The test effect evaluation of distributed optical fiber sensing technology applied to stress test of bored pile

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Abstract. The application of distributed optical fiber sensing technology to stress test of bored pile is a kind of line measurement method developed in recent years. It has the advantages of more measuring points and stronger anti-interference, but its test effect is rarely compared with other methods in practical engineering. In order to evaluate the test effect of distributed optical fiber sensing technology, the optical fiber and sliding micrometer tube were embedded at the same time during the construction of test pile, and then the static load test of pile was carried out to compare the test results of the two. The test results show that the strain distribution of the pile obtained by the distributed optical fiber sensing technology and the sliding micrometer method are the same, and the maximum strain difference between them is about 100 με. The distributed optical fiber sensing technology can better reflect the detailed deformation of the pile.

1. Introduction
At present, the method of pile stress test can be divided into point measurement method and line measurement method. The linear measurement method can obtain the continuous variation of pile strain, and the problems of local test points are not enough to affect the whole. The strain fitting link in the data processing process can partly eliminate the test error caused by the heterogeneity of concrete, and improve the overall accuracy of the test results. Compared with the point measurement method, it has obvious advantages.

The distributed optical fiber sensing technology based on Brillouin scattering is a line measurement method developed in recent years. In this method, the optical fiber is not only a transmitter but also a sensor. By using the scattering of light in the optical fiber, the deformation of each point on the optical fiber can be monitored continuously in theory. Based on the characteristics of distributed optical fiber sensing technology, the continuous deformation of bored pile can be measured by embedding optical fiber into bored pile and cooperating with the bored pile, so as to achieve the purpose of stress test of pile. Shi et al.(2006), Piao et al.(2008), Feng et al.(2014) ,Luo et al.(2014) and many others have applied it in stress test of bored pile and accumulated some practical experience.

The core sensing element of the distributed optical fiber sensing technology based on Brillouin scattering is the bare fiber in the sensing optical cable. The strain of the bare fiber is calculated by
detecting the change of the light wave energy, and then the strain distribution of the pile is obtained indirectly. If we want to get the real strain distribution of the pile, the premise is that the bare fiber and the pile deform together and keep consistent. However, in practical application, because the bare fiber is relatively fragile and easy to be damaged, coating and sheath are usually added to protect the bare fiber, but this increases the strain transmission path of the pile, resulting in the loss of the strain sensed by the bare fiber. Wu et al. (2017) and Quan et al. (2020) studied the strain transmissibility of FBG surface bonded through experiments and numerical calculation, and showed that the strain transmissibility was positively correlated with the elastic modulus and bonding length of the coating layer, and negatively correlated with the thickness of the adhesive layer. Gao et al. (2007) and Zhang et al. (2013) studied the length of the section with poor strain transmissibility by establishing a linear elastic theoretical mechanical model. It is shown that the section with poor strain transmissibility occurs at both ends of the optical fiber, and the length is very short (no more than 6cm), and the strain transmission rate of the middle section is close to 100%. The above research shows that there is a difference between the actual strain and the sensing strain, but the difference is only verified by theoretical derivation, numerical calculation and indoor test. There is little research on the comparison of distributed optical fiber and other test methods in practical engineering. In order to evaluate the test effect of distributed optical fiber sensing technology, a typical project was selected to test the stress of bored pile using distributed optical fiber sensing technology and sliding micrometer method, and the test results of the two methods were compared.

2. Research method

2.1 Test site
A super high-rise pile test project in the southern suburb of Xi'an city was selected, and the main strata include fill, Quaternary Holocene alluvial loess, medium sand, silty clay, Late Pleistocene alluvial silty clay and Middle Pleistocene alluvial silty clay. Two test piles were selected for the test study, and the test pile numbers were S1 and S2. The pile ends of the two test piles are located in the silty clay layer. The original ground elevation of the test site is about 412m. The concrete strength grade of pile is C55. Four anchor piles are used to provide static load reaction. The limit value of vertical compressive bearing capacity of single pile required by the design is 18600kN. The enlarged head above the pile top was used for reinforcement, and four jacks were used to provide pile top reaction. The pile top elevation of S1 and S2 test piles are 395.48m and 396.65 respectively, the effective pile length is 66.23m and 67.94, and the average pore diameter is 0.95m and 0.93m respectively. The field static load test of pile is shown in Figure 1.

Figure 1. Static load test of pile
2.2 Testing instrument and equipment

In order to evaluate the accuracy of distributed optical fiber sensing technology in stress test of bored pile, the sliding micrometer method is selected for comparison. Sliding micrometer method is a kind of line measurement method for testing pile stress. The equipment used is sliding micrometer. The equipment continuously measures the distance between adjacent points by using the spherical cone contact positioning principle. It is a strain (deformation, length) testing instrument with test accuracy of $10^{-3}\text{mm/m}$. Its main component is the probe, as shown in Figure 2. The sliding micrometer tube needs to be embedded in the pile in advance, which is equipped with a measuring mark every 1m. The deformation between the two points can be obtained by measuring the distance between the two markers at different times. At present, this method has been widely used in pile stress test, and its test effect has been verified in practice. It is an ideal method to verify the effect of distributed optical fiber sensing technology.

