Research and application of an improved internal thrust force measurement system for rock and soil mass based on OFDR

Pu Wang and Yimin Liu

State Key Laboratory of Hydraulic Engineering Simulation and Safety, School of Civil Engineering, Tianjin University, Tianjin, China; School of Mechanic Engineering, Tianjin University of Technology, Tianjin, China; National Institute of Natural Hazards, MEMC, Beijing, China

ABSTRACT

Internal thrust force of unstable rock and soil mass is an essential parameter for prediction of many geological hazard. Currently, fiber bragg grating (FBG) and optical time-domain reflectometer (OTDR) are widely used to measure internal stress of unstable rock and soil mass. However, these methods have disadvantages such as low spatial resolution and the paucity of distributed measurements. This paper develops a quasi-distributed thrust measurement system based on an optical frequency domain reflectometer (OFDR). Firstly, we design an optical fiber stress sensor head using the characteristics of the optical fiber microbending effect. And then, the cubic spline interpolation method is used to compensate for the nonlinear effects of the OFDR. Finally, we implement a laboratory experiment of lateral stress to make error calibration. As a result, the OFDR sensing system achieved a spatial resolution of 20 cm by using a 500 m test fiber, maximum measurement pressure reached 1.059 MPa and relative error is 8.9%. We implemented OFDR in the Chenjiagou landslide located at the Three-Gorge of Chongqing in China. The results showed that this system can accurately locate six fiber stress sensors within the landslide over a range of 0 ~ 420 m, obtaining the lateral thrusts as well.

1. Introduction

For safety monitoring of unstable slopes, slope projects, water conservation hydropower dams and tunnel chambers, a lot of measurement or monitoring ways, such as GNNS, InSAR, close-range photogrammetry, and 3D laser scanning methods, are widely used (Tang et al. 2012, Bellotti et al. 2014, Scaioni 2015, Gili et al. 2000, Wright et al. 2004, Liu 2014). However, the instability criteria for these methods are mostly based on displacement and deformation monitoring systems, so these methods
only provide basic data for the study of regional surface deformations of unstable slopes and lacking ability to reflect characteristics of the deformation and stress of deep rock and soil bodies. Moreover, the deformation and development of a monitored body is a multi-dimensional and complicated process. It is difficult to accurately detect an unstable slope’s potential sliding position and establish the corresponding relationships between the time parameters, displacements, and force changes. Therefore, early warning and prediction of the geological disaster based on these systems are not able to be achieved accurately.

