Experimental Study on Inclination Test of Fiber Bragg Grating

Kang Tan, Ping Dong, Wanchun Gou, Qi Guo, and Yi Li

Abstract Deep displacement monitoring is an important means to monitor the deformation of slope, landslide and deep foundation pit. Traditional deep displacement monitoring uses manual inclinometer, which is time-consuming and laborious, and has large manual operation error, so it is impossible to realize automatic monitoring. It is urgent to adopt new technical means to make up for these shortcomings. Based on fiber Bragg grating sensing technology and beam bending theory, this paper establishes the calculation formula of fiber Bragg grating deep inclinometer, which can calculate the deep displacement curve of inclinometer through the change of fiber Bragg grating center wavelength; The strain sensitivity coefficient of fiber Bragg grating is calibrated by indoor calibration test. The experimental results show that the center wavelength of fiber Bragg grating has a high correlation with strain, and the relationship is linear. The strain and displacement of inclinometer tube are monitored and compared by indoor model test. The test results show that the displacement error calculated by fiber Bragg grating is 2% ~ 12%, which can meet the needs of deep displacement monitoring. The relevant conclusions provide a certain reference for the research of fiber Bragg grating deep displacement monitoring.

Keywords Fiber Bragg grating · Inclination · Deep displacement monitoring · Difference algorithm · Strain sensitivity coefficient

K. Tan (✉) · W. Gou · Q. Guo · Y. Li
Technology Innovation Center of Geohazards Automatic Monitoring, Ministry of Natural Resources (Chongqing Institute of Geology and Mineral Resources), Chongqing 401120, China
e-mail: tankangmove@163.com

Chongqing Engineering Research Center of Automatic Monitoring for Geological Hazards (Chongqing Institute of Geology and Mineral Resources), Chongqing 401120, China

P. Dong
Zhong'an Mutual Inductance (Chongqing) Intelligent Technology Co., Ltd., Chongqing 401120, China

1 Introduction

With the increase of human engineering activities, artificial slopes and deep foundation pits are increasing, and slope instability and deep foundation pit collapse occur from time to time. In addition, the range of human activities is also expanding to landslides and other geological disasters prone areas. In order to ensure the safety of human life and property, it is necessary to monitor the deformation of artificial slopes, deep foundation pits and natural landslides. Deep displacement monitoring can directly and effectively reflect the deformation and development law of rock and soil, and is an important means of deformation monitoring [1].

Traditional deep displacement monitoring mainly uses manual inclinometer, which is easy to operate, but it has high labor intensity, long time consumption, low automation degree and large errors caused by manual operation. Optical fiber has the characteristics of high sensitivity, anti-electromagnetic interference and strong automatic real-time, and has been well used in power communication [2], petrochemical industry [3], aerospace [4, 5], building structure monitoring [6–8], medical equipment [9] and other fields.

Some scholars have also applied optical fiber sensing technology to the field of geotechnical inclination measurement. Pei et al. [10] used fiber Bragg grating sensing technology to monitor the slope of an expressway for a long time. Chen et al. [11] used fiber Bragg grating sensors to monitor the landslide of a pipeline. Bims et al. [12] applied fiber Bragg grating sensing technology to deformation monitoring of slope indoor model. Jia et al. [13] developed a fiber Bragg grating test system for geotechnical centrifuge, which can monitor soil displacement in real time. Peng et al. [14] used fiber Bragg grating to monitor the deep displacement of a landslide, and analyzed the position and deformation mode of its main sliding surface.

At present, although there are some application examples of fiber Bragg grating inclinometer, the monitoring effect is only verified by deformation trend analysis. Fiber Bragg grating inclinometer, as a new monitoring technology, involves a wide range of theoretical knowledge and professional technology, so it is still necessary to study its inclinometer principle and effect through indoor experiments. In this paper, the calculation formula of fiber Bragg grating inclination is established firstly, and then the strain sensitivity coefficient and strain characteristics of fiber Bragg grating are studied by laboratory calibration test. Then, through model test, the effectiveness of fiber Bragg grating inclinometer technology is studied.