![Figure 2. Slide micrometer probe](image)

The data acquisition equipment of distributed optical fiber sensing technology used in this test is fTB 5020, which is a high precision distributed optical fiber strain demodulator and made by fibrisTerre from Germany, as shown in Figure 3. The highest sampling resolution of the equipment is 0.05m, and the strain measurement accuracy is ± 2 με. It has excellent strain analysis accuracy and spatial resolution.

![Figure 3. Fiber optic strain demodulator](image)

2.3 Experiment programme

In order to better compare the difference between the two methods, the test optical cable and sliding micrometer tube were arranged along the adjacent main reinforcement. The optical cable was U-shaped distributed on the symmetrical main reinforcement. The effective test length under the top of two test piles was 65m. Two sliding micrometer tube were arranged symmetrically on the main reinforcement of each test pile. The effective test length was 15m below the top of pile S1 and 24m below the top of pile S2. Therefore, the effective contrast length of pile S1 and S2 was 15m and 24m below the pile top respectively. The spatial resolution length of distributed optical fiber sensing technology was set as 0.05m, and there were 20 data per meter, which was 20 times of sliding micrometer method. Before loading, the initial strain of the pile was obtained by the two methods, and then the loading was carried out. When the loading reached the stability standard, the tests were carried out respectively. The field test photos are shown in Figure 4 and Figure 5.
3. Research method

3.1 Comparison of original test data
When the sliding micrometer method is used for testing, it needs to stand on the crossbeam of the reaction system of static load test. Considering the safety of the test, the sliding micrometer method was used to test the pile S1 with 4 levels of load, and the maximum test load was 9300kN, pile S2 was tested by sliding micrometer method with 6 levels of load, and the maximum test load was 13020kN. The comparison of original test data between distributed optical fiber sensing technology and sliding micrometer method in effective comparison section is shown in Figure 6. It can be seen that except for some points, the test results of distributed optical fiber sensing technology and sliding micrometer method are quite close, and the overall trend of the curve is the same. The large difference of some points may be caused by uneven distribution of concrete in pile. The strain distribution of the pile obtained by distributed optical fiber sensing technology oscillates back and forth on both sides of the sliding micrometer test results, Because the test step distance of the distributed optical fiber sensing technology is only 0.05m, its distribution curve is smoother than that of the sliding micrometer method, and the feedback of the pile deformation details is more comprehensive. There is a big jump in the test results of sliding micrometer method. For example, pile S1 at the depth of 9m, 15m, pile S2 at the depth of 9m, 16m, 19m, the transition is not smooth enough.
In order to facilitate comparison, the test result of optical fiber sensing technology with 0.05m step length is converted into equivalent value of 1m step distance, and the difference of two test methods at each depth is counted, as shown in Table 1. It can be seen that at the same depth, some points differ greatly, with the maximum value of 303 με. But most of the strain differences are in dozens of με, and the average difference is relatively small, with the maximum of 28 με. Considering that the strain distribution trend of the pile measured by the two methods is very close, and the pile is uneven, this difference can not reflect the test effect. It is necessary to smooth the data and then compare them.

Table 1. Strain difference of two methods under different loads

| Depth(m) | Pile strain difference of S1(με) | Pile strain difference of S2(με) |
|----------|----------------------------------|----------------------------------|
|          | 3720 kN  | 5580 kN  | 7440 kN  | 9300 kN  | 3720 kN  | 5580 kN  | 7440 kN  | 9300 kN  | 11160 kN | 13020 kN |
| 1        | 56       | 45       | 47       | 46       | 44       | 52       | 65       | 79       | 52       | 42       |
| 2        | -92      | -107     | -131     | -137     | -96      | -112     | -127     | -145     | -181     | -191     |
| 3        | -85      | -86      | -100     | -107     | -99      | -125     | -113     | -102     | -110     | -97      |
| 4        | -71      | -100     | -113     | -117     | -88      | -99      | -101     | -98      | -119     | -112     |
| 5        | 14       | 24       | 22       | 16       | -17      | -40      | -42      | -42      | -56      | -52      |
| 6        | 130      | 113      | 97       | 77       | 126      | 157      | 178      | 204      | 210      | 229      |
| 7        | 8        | -6       | -36      | -61      | -4       | -14      | -25      | -28      | -51      | -54      |
| 8        | -51      | -97      | -135     | -165     | -12      | -75      | -93      | -142     | -207     | -261     |
| 9        | 171      | 235      | 268      | 279      | -137     | -201     | -232     | -256     | -288     | -303     |
| 10       | 52       | 37       | -13      | -59      | 76       | 50       | 39       | 31       | 21       | 23       |
| 11       | 57       | 103      | 135      | 140      | 71       | 85       | 83       | 82       | 71       | 71       |
| 12       | -18      | -11      | -55      | -126     | 26       | -14      | -48      | -73      | -95      | -98      |
| 13       | -18      | 4        | 24       | 27       | 49       | 44       | 2        | -31      | -48      | -55      |
| 14       | 15       | 3        | 15       | 3        | -1       | 26       | 40       | 25       | 6        | -8       |
| 15       | 32       | 91       | 189      | 293      | 40       | 69       | 88       | 74       | 53       | 40       |
| 16       | -19      | -25      | -50      | -140     | -195     | -219     |          |          |          |          |
| 17       | 11       | 16       | 47       | 89       | 94       | 88       |          |          |          |          |
| 18       | 15       | 37       | 80       | 90       | 76       | 72       |          |          |          |          |
| 19       | 11       | 31       | 90       | 155      | 193      | 208      |          |          |          |          |
| 20       | 4        | 7        | 11       | 10       | 0        | -3       |          |          |          |          |
| 21       | -13      | -2       | 8        | 14       | -2       | -13      |          |          |          |          |
| 22       | -6       | -7       | 0        | 7        | -11      | -28      |          |          |          |          |
| 23       | -11      | -12      | -3       | -14      | -77      | -120     |          |          |          |          |
| 24       | -9       | -4       | 30       | 75       | 134      | 176      |          |          |          |          |
| average  | 13       | 17       | 14       | 7        | -2       | -6       | -3       | -6       | -22      | -28      |