Most of the conventional monitoring methods cannot work when increased deformation or a large local deformation of rock and soil occurs, because that inclinometer tubes deform sharply lead to drilling inclinometers unavailable. However, the sensing fiber in an optical fiber sensing system is able to be used commonly as long as it is not cut off. Moreover, the sensing fiber contains so many pressure-sensing points in series that own strong resistance to scraping (Naruse et al. 2007). Among various methods, the optical time-domain reflectometer (OTDR), Brillouin time-domain reflection (BOTDR), and fiber Bragg grating (FBG) technologies have been applied for bridges, hydraulic engineering, construction, and geological hazard monitoring (Bao et al. 1995, Kee et al. 2000, Bernini et al. 2006). Kihara et al. (2002) placed optical fibers on the embankments of the Niyodo and Sendai Rivers in Japan and used polarized time-domain reflection to monitor the landslide displacements of the embankments and achieved good results. Liu (2014) established a mechanical model that is composed of FBG structure, substrate-protective, and layer-sensing fiber. The model analyzed factors affecting the measurement accuracy of the FBG sensor and deduced the analytical solution between the structural matrix and the fiber optic sensor under the action of tension and three-point pressure theoretically, and then proposed measures to improve the measurement accuracy. Zhang et al. (2006) used the OTDR technology to accomplish quasi-distributed monitoring of landslides’ internal thrust force and conducted large-scale landslide monitoring in the Three Gorges Dam area. Klar et al. (2010). used a distributed optical fiber component monitoring network to automatically detect disturbances, settlements, and other phenomena caused by tunnel excavation processes, and this optical fiber monitoring network provides a large amount of spatial distribution data and the tunnel mechanical model is analyzed and verified indoors using the measured optical fiber data. Surrey et al. placed distributed optical fibers on the surface of a steel bridge in the form of steel fiber ribbons; the sensing unit included a bare fiber sensor and a new bonded fiberglass tape with embedded fiber strain measurement capability and thermal compensation; the BOTDR strain analyzer was used to test the strain and stress distribution of the bridge during the loading process (Surrey et al. 2013). Shi et al. (2005) conducted monitoring analyses and health diagnoses of a tunnel using a BOTDR fiber strain gauge, proposed the installation of sensor fibers and temperature compensation methods, and discussed the influence of environmental factors such as temperature and vibration on the measurement results. Minardo et al. (2012) used a BOTDR fiber strain gauge to perform static load tests on highway bridges and compared the data collected by fiber measurements with finite-element simulations and vibration-wire strain gauges to verify the effectiveness of the BOTDR method for monitoring large structural deformations.
At present, the main problems of the OTDR technology are lower spatial resolution, lower sensitivity, and lower measurement accuracies. Compared with the OTDR, BOTDR technology can achieve simultaneous measurements of strain and temperature and has the advantages of high sensitivity, high measurement accuracy, and distributed measurements. However, it still has many disadvantages about complexity of optical path structure, difficulty of signal modifications and the high cost of the demodulator. By compared with the OTDR and BOTDR, the optical frequency domain reflection (OFDR) presents the advantages of quasi-distributed monitoring, high spatial resolution, high measurement accuracy, reliable performance, and strong anti-interference ability. Thus, the OFDR recently has developed in stress or strain measurement, Kreger et al. (2006) measured the change of stress by figuring out the shift in the Rayleigh backscattering spectrum, which stress measurement resolution narrow down to 1 με. Koshikiya et al. (2008) increased the test range to 30 km with coherent optical frequency domain reflectometry with SSB-SC modulator and narrow linewidth fiber laser. Du (2016) optimized the slope filter algorithm to improve the linearity of the light source to measure the vibration signal with a distance of 40 km and located the positions of two vibration points. Xie (2017) implement time-delay self-locking technology and frequency traction interlocking technology to developed an OFDR system with two model (high-precision mode and long-distance model).

Over the years we have buried many micro-bending pressure sensors in the Three Gorges reservoir area in China. We used the OTDR method to measure the internal thrust previously, so this study uses a more advanced OFDR method instead of OTDR and FBG. Therefore, the OFDR is suitable for internal stress monitoring of rock and soil mass during the entire process from creep to accelerated deformation.

In this paper, the OFDR technology is used to measure the internal stresses of rock and soil mass. First, a fiber optic micro-bending stress sensor was designed as the stress detection device and a detuning filter algorithm was used to compensate for the spatial measurement errors created using the nonlinear sweep frequency band of the light source. In laboratory tests, quasi-distributed stress measurements were realized within a sensing distance of 500 m. The spatial resolution was less than 20 cm, the maximum measurement pressure reached 1.059 MPa, and the maximum relative error did not exceed 8.9%. Field engineering application results show that the system can accurately sense stress locations and magnitudes.

2. Design the OFDR sensing system

2.1. Design the OFDR sensing system

2.1.1. Design of the OFDR sensor

The lateral stress can be converted into a physical quantity of optical power loss caused by the bending of the optical fiber for measurement by utilizing the characteristics of the bending loss in an optical fiber upon bending(Takada 1992, Liu 2014). In order to convert the lateral stress into bending of the optical fiber, the pressure-sensitive element of sensor uses an elastic membrane and a micro-bending modulation mechanism performs micro-bending processing on the single-mode fiber and senses the pressure distribution along the fiber axis (Zhou et al. 2004). As shown in
Figure 1, the elastic membrane is fixed on a rigid body, and the periodic toothed pressure plate is composed of a moving tooth plate and fixed tooth plate. The moving tooth plate is fixed to the center of the elastic membrane, and the tooth plate is fixed to the base of the rigid body. The pressure (P) is applied to the elastic membrane to generate the strain ($e$). The moving tooth plate generates a corresponding displacement that changes the micro-bending amplitude of the optical fiber between the toothed plates, such that the loss due to micro-bending changes.

As shown in Figure 2, when the tablet is compressed by stress P, the sensor’s optical fiber will be squeezed. Therefore, it affects the light propagation in the optical fiber and the Rayleigh scattering signal, causing transmission power changes. Figure 3 is a spectral diagram of a backward Rayleigh scattering signal after the sensor is subjected to stress. In the graph, the blue line represents the case where the sensor is not subjected to stress, and the red line represents the case where the sensor is subjected to a 30 kg weight.