2 Principle of Fiber Bragg Grating Inclination Test

2.1 Characteristics of Fiber Bragg Grating

As shown in Fig. 1, when light waves are incident into the fiber, the grating will reflect light waves of a specific wavelength, which meets the following specific conditions:
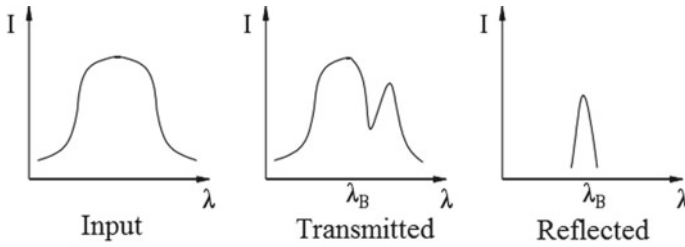
Fig. 1 Light wave propagation diagram of fiber Bragg grating

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where λ_B represents the central wavelength of reflected light; n_{eff} represents the effective refractive index of optical fiber; Λ represents the pitch of the fiber Bragg grating.

The relationship between λ_B and ambient temperature T and strain ε is as follows:

$$\frac{\Delta\lambda_B}{\lambda_{B0}} = (\alpha + \xi)\Delta T + (1 - p^{eff})\Delta\varepsilon \tag{2}$$

where $\Delta\lambda_B$ represents the change of the central wavelength; λ_{B0} is the initial center wavelength of the grating at 0 °C without external force; $\Delta\varepsilon$ and ΔT represent the strain and temperature changes of fiber Bragg grating respectively. α, ξ and p^{eff} represent the thermal expansion coefficient, thermo-optical coefficient and photoelastic coefficient of optical fiber, respectively.

Equation (2) can be rewritten as:

$$\Delta\lambda_B = c_\varepsilon\lambda_{B0}\Delta\varepsilon + c_T\lambda_{B0}\Delta T \tag{3}$$

where: $c_\varepsilon = 1 - p^{eff}$, $c_T = \alpha + \xi$.

2.2 Principle of Fiber Bragg Grating Inclination Measurement

It is generally necessary to install an inclinometer tube with fiber Bragg grating in the monitoring position, collect the reflection center wavelength of fiber Bragg grating by fiber demodulator, and calculate the deep displacement of rock and soil by analyzing the wavelength change.

In order to accurately measure the strain of the inclinometer tube, it is necessary to eliminate the influence of temperature on the wavelength, and the temperature compensation can be carried out by pasting fiber Bragg grating on both symmetrical

sides of the inclinometer tube. When the inclinometer tube is deformed, the wavelength changes of the reflection center of the symmetrical grating on both sides are as follows:

$$\Delta\lambda_{B1} = c_{\varepsilon 1}\lambda_{B10}\Delta\varepsilon_1 + c_{T1}\lambda_{B10}\Delta T_1 \tag{4}$$

$$\Delta\lambda_{B2} = c_{\varepsilon 1}\lambda_{B20}\Delta\varepsilon_2 + c_{T1}\lambda_{B20}\Delta T_2 \tag{5}$$

Fiber Bragg gratings of the same batch are used on symmetrical sides of inclinometer tubes, $c_{\varepsilon 1} \approx c_{\varepsilon 2}$, $\lambda_{B10} \approx \lambda_{B20}$, $c_{T1} \approx c_{T2}$. The temperature changes of symmetrical gratings on both sides are equal, namely $\Delta T_1 = \Delta T_2$. Therefore, the following formula can be obtained by (4) and (5):

$$\Delta\varepsilon_1 - \Delta\varepsilon_2 = \frac{\Delta\lambda_{B1} - \Delta\lambda_{B2}}{\lambda_{B0}c_{\varepsilon}} \tag{6}$$

From Eq. (6), it can be seen that temperature compensation can be realized by symmetrical double grating structure.

