Evaluation and research of comprehensive seismic observation technology based on optical fiber sensing

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Abstract
As one of the most important methods in geophysical exploration, seismic exploration is widely used in geological resource exploration, geological disaster early warning, and other fields. Existing seismic exploration instruments mostly use electromechanical geophones for sensing, and electromechanical geophones are point sensors. In oil and gas exploration and natural seismic monitoring, point sensors must be arrayed to ensure the continuity of the seismic wave distribution. There are problems such as difficult deployment and long-term maintenance, and its detection capacity and density are also limited by cost. Optical fiber is both a sensor and a transmission medium. A large number of sensor arrays can be realized by using optical fiber. In exploration applications, only one optical cable needs to be deployed or the existing communication optical cable is directly used, which is relatively low in difficulty and cost. Under the premise of ensuring high-level data and high-density acquisition, it can still achieve a detection length of tens of kilometers, which has important potential application value in the field of seismic exploration where exploration targets are increasingly deep and refined. The seismic prospecting instrument participated in a ground fissure state monitoring test based on an active source in a certain area. In the test, the existing buried and underground fiber optic cables were used to successfully monitor the seismic waves, and the monitoring track spacing reached 4 m; the output waveform that is consistent with the existing geophones is obtained, which shows a higher sensitivity than the existing geophones.

Keywords Optical fiber sensing · Earthquake · Comprehensive observation · Evaluation research

Introduction
Since the reform and opening up, China's economy has developed rapidly and industrialization has been accelerating. The rapid development has not only improved people’s living conditions, but has also generated huge energy demand. The domestic oil and gas resource output is far from being able to meet energy consumption needs. In the context of the current trade war, the issue of energy security cannot be ignored. On the other hand, China is located between the Pacific Rim seismic belt and the Eurasian seismic belt. It is compressed by the Indian plate, the Pacific plate, and the Philippine Sea plate, and geological changes are very active. Seismic activity in China is characterized by shallow focus, high intensity, wide distribution, and high frequency. The earthquake is the deadliest natural disaster in China. In seismic exploration, artificial seismic sources or natural earthquakes are used to generate seismic waves (Barton and Choubey 1977). Seismic waves will be reflected and refracted when they encounter formation interfaces of various properties. In underground and water wells, by using the geophone to receive seismic waves, processing and inverting them, the underground geological structure can be estimated (Chiu et al. 2013). It is widely used in geological resource exploration, regional geological research, crustal research, etc. It also plays an important role in early warning of geological disasters (Coll and Lambert 2014). The seismic detection system consists of a geophone and a seismograph. Geophones are sensors for seismic exploration, which convert seismic waves into electrical or optical signals (Deere et al. 1966). This is the first link to
obtain very important data in seismic exploration. The seismic instrument amplifies and records the seismic signal output by the geophone. Divided by the way the geophone is deployed, the seismic observation method can be divided into the ground seismic section method and the vertical seismic section method (Huang et al. 2014). The ground seismic profile method deploys geophones on the surface and makes observations at the geophone points arranged along the ground survey line; in the vertical seismic survey method, a siphon is configured in the well, and detection points of different depths are used along the side of the well. In the seismic curve method, the difficulty of equipping the geophone is relatively low, and the seismic wave measurement range is very wide (Ivars et al. 2011). In the vertical seismic section method, since the geophone is placed downhole, the geophone is closer to the target layer, which avoids near-surface and environmental interference, and can obtain seismic exploration data with higher signal-to-noise ratio, resolution, and fidelity (Lee et al. 2004). At present, the major foreign DAS manufacturers do not sell instruments to China, but only provide testing services (Patton 1966). The domestic DAS equipment is mainly oriented to perimeter security, structural health monitoring, and other fields, and its combination with seismic exploration is not mature. Its frequency response range and other indicators cannot meet the needs of seismic exploration (Shen and Zhu 2004). There are also low integration levels and immature supporting software. The real-time calculation and display capabilities of seismic data are insufficient (Singh and Basu 2016). This article summarizes the development of optical fiber sensing technology and optical fiber ultrasonic sensing technology, and discusses the basic principles and methods of interferometer optical fiber sensors, which will be helpful to China’s seismic observation (Wang et al. 2018).