Figure 3 shows that a reflection peak appears in the distance domain signal at 807.71 m compared to the case without stress, because part of the light transmitted in the fiber is reflected back to the effects of fiber bending. Simultaneously, owing to the signal loss caused by the optical fiber’s bending, the amplitude of the Rayleigh scattering signal after this position is reduced as a whole.

As shown in Figure 4, multiple OFDR micro-bending pressure sensors are arranged along the testing fiber, and the stress sensing array is connected in series. The OFDR demodulator can measure the stress distributions at multiple locations along the testing fiber.

2.1.2. Composition of the demodulator

The system structural block diagram of the stress sensing demodulator based on OFDR is shown in Figure 5. A tunable laser was selected as the system frequency sweeping light source, and its nonlinear effects were compensated by the software algorithms (Wu et al. 2017).

The light source used in this demodulator is a Santec TSL-710 external cavity wavelength-tunable laser. Its static line width is 100 kHz, the tunable range of the wavelength scanning speed is 0.5 ~ 100 nm/s, and the tunable wavelength ranges
Figure 2. Lateral stress acts on the sensor.

Figure 3. Spectral diagram of a backward Rayleigh scattering signal.

Figure 4. Spectral diagram of a backward Rayleigh scattering signal.
1,480 ~ 1,640 nm. To compensate for the nonlinear frequency sweep effect of the light source, an auxiliary interferometer structure with a fixed delay is added to the main interferometer structure where the fiber under test is located; both the interferometer structures are MZ interferometer structures (Wang 2015). In order to improve the signal-to-noise ratio of the coherent OFDR signals, we use a Thorlabs PDB430C with a bandwidth of 350 MHz as the balanced detector, and the acquisition card uses a Spectrum M4i.4421 with four channels with the highest sampling rate for each channel(250 MHz). Additionally, to suppress the single-mode fiber’s polarization fading effect, a polarization diversity receiving device has been added. The splitting ratio of the optical couplers OC1 is 95/5, OC2 is 99/1, and OC3, OC4, and OC5 are all 3 dB optical couplers, meaning that the splitting ratios are 50/50 for these couplers (Malatesta et al. 2000). To ensure that the wavelength scanning of the light source is synchronized with the data acquisition, the TTL trigger signal of the TSL-710 can be used as an external trigger signal for the data acquisition card. Since the transmission of light in the optical path takes time, the data initially collected by the acquisition card are actually the data from the previous scan period, so the trigger delay needs to be set for the acquisition card. The trigger delay time is determined by the optical path delay time.

2.2. Design of a nonlinear effect compensation algorithm and simulation analysis

To address the problem of the low spatial resolution of the OFDR for long-distance measurements, the cubic spline interpolation method, as shown in Figure 6, adopted in this section perform accurate estimations of phase for the light source outputs, and a short-time Fourier algorithm to obtain the time-frequency curve to determine the length of the delay fiber in the auxiliary interferometer. The nonlinear phase is then estimated by a high-order Taylor expansion to obtain the nonlinear phase of the intrinsic light.

In order to verify the effectiveness of the cubic spline interpolation method in compensating for the nonlinear frequency sweep effect of the light source, this section uses LabVIEW software for simulation and then compares this simulation with the laboratory experimental data.
Assume that the nonlinear phase of the reference light is \( e(t) = A_n \cos(2\pi f_n t) \), and \( A_n \) and \( f_n \) are the amplitude and frequency, respectively. The frequency sweep rate \( \gamma(t) \) can be written as \( \gamma(t) = \gamma_0 - (2\pi f_n)^2 A_n \cos(2\pi f_n t) \), where \( \gamma_0 \) is the linear frequency sweep rate and a constant term, \((2\pi f_n)^2 A_n \cos(2\pi f_n t)\) changes with time as a sinusoid that is the interference term, the ratio of the amplitude \((2\pi f_n)^2 A_n\) of the interference term of \( \gamma(t) \) to the constant term \( \gamma_0 \) is defined as \( K \), which is easy to represent the degree of fluctuation of the frequency sweep rate \( \gamma(t) \). The larger the \( K \) value, the greater the degree of fluctuation of \( \gamma(t) \), indicating that the linearity of the frequency sweep of the light source is worse. In the simulation, the linear frequency sweep rate is taken as a fixed value \( \gamma_0 = 625 \text{ GHz/s} \) and the corresponding wavelength sweep rate is 5 nm/s (the central wavelength is 1,550 nm). Simultaneously, it is assumed that a strong reflection peak exists at a certain position on the optical fiber to be tested and the simulation function is shown in Equation (1).