According to the beam bending theory, the deflection of the inclinometer tube is calculated from the strain of the inclinometer tube as follows:

$$S(z) = \int_L^z \int_L^z \frac{\Delta\varepsilon_1(z) - \Delta\varepsilon_2(z)}{2R} dz dz \tag{7}$$

where: L represents the length of the inclinometer, z represents the depth, and R represents the radius of the inclinometer.

The following formula can be obtained by substituting Eq. (6) into Eq. (7):

$$S(z) = \frac{1}{2Rc_{\varepsilon}\lambda_{B0}} \int_L^z \int_L^z [\Delta\lambda_{B1}(z) - \Delta\lambda_{B2}(z)] dz dz \tag{8}$$

After the change of reflection center wavelength of grating point is collected in the field, Eq. (8) can be solved by difference method.

3   Fiber Bragg Grating Calibration Test

The strain sensitivity coefficient of fiber Bragg grating is affected by the type of fiber and grating writing process. In order to ensure the accuracy of monitoring results, it is necessary to calibrate the strain sensitivity coefficient before using fiber Bragg grating to measure inclination.

3.1 Experimental Steps

(1) Fix the two slides to the 32a channel steel base respectively, and then paste the two ends of the 3-m-long optical fiber to the two slides respectively with 502 glue (see Fig. 2) to ensure that the stretched part of the optical fiber has three grating areas.

(2) Lock one sliding table to ensure that it cannot move, rotate the handwheel of the other sliding table to pre-tighten the optical fiber, measure the length of the optical fiber at this time with a steel tape measure, install a dial indicator on the movable sliding table and adjust it to zero, and then use an optical fiber demodulator to read the initial value of the central wavelength of three grating points in the tension area.

(3) Turn the handwheel of the movable sliding table to stretch the optical fiber, control the amount of optical fiber stretching according to the reading of the dial indicator, test the stretching of 1 mm in each stage, and read the grating center wavelength after stretching in each stage (see Fig. 3a).

(4) Stretch until the point wavelength of the grating is abnormal, then move the slider in the opposite direction to shrink the fiber, shrink 1 mm in each stage, continue to the initial pre-tightening length in step 2, and read the center wavelength of the grating after shrinking in each stage (see Fig. 3b).
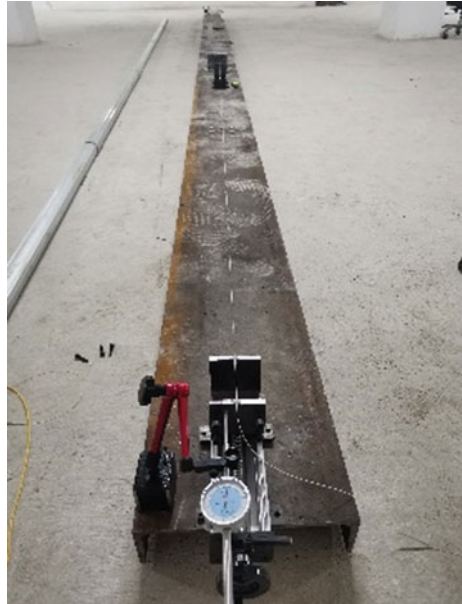
Fig. 2 Calibration test device

（a）Tensile process 　　　（b）Shrinkage process

Fig. 3 Calibration test readings

3.2 Test Results and Analysis

The relationship between the measured strain and the central wavelength is shown in Fig. 4.

The following results can be obtained from Fig. 4 and linear fitting results:

(1) The correlation coefficient R^2 of the three grating points is greater than 0.999, the correlation between the center wavelength and strain is very high, and the fitting relationship is linear.
(2) The relationship between strain and wavelength of 1# grating point is: $\lambda = 0.00121\mu\varepsilon + 1548.975$, the relationship between strain and wavelength of 2# grating point is: $\lambda = 0.0012\mu\varepsilon + 1531.220$, the relationship between strain and wavelength of 3# grating point is: $\lambda = 0.00122\mu\varepsilon + 1549.063$, and the average strain sensitivity coefficient $c_\varepsilon\lambda_{B0}$ of three grating points is 0.00121.