3.2 Comparison after data smoothing

The result of synchronization distance of the two test methods are fitted by cubic polynomial, and the comparison curve is obtained as shown in Figure 7. It can be seen that the results and trend of the two test methods are similar in the area of pile S1 within 13m, but there is a certain difference in the position of 13 ~ 15m. The test results of pile S2 are close to each other in numerical value and trend. The difference between the results of the two test methods along the pile is statistically shown in Table 2. The maximum difference is 128 με, which has been greatly reduced, and the maximum difference average is 39 με, which is quite small.
Figure 7. Strain fitting curves under different loads

Table 2. Strain difference of two methods under different loads

| Depth(m) | Pile strain difference of $S_1$ (με) | Pile strain difference of $S_2$ (με) |
|----------|-------------------------------------|-------------------------------------|
|          | 3720kN                              | 5580kN                              |
|          | 7440kN                              | 9300kN                              |
| 1        | -15 -18 -25 -29 -46 -39 -20 -4      | -39 -20 -4 -20 -48 -48 -45 -71       |
| 2        | -30 -43 -53 -56 -39 -44 -36 -28     | -48 -82 -87 -95 -91 -98 -88 -95     |
| 3        | -32 -51 -63 -68 -32 -46 -46 -45     | -69 -71 -71 -71 -71 -71 -71 -71     |
| 4        | -25 -44 -58 -66 -25 -46 -52 -57     | -57 -82 -87 -91 -91 -91 -91 -91     |
| 5        | -11 -27 -43 -53 -19 -43 -54 -63     | -89 -95 -95 -95 -95 -95 -95 -95     |
| 6        | 7 -3 -20 -34 -12 -32 -47 -62        | -91 -98 -98 -98 -98 -98 -98 -98     |
| 7        | 26 23 6 -12 -6 -32 -47 -62          | -88 -95 -95 -95 -95 -95 -95 -95     |
| 8        | 44 48 31 10 0 -25 -40 -56          | -81 -88 -88 -88 -88 -88 -88 -88     |
| 9        | 57 68 53 30 5 -17 -31 -47          | -71 -78 -78 -78 -78 -78 -78 -78     |
| 10       | 64 80 67 43 10 -8 -20 -37          | -58 -65 -65 -65 -65 -65 -65 -65     |
| 11       | 60 78 70 46 14 0 -9 -25            | -44 -50 -50 -50 -50 -50 -50 -50     |
| 12       | 44 61 58 35 18 9 3 -12             | -29 -35 -35 -35 -35 -35 -35 -35     |
| 13       | 13 23 28 9 20 16 14 1             | -14 -20 -20 -20 -20 -20 -20 -20     |
| 14       | -37 -39 -25 -37 22 23 25 13        | 0 -5 -5 -5 -5 -5 -5 -5              |
| 15       | -108 -128 -104 -107 22 28 34 24    | 13 7 13 7 13 7 13 7                |
| 16       | 22 31 40 34 23 17                 |                                  |
| 17       | 20 32 45 41 30 24                 |                                  |
| 18       | 17 31 46 45 33 25                 |                                  |
| 19       | 12 27 44 45 32 22                 |                                  |
| 20       | 6 19 37 41 25 12                 |                                  |
| 21       | -2 8 26 32 11 -4                 |                                  |
| 22       | -11 -8 9 17 -9 -29               |                                  |
| 23       | -23 -28 -14 -4 -37 -62           |                                  |
| 24       | -36 -52 -43 -32 -74 -105         |                                  |
| average  | 4 2 -5 -19 -3 -8 -6 -10           | -31 -39 -39 -39 -39 -39 -39 -39    |
4. Conclusion
Compared with the sliding micrometer method, the distributed optical fiber sensing technology can obtain more strain test data of the pile and reflect the details of the pile deformation, the strain distribution of the pile is smoother, and the local test error has less influence on the whole. The strain distribution of the pile obtained by the distributed optical fiber sensing technology is very similar to that of the sliding micrometer method. The maximum difference between the two methods is about 100 με.

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