\[
I(t) = \cos \left\{ 2\pi \left( \gamma_0 t + \nu_0 t^2 - \frac{1}{2} \gamma_0 \nu_0 t^2 + A_n \cos (2\pi f_n t) - A_n \cos \left[ 2\pi f_n (t - \tau) \right] \right) \right\} \tag{1}
\]

The amplitude \( I(t) \) is taken as 1. During the simulation, \( I(t) \) needs to be discretized; the sampling rate is set to 1 MS/s and the sampling time is 1 s. Additionally, it is assumed that the position of the strong reflection point along the optical fiber to be measured is at 20.55 m, and the corresponding group delay is \( \tau = 2 \times 10^{-7} \text{ s} \). According to the magnitude of the nonlinear effect, it is discussed as follows:

1. let \( A_n = 5 \times 106 \), \( f_n = 25 \text{ Hz} \) and the group delay \( \tau \) is still \( 6 \times 10^{-7} \text{ s} \), corresponding to the fiber position 61.65 m; at this time the \( K \) value is still 0.2 and

![Sampling diagram of the cubic spline interpolation.](image)
the other parameters are unchanged. The effect of the one-dimensional interpolation method before and after compensation is shown in Figure 8. Comparing Figures 8(a) and (b), it can be seen that the reflection peak broadens considerably when it is not compensated, and its interval is approximately 49.5 to 73.5 m. However, the reflection peak after compensation is extremely sharp, indicating that the spatial resolution of the system has been greatly improved.

2. To test the compensation effect of the one-dimensional interpolation method for multiple reflection points, a second strong reflection peak position is added, namely $\tau_1 = 4 \times 10^{-7}$ s and $\tau_2 = 6 \times 10^{-7}$ s. At this time, the preset reflection point positions are now at 41.10 m and 61.65 m. When uncompensated, as shown in Figure 9(a), two reflection peaks overlap and an overlapping interval are observed at approximately 33.0 to 73.5 m. The position information of the two reflection points cannot be obtained at all, and the system spatial resolution is seriously degraded. After compensation by the one-dimensional interpolation method, as shown in Figure 9(b), two reflection points are separate and the widths of their reflection peaks are significantly narrower. The corresponding fiber positions are also consistent with the preset positions. It is thus demonstrated that the cubic spline interpolation method effectively removes the phase noise in the light source and the compensation effect for multiple reflection points is still significant.

For the case of the same simulation model, Compared to most severe nonlinear frequency sweeping effects of the light source, the one-dimensional interpolation
method greatly improves the spatial resolution of the system, narrows the width of the reflection peaks significantly, and obtains the position information of the reflection points. Like the single-point compensation, we make one-dimensional interpolation for the same set of experimental data. Figure 10 shows the effects before and after compensation.

Figure 10(b) shows that the problem of reflection peak expansion has been solved after the cubic spline interpolation method. There is an extremely sharp reflection peak at 56 m where the energy is concentrated, and the system spatial resolution is greatly improved. The position information of the testing fiber reflection points is restored again. Therefore, the cubic spline interpolation method has notable compensation effects that can achieve higher system spatial resolutions and have lower noise floors and higher system signal-to-noise ratios.

2.3. Calibration experiments

In the calibration experiment, the testing fiber consists of three sections with a total length of 809.29 m. The lengths of the three segments are 595.96 m, 3.43 m, and 209.9 m, respectively; the fiber with the length 3.43 m has a plastic outer tube, and this section is mainly used for lateral stress application and measurement, while the remaining two sections consist of ordinary single-mode fiber. At the beginning of the experiment, we use a Santec TSL-710 tunable wavelength scanning light source. The light source power is set to 10 mW, the frequency sweep rate is 16 nm/s, the acquisition card sampling rate is 250 MSa/s, and the number of sampling points is 4 M. When no stress is applied, i.e., the elastic diaphragm is in a natural state and the nonlinearity of the light source is compensated by the dechirp compensation filter algorithm. The distance signal obtained is shown in Figure 11. The reflection peak is clearly visible and the spatial resolution is significantly improved after compensation. Simultaneously, the amplitude of the Rayleigh scattering spectrum is relatively uniform and does not exhibit major changes.