Fig. 4 Relationship between grating point strain and center wavelength
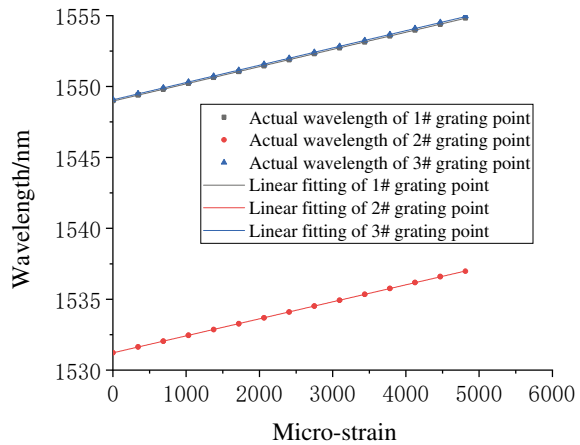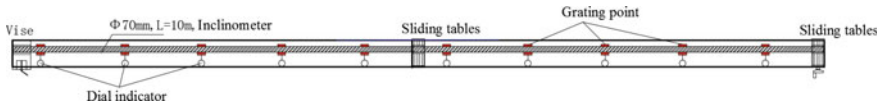
Fig. 5 Schematic diagram of test device

(3) The central wavelength in the stretching process and the central wavelength in the shrinking process basically coincide, which shows that the relationship between the strain and the central wavelength of the fiber has good repeatability and no fatigue phenomenon.

(4) The length of the fiber is 2909 mm. When the fiber is stretched 15 mm, that is, the strain reaches 5156με, the wavelength data is lost, which shows that the limit micro-strain of the fiber Bragg grating used in the test is about 5156με.

4 Indoor Model Test

In order to analyze the error of inclinometer formula and verify the validity of inclinometer with fiber Bragg grating, indoor model test is needed.

4.1 Test Ideas

Channel steel is used as the base, a vise is installed at the tail of the base, and a sliding table is installed at the middle and end parts respectively. The inclinometer tube attached with fiber Bragg grating and strain gauge is placed on the vise and sliding table, and the sliding table at the end is moved to make the inclinometer tube displacement. The strain of the inclinometer tube is measured by fiber demodulator and strain gauge, and then the displacement of the inclinometer tube is solved, and the actual displacement of the inclinometer tube is measured at the same time. See Fig. 5 for the schematic diagram of the test device.

4.2 Experimental Steps

(1) Calibration of grating point position. The point spacing of the fiber Bragg grating used this time is 1 m. The manufacturer has marked the point position of the purchased fiber Bragg grating, but there may be some deviation in the point position of the grating due to machining error, so it is necessary to recalibrate the point position of the grating. It is preferred to use an optical fiber fusion splicer to fusion the armored lead cable with the optical fiber, and then connect the optical fiber to the optical fiber demodulator, slightly stretch at the raster points

Fig. 6 Calibration of grating point position

marked by the manufacturer, If the demodulated wavelength increases sharply, the position of the grating point is accurate. If the demodulated wavelength does not change, stretch near the position of the grating point calibrated by the manufacturer until the position where the demodulated wavelength increases sharply is found, which is the accurate position of the grating point. After calibration, mark the position of the grating point with a marker pen, as shown in Fig. 6.