Materials and methods

Seismic observation site design

Since 2010, the Geotechnical Research Center has deployed a number of strain-sensing optical cables in the earthquake zone for monitoring the development of ground fissures and ground subsidence. The fiber optic cable layout methods include drilling optical horizontal and trench horizontal burying. The vertical drilling is located at Zhengjiatang, Guangming Village, Xibei Town, W City, with a depth of 145 m. There is a 140-m long metal base in the hole, cable-shaped fiber optic cable, and 10-m fixed-point single-core fiber optic cable with a length of 65 m. The fiber optic cable layout of the vertical borehole is shown in Fig. 1.

From Table 1, the horizontal groove starts from point A in the figure and point B as the end point, and the total length is 174 m. It uses the method of excavating the trench and backfilling to lay the optical cable. There are three types of optical cables in the trench: metal base cable, 3-m fixed-point optical cable, and GFRP-reinforced strain optical cable.

It can be seen from Fig. 2 that this field test will use the metal-based cable-shaped cable in the vertical drilling and horizontal grooves as the sensor cable for testing. The structure of the metal-based cable-shaped cable is shown in Fig. 2, with a diameter of 5 mm. The sheath and the optical fiber are protected by metal reinforcing ribs.

Analysis of the mechanical model of optical fiber sensing

When the vibrating subsystem is subjected to external vibration, the external force will act on the shock vibrator. The relationship between external force and acceleration is as follows:

\[ F = \frac{Ma}{l} = 2K_m l + 4K_i l \]  

Here, \( K_m \) is the stiffness coefficient of deformation caused by the force in the axial direction, and \( K_i \) is the stiffness coefficient of deformation caused by the force in the radial direction.

\[ M_a = 2C \pi \lambda K_m \]  

\( C \) is the limiting factor, \( C > 1 \); this is because a suitable deformed cylinder will produce a slight energy loss when it is subjected to radial distortion and tilt caused by radial vibration.

Due to the change in the length of the attached cylinder, the phase change of the optical fiber is as follows:

\[ \delta \varphi = \frac{2\pi n}{\lambda} \times \delta L \]  

Among them, \( N \) is the refractive index of the fiber core, \( L \) is the length of the fiber, and \( \lambda \) is the light wavelength of the fiber. Considering the volume invariance of the cylinder, there are

\[ \delta L = N \pi \delta D = \frac{N \pi D}{2h} \times \delta h \]  

According to the formula, there are

\[ Na = 2CK_m \delta h \]  

Therefore, \( \delta L = \frac{N \pi DM_a}{4hCK_m} \) the acceleration sensitivity is \( \delta \varphi / \alpha = \frac{2\pi n \lambda M}{\lambda CK_m} \)

As shown in Fig. 3, in fact, the cylinder is a converter, and its volume incompressibility causes the distortion in the axial direction to be transmitted in the radial direction. By tightening the optical fiber wound on the cylinder, its length changes.

As shown in Fig. 4, the cylinder will bend or tilt due to the stress in the radial direction. At this time, with the slight change in the height of the cylinder, due to the invariant...
volume, its cross-sectional area hardly changes, so the diameter hardly changes.

**Experimental plan design**

It can be seen from Fig. 5 that at a height of 1 m, a heavy hammer is used to hit the ground around the vertical borehole 5 times, and the response of the seismic prospecting instrument is obtained. The position at 0 m is the position of the borehole, and the horizontal axis is the corresponding length of the optical fiber below the surface. The vertical axis is time; the line parallel to the time axis represents the seismic trace at that location, and the fluctuation degree of the corresponding line of the seismic trace on the distance axis represents the intensity of the vibration monitored by the trace. It can be observed from the figure that at 5 s, the heavy hammer hits for the first time, and then hits every 4.5 s, for a total of 5 hits. As the depth increases, the seismic wave gradually weakens. The seismic wave generated by a heavy hammer hitting at a height of 1 m has an obvious response at the 10th seismic track, which is 36 m below the ground.