To measure the variation in the backscattered Rayleigh signal under different stresses, as described in Section 2.2, and Figure 7 express the process of testing and calibration in detail, weights with different masses are applied to the sensor head; the
weights are 5 kg, 10 kg, 15 kg, 20 kg, 30 kg, 54 kg, and 77.5 kg. (The stress area of the compressing tablet in Figure 2 is $7.25 \times 10^{-4} \text{m}^2$, providing corresponding pressure values of 0.069 MPa, 0.138 MPa, 0.207 MPa, 0.276 MPa, 0.414 MPa, 0.746 MPa, and 1.059 MPa). The distance domain images of the backscattered signals under different lateral stress conditions are shown in Figure 12.

Due to the stress application, a reflection peak appears at this position, and the loss difference is obtained by averaging the amplitudes of the 100 points to the left and right of the reflection peak and subtracting them. Figure 12 shows that with the continuous increase of the mass of the weight, the fiber is squeezed more by the pressing teeth, the larger the bending curvature radius generated, and the more the Rayleigh scattering signal decreases. Simultaneously, greater stresses produce higher peak values for the reflection peak caused by the bending, which reduces the optical power received by the subsequent optical fiber and causes the overall reflection peak generated at the end of the fiber to decrease in amplitude. It can also be seen from Figure 12(g) that when the mass of the weight reaches 77.5 kg, the amplitude of the Rayleigh scattering spectrum after the stress application point is still greater than the noise amplitude, indicating that the measurement range of the system has not reached its limit. As the mass of the weight continues to increase, the
Rayleigh scattering spectrum continues to decrease until it is flooded by noise in the fiber at the back of the sensor head and the peak-to-peak reflection amplitude at the end of the fiber is reduced to the noise amplitude. The fiber is nearly broken at this time.

The measured weight masses and the Rayleigh signal intensity difference data are listed in Table 1 and polynomial fitting is performed. The fitting results show that the coefficients of the fourth-order polynomial and the higher-order terms are very small and can be ignored. Herein, a cubic polynomial is used for fitting and the fitting results are shown in Figure 13. The signal strength difference measured by using a value of 20 kg is 2.93 dB and the mass of the calculated weight is 21.78 kg. Thus, it is known that the measurement error of the stress is 8.9%.

3. Field engineering application

In order to verify the practicability of the OFDR measurement system, this section introduces the field engineering application of the Chenjiagou landslide in Fengjie County, Chongqing Municipality, in the Three Gorges Reservoir Area, and analyze the measurement results.

3.1. Description of the field engineering application site

The Chenjiagou landslide is located approximately 1 km from Fengjie Old County and 0.4 km from the Yangtze River, Chongqing City. There are two large gullies on both sides of the main sliding body. The main sliding body boundary for which the right boundary is the Yaowancun Gully is oriented NE–SW; the left boundary is Chenjiagou and the right boundary is approximately 340 m away from the NE point of the Fujun Bridge; the trailing edge has an elevation of approximately 385 m and a width of approximately 100 m; the leading edge has an elevation of 135 m and this side of the Linmeixi River is submerged. The main axial length of the landslide is approximately 500 m and its width is approximately 380–400 m, the average thickness of the landslide is 60 m, and the thickest part is approximately 99.35 m in the middle of the landslide. The existing distribution area of the landslide is approximately
Figure 12. Distance domain images of the OFDR signals under different stresses, they should be listed as: (a) 5 kg, (b) 10 kg, (c) 15 kg, (d) 20 kg, (e) 30 kg, (f) 54 kg, and (g) 77.5 kg.
Table 1. Relationship between lateral stresses and Rayleigh scattering signal intensity differences.

| No. | Counterweight (kg) | Light intensity difference (dB) |
|-----|--------------------|--------------------------------|
| 1   | 5                  | 1.72                           |
| 2   | 10                 | 1.9                            |
| 3   | 15                 | 2.38                           |
| 4   | 20                 | 2.93                           |
| 5   | 30                 | 3.26                           |
| 6   | 54                 | 3.42                           |
| 7   | 77.5               | 4.69                           |

Figure 13. Fitting graph of the weight masses and signal intensity differences.

18.4 × 10^4 m², its volume is approximately 1.104 × 10^7 m³, and it is a second-class large-scale soil landslide (Wu et al. 2005). Figure 14(a) shows the entire Chenjiagou landslide.