(2) Fabrication of fiber Bragg grating inclinometer. This time, the length of a single section of aluminum alloy inclinometer pipe is 2 m, and five inclinometer pipes are connected by casing. Four rows of casing joints are drilled with six holes in each row, and then rivets are used for anchoring to ensure that the inclinometer pipes are firmly connected. According to the calibrated grating point position, mark the grating point sticking position on both symmetrical sides of the inclinometer tube with a marker pen. The fiber Bragg grating is arranged in U-shaped loop at the end of inclinometer tube, In order to make the grating closely fit with the surface of the inclinometer tube, And better coupled together, Use sandpaper to polish around the sticking point, After the surface is rough and scratched, use cotton swabs dipped in alcohol to wipe off dust, oil stains and other pollutants on the surface of the inclinometer tube, Align the center of the grating point with the marked point, paste one end of the grating area on the inclinometer tube with 502 glue, then pretighten the fiber Bragg grating, paste the other end of the grating area on the inclinometer tube with 502 glue, and then apply epoxy resin glue to the grating point area, so that the grating point and the inclinometer tube are completely glued together. See Fig. 7 for the schematic diagram of the fabricated fiber Bragg grating inclinometer tube.

(3) Installation of strain gauge. A resistance strain gauge is pasted on the symmetrical side of the protrusion of the inclinometer tube for comparative monitoring, as shown in Fig. 7. Before mounting, the mounting part of the inclinometer tube is polished with fine sandpaper, Remove the oxide layer, the grinding direction is about 45° with the wire grid direction of the strain gauge, then wipe the patch with cotton swab dipped in absolute alcohol, then drop 502 glue on the strain
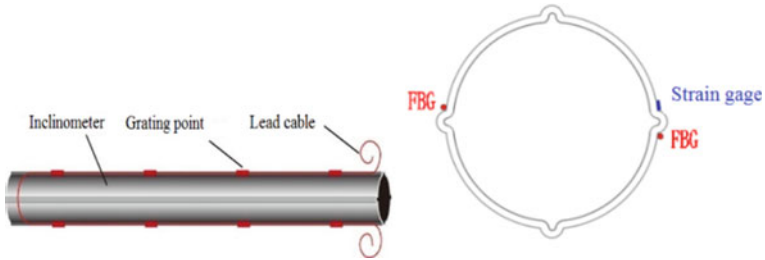
Fig. 7 Schematic diagram of fiber Bragg grating inclinometer

Fig. 8 Inclinometer model
test device

gauge, and then paste it to the patch position. During the pasting process, roll
it evenly with fingers to ensure that the excess glue is extruded out, so that the
bonding place is uniform and free of bubbles.

(4) Installation of test device. 5 sections of 2 m long 32a channel steel are assembled
into a 10 m long base. A vise is fixed at the tail of the channel steel for clamping
the fixed simulated fixed end at the tail of the inclinometer pipe. Sliding tables
are respectively installed at the end and middle of the channel steel, and the end
sliding tables can be moved left and right by shaking the handwheel to make

the end of the inclinometer pipe displacement. The middle sliding table can slide freely, which is used to prevent the inclinometer tube from drooping and contacting the channel steel base from affecting the test results Fig. 8.

(5) Fiber Bragg grating inclinometer installation. Three days after the fiber Bragg grating is attached to the inclinometer tube, the epoxy resin glue is completely cured. Install the inclinometer tube on the test device, and make the vise clamp the tail of the inclinometer tube. Starting from the tail of the inclinometer, a dial indicator is installed at each grating point and zeroed, with a total of 6 indicators installed. Because the displacement of the end is larger than the measuring range of the dial gauge during the test, the displacement of the remaining four grating points at the end is calculated by marking the channel steel base with a line.

(6) Data measurement. Connecting the optical fiber demodulator with the optical fiber Bragg grating to read the initial wavelength of each grating point; Connect the strain gauge to the strain gauge and zero it. This test is divided into three times of loading, that is, moving the end sliding table three times, reading the wavelength of each grating point after displacement by optical fiber demodulator, and reading the strain value at the grating point after displacement by strain gauge.