**Results**

Calibration of seismic exploration instrument parameters based on optical fiber sensing

It can be seen from Fig. 6 that after the structure of the seismic prospecting instrument is designed and packaged, the whole machine parameter calibration test is carried out to ensure that its performance parameters meet the design requirements. The whole machine parameter calibration test includes detection distance test, spatial resolution test, frequency response range test, minimum detectable strain test, and vertical response distance test. The detection distance test structure of the seismic prospecting instrument is shown in Fig. 6. Connect 60-km optical fiber, 10-m optical fiber patch cord, and 2-km optical fiber to the detection optical output port of the prospecting instrument in sequence. The test method is to continuously tap the 10-m optical fiber patch cord, and observe the response in the supporting software. The test parameters are pulse width.

| Table 1 | Drilling hole backfilling material reloading table |
|---------|--------------------------------------------------|
| Backfill materials | Backfill dept/m | Backfill/m³ |
| Clay | 0–49 | 1.5 |
| Sand | 49–62 | 0.3 |
| Clay | 62–80 | 0.4 |
| Sand | 80–95 | 0.3 |
| Clay | 95–147 | 1.3 |

**Fig. 2** Metal base cable-like optical cable structure
of 200 ns, repetition frequency of 1 kHz, and measurement length of 65 km.

It can be seen from Fig. 7 that there is an obvious continuous response at 60 km in the waterfall diagram, and the obvious change in the phase of the scattered light can be seen from the corresponding position in the time domain, that is, the seismic prospecting instrument can still respond to vibration within the fiber length of 60 km. Therefore, the detection distance of the seismic prospecting instrument is greater than 60 km.

As shown in Fig. 8, the spatial resolution refers to the minimum distance between two disturbance positions that the DAS can distinguish in space, and is usually defined as the full width at half maximum of the vibration peak of a single-point vibration event. The test structure diagram of the spatial resolution of the seismic prospecting instrument. Connect 500-m optical fiber, 4 m-optical fiber patch cord, and 500-m optical fiber to the detection optical output port of the prospecting instrument. The test parameters are pulse width of 20 ns, and repetition frequency of 1 kHz. The measuring length is 1 km.

It can be seen from Fig. 9 that in the first test, only the position of point 1 in Fig. 4 was tapped, and the vibration peak excited by this tap was obtained. The full width at half maximum of the single-point vibration peak was 4 m. In the second test, tap the positions of points 1 and 2 in Fig. 4 at the same time to obtain the vibration peaks excited by this tap. The two vibrations at a distance of 4 m in space are reflected in the figure as two vibration peaks with a spacing of 4 m. The full width at half maximum of the single-point vibration peak of the seismic prospecting instrument is 4 m, and it can distinguish two vibrations occurring at the same time with a distance of 4 m in space, indicating that the spatial resolution can reach 4 m.

It can be seen from Fig. 10 that PZT is a material that uses the piezoelectric effect to convert electrical and mechanical energy. There are two types of piezoelectric effects. One is the positive piezoelectric effect that the surface of the medium is charged when the force is deformed. The other is the deformation of the medium due to the excitation electric field, which is the inverse piezoelectric effect. In this experiment, the inverse piezoelectric effect of the PZT is used to wind about 40 m of optical fiber on the PZT, and a sine wave signal of a specific amplitude and frequency is applied to the PZT through a function generator. PZT is excited by the electric field of a sinusoidal signal to produce vibrations of the same frequency, and transmits this vibration to the optical fiber wound on its surface, so that the optical fiber also vibrates at the same frequency. The test method of the frequency response range is to adjust the frequency of the sine signal output by the function generator, demodulate the phase information of the scattered light at the position of the optical fiber on the PZT, and perform spectrum analysis. When the function generator outputs a sine signal at 500 Hz, the frequency spectrum of the corresponding position of the PZT has an obvious response at 500 Hz. Figure 10 is the frequency spectrum of the corresponding position of the PZT when the output sine signal of the function generator is 500 Hz, and there is an obvious response at 500 Hz.

