen the saved files and check the integrity of the data. |
| The data increase or decrease in whole.  | The testing parameters are changed during the field testing, which causes the testing data to shift in whole compared with the previous data. The original data file or the previous data file shall be called to recover the parameters and retest. |
| The data length is incomplete. | It is usually caused by the breakage of the external cable lead. It is necessary to locate the breakpoint, fusion splice again, and fix for protection. When the breakpoint occurs inside the pile body, a fiber optic patch cord may be spliced on the other end of the optical sensing cable. A single-end optical interrogator such as BOTDR can be used to test the optical sensing cable from both ends separately. |
| The Brillouin spectrum is not smooth. | The Brillouin spectrum has obvious abnormal phenomena such as step jumping, missing the middle part, or fluctuation. It is often caused by the loose connection of the fiber optic patch cord or the wind blows, stampedes, or stretching on the lead of optical cable during testing. It is required to check the connector, re-fix the lead and collect the data. If the abnormality is not eliminated after taking the above measures, it may be the reason of the optical interrogator, which needs to be sent back to the manufacturer for repair.  |
| The intensity of the Brillouin spectrum is low. | The intensity of the Brillouin spectrum has significantly decreased compared with the previous ones, which is often caused by the dirty or bad connector, or the fiber bending. It is necessary to clean or replace the fiber optic patch cord connector, check the optical cables and retest. |

After data collection, it is necessary to check whether the file is saved, whether the Brillouin spectrum is complete and smooth, and whether the spectrum intensity is normal. The next level of the load may be applied if the above checks pass.

**7 Data Processing and Testing Report**

7.0.1 It is necessary to check whether the testing parameters of each data are consistent before data processing.

Data standardization is to adjust the data with different sampling resolutions to unify the sampling interval. The weighted average method can be used for data interpolation and extraction. The weight coefficients are the inverse of the nearest distance between two sampling points (Inverse distance weighted interpolation).

Because of the replacement of the cable leads, fusion splicing, thermal expansion and other reasons, the length of optical sensing cable will change, which results in the shift of the sampling points between different collected data. The alignment of the sampling points may be achieved by manual or automatic translation. The manual translation refers to manually adjusting the position of data according to the characteristics of the data distribution to align the data of different times. The automatic translation is to move the data to be aligned within a certain range according to the sampling resolution and to calculate the mean square deviation between the moved data and the reference data each time. The position with the minimum mean square deviation is taken as the aligned position.

Data locating refers to accurately mapping the testing data on the pile according to the layout of the optical sensing cable and the strain distribution characteristics under different loads. The key to data locating is to determine the position of the optical sensing cable entering and exiting the pile top. The following methods are recommended:

1. Temperature marking method: The hot water, heating bag, hot air blowing and other methods may be applied to heat the optical cables with a length of about 0.5m-1m near the outlets of the optical cable on the pile top. The location is determined according to the strain anomaly caused by temperature changes. (Fig. 1).



Figure 1 Temperature marking method

① - distance; ② - strain; ③ - temperature marking point A; ④ - temperature marking point B

2. Micro bending method: A microbend of the optical cable is made at the outlets of the optical cable on the pile top. The microbend position is located by the optical time domain reflectometry (OTDR) (Fig. 2);



Figure2 Microbending method

①—distance; ②—light intensity; ③—microbend marking point A; ④—microbend marking point B

3. Characteristic curve method: Two sets of data with a large temperature difference are selected. The data locating is based on the characteristics that the optical sensing cable outside the pile top is largely affected by the temperature (Figure 3).



Figure 3 Characteristic curve method

①—distance; ②—light intensity; ③—temperature affected zone

4. Actual measuring method: The data locating is based on the actual length of the optical cable between the instrument and the pile top by using the tape measure.

The deduction method may be used to locate the pile toe. Based on the pile top positioning, the position of the pile toe may be determined according to the length of the optical cables installed in the pile. The characteristic curve method may also be used for positioning. The difference value between the testing data and the initial value of a complete U-bend sensing cable usually shows a "V" shape symmetrical distribution, the center of which is the pile toe.

The data of each optical sensing cable of the pile is divided and extracted after the data positioning. The X axis of the data is redefined by the depth of the pile. The extracted data length of each optical sensing cable shall be consistent.

The strain distribution of the pile may fluctuate in varying degrees because of the inhomogeneity of the pile and the different piling quality. To facilitate data processing, it is necessary to smooth the strain data. The moving average method is commonly used for smoothing, by which all the data within a certain interval D before and after a sampling point are averaged. The average value is taken as the measured value of the sampling point. The new strain distribution may be obtained by averaging forward at the step of the sampling resolution. The interval D shall be between 0.5m and 3m.

7.0.2 This term mainly introduces how to calculate the axial force of the pile according to the testing strain.

The strain distribution  of each optical sensing cable under different loads is obtained according to the frequency shift of the optical fiber Brillouin scattered light. The average strain at depth z is obtained by averaging the strain data of each optical sensing cable at the same depth.

The elastic modulus of the pile is the main parameter for calculating the axial force of the pile. There are mainly three methods for obtaining the elastic modulus:

Method by testing: The laboratory material compression tests on the concrete samples remained on site is applied to obtain the elastic modulus.

Method by fitting on the pile top: The strain data of the pile within the range of 2 to 5 meters below the pile top is used to obtain the elastic modulus of the pile based on the relationship between the strain and the load.

Method based on codes: The elastic modulus reference value is obtained by consulting the concrete structure design codes according to the concrete grade and the reinforcement ratio.

7.0.3 The calculation methods of shaft resistance and toe resistance of the pile are introduced in this term. The average strain value of 1.0m～2.0m length at the bottom of the pile can be used for the calculation to reduce the calculation error of the pile toe resistance.

7.0.4 In this term, the displacement of the pile top is the settlement or the uplift of the pile obtained by the displacement meter during the pile static load testing. The displacement of the pile top can be obtained by a level survey for long-term monitoring.

7.0.5 The calculation of the bending moment and deflection of the pile is introduced in this term. It is assumed that the pile shall have no translation and rotation at the pile toe. The bending moment and deflection of the pile are calculated based on the strain difference of the two symmetrically installed cables at the same depth. The direction of the deflection is determined according to the following principles: the positive calculated deflection indicates that the pile bends to the side of direction b, and the negative value means that the pile bends to the side of direction a.