4.3 Experimental Results and Analysis

(1) Comparative analysis of fiber Bragg grating strain and strain gauge strain.
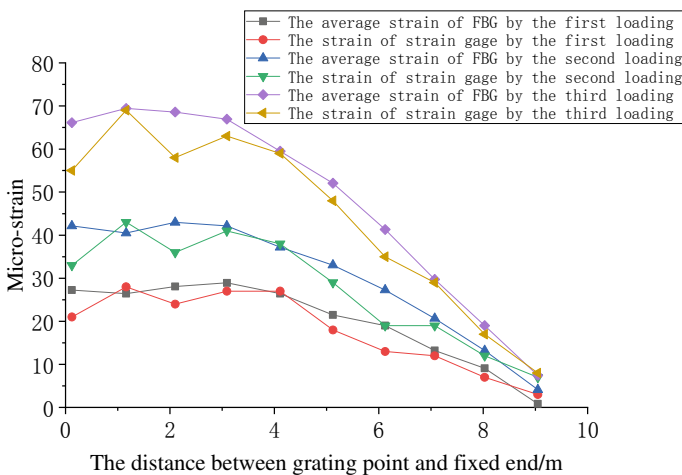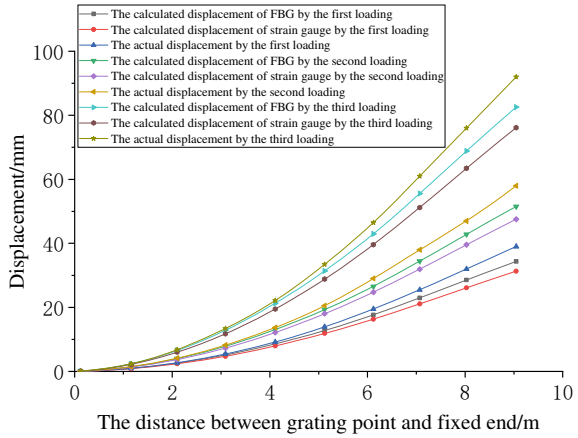
As can be seen from Fig. 9:

Fig. 9 Strain comparison analysis diagram

Fig. 10 Displacement comparison analysis diagram

① In the three tests, the strain calculated by fiber Bragg grating and the strain measured by strain gauge are basically the same, and the strain gradually decreases from the tail to the end of the inclinometer tube, which accords with the strain change law of cantilever beam.

② On the whole, the strain curve measured by strain gauge has larger twists and turns, while the strain curve calculated by fiber Bragg grating has smaller twists and turns, and the curve is more uniform and smooth.

(2) Comparative analysis of displacement calculated by fiber Bragg grating, displacement calculated by strain gauge and actual displacement.

It can be seen from Fig. 10: ① In the three tests, the displacement law calculated by fiber Bragg grating and strain gauge is the same, and the displacement from the tail to the end of inclinometer gradually increases, which accords with the displacement change law of cantilever beam. ② The calculated displacement of fiber Bragg grating and strain gauge are smaller than the actual displacement, and the calculated displacement of fiber Bragg grating is closer to the actual displacement.

It can be seen from Fig. 11: ① With the increase of end displacement (loading amount), the calculation displacement error of fiber Bragg grating and strain gauge decreases continuously. The error of the first point at the tail of the inclinometer is large, mainly because the actual displacement of this point is small, while the dial indicator can only be accurate to 0.01 mm. ② The error of displacement ratio calculated by fiber Bragg grating is 2% ~ 12%.

The calculated displacement of fiber Bragg grating is smaller than the actual displacement, which may be caused by the following reasons: ① The deformation of inclinometer tube is transmitted to fiber Bragg grating through glue, and there is a certain transmissibility. ② There is casing joint in inclinometer pipe. Although the joint is connected by rivets, there will be some gap looseness.