According to the characteristics of the Chenjiagou landslide and its site survey, we mainly conducted GPS surface displacement monitoring and internal thrust monitoring of the landslide. The locations of the monitoring points are shown in Figure 14(b). For the internal thrust monitoring scheme of the landslide body, we used an OFDR-based quasi-distributed optical fiber stress sensing system and installed it in the annular gap between the thrust measurement tube and the borehole, as shown in Figure 15. By measuring the pressure on each pressure sensor in the four directions of the design installation hole depth (segmented by the sliding zone), the thrust force of each hole segment is obtained by the segmented integral method to determine the force of the slip zone, creating conditions that can provide reliable data support for the entire landslide monitoring process.
3.2. Data analysis

As shown in Figure 14(b), the main section of the Chenjiagou landslide is equipped with two optical fiber thrust monitoring holes. Therefore, in this field application, the OFDR prototype was used to perform internal thrust tests of the two monitoring holes in the sliding body. Since the OFDR demodulator cabinet is placed at a distance from the thrust monitoring hole on the landslide body, a fiber optic jumper with a length of 220 m is used to connect the cabinet to the fiber connector in the borehole. Photos of the Chenjiagou landslide monitoring sites and the data collection equipment are shown in Figure 16.
3.2.1. Data analysis of the TK-01 monitoring site

Figure 17 shows the OFDR signal measured by the TK-01 fiber that was connected to the fiber jumper. The start and stop positions of the TK-01 testing fiber are 222.849 m and 424.075 m, respectively, and the length of the testing fiber is 202.226 m. The positions of the OFDR sensors and the pressure values subjected to the lateral thrust can be obtained by processing the data of the OFDR signals, as shown in Figure 18.

Figures 17 and 18 show that the testing fiber exhibits obvious signal strength differences at the six positions at where 261.752 m, 286.213 m, 308.910 m, 329.585 m, 359.518 m, and 381.501 m (including the 220 m optical fiber jumpers). There are obvious signal intensity differences at these locations that are caused by the stresses on the sensors. The signal strength difference showing a strong reflection peak at 425.075 m, which is caused by Fresnel reflection at the end of the sensing fiber.
The test results of the stress positions show agreement with the positions of the sensors installed along the sensing fiber (the actual installation positions of the sensor are 40 m, 65 m, 90 m, 110 m, 140 m, and 160 m). Table 2 shows that the measured positions and pressure values for six stress sensors along the testing fiber.

We also select the pressure monitoring data of TK-01 monitoring site from February 2017 to December 2019, and the data table and pressure-time curve are shown in Table 3 and Figure 19. The OFDR thrust measurement system operates normally for a long time, and the data of OFDR sensor component are relatively stable, which means the landslide is in a creep state.

**Figure 18.** Pressure positions and their values for the TK-01 testing fiber.

**Table 2.** Positions and measured pressure values of sensors of TL-01.

| No. | Installation position (m) | Measured position (m) | Location error (m) | Measured pressure (MPa) |
|-----|---------------------------|-----------------------|--------------------|-------------------------|
| 1   | 40                        | 41.752                | 1.752              | 0.04026                 |
| 2   | 65                        | 66.213                | 1.213              | 0.05627                 |
| 3   | 90                        | 88.910                | 1.090              | 0.0589                  |
| 4   | 110                       | 109.585               | 0.425              | 0.04215                 |
| 5   | 140                       | 139.518               | 0.498              | 0.09072                 |
| 6   | 160                       | 161.501               | 1.501              | 0.08539                 |