As shown in Fig. 11, the vertical response distance of a DAS-based seismic prospecting instrument refers to the distance from the optical fiber to the vibration source that occurs
in the radial direction of the sensing fiber that the prospecting instrument can respond to. The vertical response distance can reflect the minimum detectable strain and sensitivity of the seismic prospecting instrument, but in addition, it is also related to factors such as fiber optic cable type, layout method, vibration source strength, vibration propagation medium, environmental noise, and signal processing algorithm. The use of fragile bare fiber or tight-buffered optical fiber sensing has a significant improvement in the vertical response distance, but a tougher fiber optic cable is more suitable in complex practical application environments. In practical applications, due to various conditions and external factors, the types of optical cables, laying methods, and vibration propagation media are different. Therefore, the vertical response distance of the same seismic prospecting instrument under different conditions is also different. When the function generator outputs a sine signal of 0.1 Hz, the spectrogram of the corresponding position of the PZT has the highest peak at 0.1 Hz on the spectrogram. The test parameters are pulse width of 50 ns, repetition frequency of 1 kHz, and measurement length of 1 km. The above two sets of experiments show that the lowest response frequency of the seismic prospecting instrument is less than or equal to 0.1 Hz, and the highest response frequency is more than or equal to 500 Hz.

**Analysis of comprehensive seismic observation results**

It can be seen from Fig. 12 that as the depth increases, the seismic wave gradually weakens. The deepest seismic wave generated by hitting with a heavy hammer at a height of 1 m has an obvious response at the 10th seismic track, which is 36 m below the ground.

It can be seen from Fig. 13 that according to the slope of the diagonal line formed by the seismic wave propagation in the figure, the propagation velocity of the seismic wave in the soil can be estimated. The two dashed lines in the figure mark the time for the seismic wave to propagate from the ground to the 9th (32 m) and 19th (72 m) channels, which are 39.25 s and 39.5 s, respectively. Therefore, the seismic wave in the direction perpendicular to the ground can be estimated. The propagation speed is approximately \((72 - 32)/(39.5 - 39.25) = 160\) m/s. In response to a single impact of a heavy hammer with a height of 2 m on the ground around the vertical borehole, the seismic waves generated from the ground are continuously reflected at a depth of about 30 m in the shallow underground and lasted for a long time. Below 30-m underground, the propagation of seismic waves in the soil forms a diagonal line on the time-space map. It can be observed from the figure that...
the response of the exploration instrument is more obvious within 80-m depth, and the response is obviously weakened below 80-m depth. However, it can be seen from the straight line fluctuations of the seismic trace in the solid line box that at a depth of 100 m from the borehole, the seismic prospecting instrument still has a weak response.

It can be seen from Fig. 14 that when a heavy hammer hits the ground around the horizontal trench at a height of 2 m, the responses shown in Fig. 14a, b can be obtained. Figure 14a is a waterfall diagram; the horizontal axis is the corresponding length of the fiber under the groove; the vertical axis is time, and the chromaticity represents the vibration strength of the corresponding length and time. Since the smashing point is located in the horizontal center of the groove, the seismic wave generated by the smashing is centered on the length corresponding to the smashing point, and two symmetrical diagonal lines are formed on the two time-space maps (marked with red lines in the figure). This oblique line is similar to the oblique line formed in the vertical borehole test, which reflects the propagation of seismic waves in the horizontal direction and the direction perpendicular to the ground, respectively. According to Fig. 14b, the time for the seismic wave to propagate to the 23rd channel (88 m) and 32nd channel (124 m) are respectively 19.12 s and 19.3 s, so the seismic wave propagation velocity in the horizontal direction of the ground can be estimated as (124–88)/(19.3–19.12)=156.5 m/s; the estimated seismic wave propagation velocity in the two directions is basically the same. After obtaining the seismic wave propagation velocity in the soil, if the active source, that is, the vertical distance between the impact point and the sensor cable in this article, changes, the active source and the seismic wave propagation velocity can also be calculated based on the slope of the seismic wave formed in the time-space map, the vertical distance of the sensor cable. In the ground fissure evolution-monitoring test, artificial smashing at a height of 2 m was used as the active source, and vibration was applied to the total length of the horizontal trench of 174 m at intervals of 10 m. DAS was used to observe and continuously record data in real time. The seismic travel time analysis conducted by the cooperative unit using DAS-recorded data can well reflect the propagation process of artificial seismic wave signals in the formation and calculate the evolution state of the ground fissure.
It can be seen from Fig. 15 that in addition to DAS, electromechanical geophones were deployed at some nodes of the horizontal groove in this test, and DAS data was used as a reference for each other. Due to cost constraints, only three electromechanical geophones were deployed in the experiment, with a track spacing of about 80 m, while DAS used existing buried optical cables to achieve a track spacing of 4 m.