Fig. 11 Error between
calculated and actual
displacement
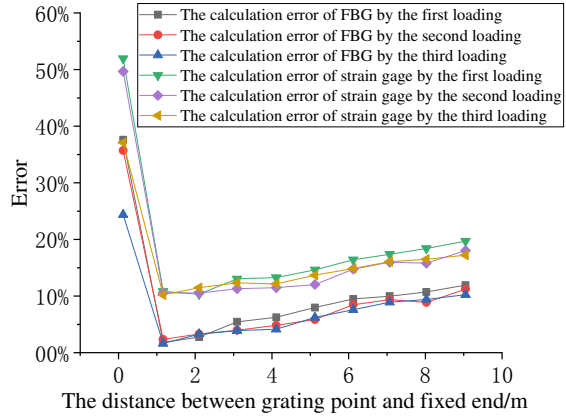
5   Conclusion

(1) Based on fiber Bragg grating sensing technology and beam bending theory,
     the calculation formula of fiber Bragg grating inclination measurement is
     established.
(2) The correlation between the center wavelength of fiber Bragg grating and the
     strain measured by indoor calibration test is very high, and the fitting relationship
     is linear. The average strain sensitivity coefficient of grating points is 0.00121,
     and the limit micro-strain of fiber Bragg grating is about 5156 μm.
(3) The displacement calculated by using fiber Bragg grating is closer to the actual
     displacement than that calculated by using strain gauge. The displacement error
     calculated by fiber Bragg grating is 2% ~ 12%, which can meet the needs of
     deep displacement monitoring.

References

1. Ding Y, Wang QC (2009) Remediation and analysis of kinematic behavior of roadway landslide
    in the upper Minjiang River, Southwest China. Environ Geol 58(7):1521–1532
2. Bjerkan L (2000) Application of fiber-optic Bragg grating sensors in monitoring environmental
    loads of overhead power transmission lines. Appl Opt 39(4):554–560
3. Spirin VV, Shlyagin MG, Miridonov SV et al (1999) Fiber Bragg grating sensor for petroleum
    hydrocarbon leak detection. Opt Laser Eng 32(5):497–503
4. Di SR (2015) Fibre optic sensors for structural health monitoring of aircraft composite
    structures: recent advances and applications. Sensors 15(8):18666–18713
5. Li P, Liu YJ, Leng JS (2014) A new deformation monitoring method for a flexible variable
    camber wing based on fiber Bragg grating sensors. J Intell Mater Syst Struct 25(13):1644–1653

6. Majumder M, Gangopadhyay TK, Chakraborty AK et al (2008) Fibre Bragg gratings in structural health monitoring-present status and applications. J Lightwave Technol 35(18):150–164
7. Zhu HH, Yin JH, Jin W et al (2010) Health monitoring of foundations using fiber Bragg grating sensing technology. Chin Civil Eng J 43(6):109–115
8. Ou JP, Zhou Z, Wu ZJ et al (2004) Intelligent monitoring of Heilongjiang Hulan River bridge based on FBGs. Chin Civil Eng J 37(1):45–49
9. Mishra V, Singh N, Tiwari U et al (2011) Fiber Bragg grating sensors in medicine: current and emerging applications. Sens Actuators 167(2):279–290
10. Pei HF, Yin JH, Zhu HH et al (2010) In-situ monitoring of displacements and stability evaluation of slope based on fiber Bragg grating sensing technology. Chin J Rock Mechan Eng 29(8):1570–1576
11. Chen PC, Li J, Liu JP et al (2010) Monitoring technology of pipelines using fiber Bragg grating and its application in landslide areas. Chin J Rock Mechan Eng 32(6):897–902
12. Bimis A, Karalekas D, Bouropoulos N et al (2016) Monitoring of hardening and hygroscopic induced strains in a calcium phosphate bone cement using FBG sensor. J Mech Behav Biomed Mater 60:195–202
13. Jia LX, Shi B, Wei GQ et al (2017) Fiber Bragg grating test system and model tests based on geotechnical centrifuge. Chin J Geotech Eng 39(5):896–905
14. Peng HY, Chen BL, Dong P et al (2020) Application of FBG sensing technology to internal deformation monitoring of landslide. Adv Civ Eng Article ID 1328945