**Table 3.** The pressure data table of TK-01.

| Measurement Time | 1# Sensor | 2# Sensor | 3# Sensor | 4# Sensor | 5# Sensor | 6# Sensor |
|------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 2017/2/1         | 0.0403    | 0.0563    | 0.0589    | 0.0422    | 0.0907    | 0.0854    |
| 2017/5/5         | 0.0453    | 0.0653    | 0.0609    | 0.0405    | 0.0885    | 0.0863    |
| 2017/8/15        | 0.0545    | 0.0764    | 0.0779    | 0.0400    | 0.1154    | 0.0854    |
| 2017/9/14        | 0.0519    | 0.0763    | 0.0754    | 0.0325    | 0.1134    | 0.0868    |
| 2017/11/15       | 0.0462    | 0.0662    | 0.0765    | 0.0399    | 0.1200    | 0.0862    |
| 2018/2/13        | 0.0457    | 0.0668    | 0.0741    | 0.0302    | 0.1053    | 0.0854    |
| 2018/5/14        | 0.0562    | 0.0685    | 0.0699    | 0.0266    | 0.1193    | 0.0863    |
| 2018/7/10        | 0.0554    | 0.0713    | 0.0706    | 0.0321    | 0.1193    | 0.0860    |
| 2018/8/17        | 0.0662    | 0.0746    | 0.0724    | 0.0303    | 0.1104    | 0.0862    |
| 2018/9/11        | 0.0625    | 0.0710    | 0.0703    | 0.0265    | 0.1255    | 0.0855    |
| 2018/12/19       | 0.0557    | 0.0700    | 0.0685    | 0.0325    | 0.1188    | 0.0867    |
| 2019/2/16        | 0.0512    | 0.0751    | 0.0710    | 0.0299    | 0.1104    | 0.0888    |
| 2019/5/15        | 0.0572    | 0.0891    | 0.0700    | 0.0365    | 0.1223    | 0.0862    |
| 2019/7/17        | 0.0592    | 0.0769    | 0.0751    | 0.0333    | 0.1224    | 0.0867    |
| 2019/8/16        | 0.0685    | 0.0899    | 0.0891    | 0.0370    | 0.1235    | 0.0867    |
| 2019/12/24       | 0.0652    | 0.0799    | 0.0875    | 0.0370    | 0.1158    | 0.0863    |
Figure 19. Monitoring data curves of multiple sensors.

Figure 20. OFDR signal of the TK-02 testing fiber.

Figure 21. Pressure positions and their values for the TK-02 testing fiber.
3.2.2. Data analysis of the TK-02 monitoring site

Figure 20 shows the OFDR signal measured by the TK-02 fiber that is connected to the fiber jumper. The start and stop positions of the testing fiber are 222.053 m and 421.506 m, respectively, and the length of the testing fiber is 199.453 m. The positions of the OFDR sensors and the pressure values subjected to lateral thrust can be obtained by processing the data of the OFDR signals, as shown in Figure 21.

Figure 20 and 21 show that the testing fiber exhibits obvious signal strength differences at the six positions, including 255.952 m, 276.255 m, 296.933 m, 322.125 m, 352.520 m, and 378.568 m (containing the 220 m optical fiber jumpers). There are obvious signal intensity differences at these locations and these are the differences caused by the stresses on the sensors. Because that Fresnel reflection at the end of the sensing fiber, the difference of signal intensity with a strong reflection peak at 425.075 m.

The test results of the stress positions agree well with the sensor positions installed on the sensing fiber (the actual installation positions of the sensors are 35 m, 55 m, 75 m, 100 m, 130 m, and 170 m). Table 2 shows that there are six stress sensors on the testing fiber, and the positions and measured pressure values of each sensor are also shown in Table 4.

4. Discussion

The OFDR beat frequency is linearly proportional to the time delay ($t$). The beat point frequency can be used to locate the measurement point with high accuracy. Therefore, OFDR has high requirements for the frequency linearity of the sweep frequency source. The optical frequency of the actual sweep frequency light source changes nonlinearly with time. At present, software methods are mainly used to compensate for the nonlinear effect of the light source such as the non-uniform fast Fourier transform method (NUFFT), the one-dimensional interpolation method, and the dechirp filter algorithm. The compensation process is shown in the Figure 22.

The NUFFT method transforms the data from a non-uniform grid to a uniform grid (Duijndam and Schonewille 1999). The primary function of the NUFFT method is to compensate for the nonlinearity of the light source and to obtain instantaneous optical frequency information of the sweep frequency light source from the sub-interferometer. The specific process is to obtain the beat frequency signal with time delay information from the sub-interferometer and to obtain the instantaneous optical frequency $\nu(t)$ after use of a Hilbert transform to normalize and discretize the instantaneous optical frequency to obtain $\nu n$. The NUFFT method is then used to calculate the distance domain information. This method mainly uses the convolutional
property of the Fourier transform (e.g., the Fourier transform of the convolution of two functions is equal to the product of the respective Fourier transforms of the two functions) to perform the deconvolution operation, as shown in Eq. (2) (Fessler 2007).

\[ X(z_n) = \frac{X_G(z_n)}{W(z_n)} \tag{2} \]

In Equation (2), \(W(z_n)\) is the Fourier transform of a Gaussian function \(W(\nu n)\). Similarly, LabVIEW software is used to simulate Equation (1) to verify the compensating effect of the NUFFT method. The parameter setting is the same as that for the one-dimensional interpolation method discussed in Section 3. During the simulation process, \(I(t)\) needs to be discretized while considering the size of the nonlinear effect.

1. When the short-distance measurement is in the range 0–40 m, the nonlinear frequency sweep effect of the light source becomes larger without compensation as shown in Figure 23(a). When the NUFFT method is used for compensation, Figure 23(b) shows that broadening phenomenon of the reflection peak owing to the nonlinear effect is greatly improved and there is a significant reflection peak at 20.55 m. Therefore, under short-range measurement conditions, the NUFFT method can effectively compensate for the nonlinear frequency sweep effect of the light source and improve the spatial resolution of the system.

2. When the measurement distance increases to 80 m, a comparison of Figure 23(a) and Figure 24(a) shows that the width of the broadened reflection peak (with no compensation) further increases, indicating that when the measurement distance increases, the linear effect grows stronger. Figure 24(b) shows the result after NUFFT compensation. It can be seen that NUFFT effectively eliminates the phase noise of the light source and can clearly distinguish a strong reflection point around 61.65 m.

However, Figure 24(b) shows that the light source signal exhibits drastically changing noise after 76 m that may indicate the need for deconvolution when performing NUFFT operations. As shown in Figure 25, the Gaussian function spectrum \(W(z_n)\) is the dividend in Equation (2) which shows a good concentration. Therefore, its value is small and is close to zero at long distances (e.g., after 76 m) and the divisor...
Figure 23. NUFFT method to compensate for the nonlinearity of the light source under short-range measurement conditions: $A_n = 5 \times 10^6$, $f_n = 25 \text{Hz}$, and $\tau = 4 \times 10^{-7} \text{s}$. (a) distance domain signal of the main interferometer without compensation; (b) distance domain signal of the main interferometer after compensation.

Figure 24. NUFFT method to compensate for light source nonlinearity under longer-distance conditions (a) distance domain signal of the main interferometer without compensation; (b) distance domain signal of the main interferometer after compensation.

Figure 25. The form of the Gaussian function distance domain in the NUFFT.
XG(zn) in Equation (2) is also close to zero at this distance. When two extremely small numbers are divided, this operation may cause major errors and even exceed the actual nonlinear phase noise.

Similarly, the NUFFT method is used to compensate for the single and double reflection points. From the simulation results, we know that within a short measurement range (generally no greater than 40 m), the main interferometer shows a narrow reflection peak in the distance domain signal, which means the system spatial resolution has greatly improved. However, when the measurement distance exceeds 40 m, two minimal vectors, W(zn) and XG(zn), will occur for division when the NUFFT is deconvolved. There will be side-lobes around the reflection peak indicating that the phase noise has not been completely eliminated; therefore, using the NUFFT method for light source compensation will generate larger errors and risks in the long-distance measurements.

Both the NUFFT and one-dimensional interpolation algorithms are resampling methods. These methods can achieve high spatial resolution for measurements over short distances. However, when the test distance increases, the difference between the test point delay on the main interferometer and the auxiliary interferometer delay becomes too large. Compared with the dechirp filter algorithm, the compensation effect is not as effective. When using the dechirp filter algorithm, the spatial resolution cannot be as high as when using resampling at short distances. Therefore, a compensation method combining a resampling method and de-slope filtering algorithm should be studied in the future work to improve the nonlinear compensation effects for the OFDR light source that can achieve higher spatial resolutions for both short and long-distance measurements.

5. Conclusions
This paper proposes a quasi-distributed thrust measurement system based on OFDR. In order to accomplish quasi-distributed monitoring with characteristics of long measurement distances, high spatial resolutions/sensitivities and rapid responses, the system combines an optical fiber stress sensor based on the optical micro-bending effect and the OFDR demodulator owning high-resolution and high-precision. At last, it also has successful engineering application on a landslide in the Three Gorges Dam area. This measurement system is a new method for internal stress testing of rock and soil mass, which can be implemented to such safety-related monitoring fields like unstable slopes, slope engineering and hydropower dams with a great practical value and application prospects.

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Data availability statement
The data that support the findings of this study are available from the corresponding author, Yimin Liu, upon reasonable request.

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