It can be seen from Fig. 16 that the output waveforms of the traditional geophone and DAS after the heavy hammer hits the ground are in good agreement, and DAS is more sensitive and can capture weak signals before and after the arrival of seismic waves.

**Discussion**

**Distributed sound field sensing technology**

Sound is a very important information carrier. Its essence is a vibration wave, which has two important characteristics: intensity and frequency. After a vibration event occurs, the vibration wave emitted by the vibration event will propagate in the sound field, affecting the optical fiber for sensing, and the various characteristics of the optical fiber will also change. DAS perceives the intensity and frequency of the sound field through changes in the characteristics of the optical fiber. This is very consistent with the requirements of seismic exploration.

Scattering and optical time domain reflection technology in optical fiber

Optical fiber has Rayleigh scattering, Brion scattering, and Raman scattering. Among them, Rayleigh scattering is a process of elastic scattering and linear collision. Just change the propagation direction of the photon, it will not change the energy of the photon. Therefore, the frequency of Rayleigh-scattered light is the same as that of incident light. Brion scattering and Raman scattering are inelastic scatterings. Inelastic scattering is the result of the interaction of photons and phonons, which changes the energy of the photons, resulting in a frequency shift of the scattered light relative to the incident light. Brion scattering is produced by the interaction of photons and acoustic phonons, and the frequency shift of Brion is 9–11 GHz. Raman scattering is caused by the interaction of photons and optical phonons, and the Raman frequency shifts by about 13.2 THz, scattering spectra of three kinds of scattered light. The power of the RBS signals is proportional to the power of the incident-pulsed light.
The loss of light during the propagation of the optical fiber causes the incident light to gradually attenuate, and it also causes the RBS signal to gradually attenuate. The RBS signal generated along the optical fiber is received by a photodetector, and the RBS power information at any position along the line can be obtained; by calculating the time difference between the RBS signal returning to the incident end, the corresponding relationship between the power information and the position information of the scattering point can be obtained. This is the most mature optical time domain reflectometer used in distributed optical fiber sensing.

Distributed acoustic field sensing technology based on backscattered light

DAS is based on the principle of OTDR. By injecting probe light pulses into the optical fiber, scattered light at various positions in the middle can be obtained. According to the change in the phase of the scattered light, the sound field can be monitored. According to Raman optical time-domain reflectometry (ROTDR), Raman optical time domain reflectometry (ROTDR) is a very mature distributed temperature-sensing method due to its high temperature sensitivity to backscattered light. However, because Raman scattering is not easily affected by distortion and vibration, it is not suitable for distributed sound field sensing. The continuous light output from the laser is divided into two methods: one is modulated by pulsed light and incident on the sensing fiber. In contrast to the scattered light in the self-radiation returning to the rear, it enters the photodetector through the coupler. By detecting the frequency and intensity of Brian-scattered light, temperature and distortion can be measured. BOTDA is used
to monitor and sense Brian-scattered light. The continuous light radiated from the laser light 1 is pulse-modulated by the optical fiber. The laser 2 on the other side of the optical fiber emits continuous light, and the two light beams are transmitted to each other in the optical fiber. If the frequency difference between the two beams is the Brion frequency shift in the optical fiber, the energy of the continuous beam is transmitted to the pulsed light, and the pulsed light is amplified. By adjusting the frequency difference of the two beams of light and monitoring the power of the backscattered light by the laser frequency sweep, the Brillouin frequency shift distribution along the fiber can be obtained, thereby realizing the measurement of temperature and strain. Compared with other types of DAS technology, there is no obvious advantage in the monitoring of small strain. Therefore, the lower dynamic frequency measurement range and strain resolution of BOTDR/A are difficult to meet the requirements of sound field sensing. Based on the distributed acoustic field sensing technology of the Rayleigh scattering phase sensing optical time-domain reflectometer, vibration is used to detect the phase change of the optical sensor. The narrow linewidth laser is used as the narrow linewidth laser pulse light of the optical fiber. Strong coherent light pulses, pulses interfering with post-Rayleigh-scattered light generated in the optical fiber, have obvious coherent effects. When the perturbation is applied to the fiber, it will cause the phase change of the backscattered light, and the interference signal will change significantly. By demodulating the interference signal, the phase and amplitude of the scattered light along the optical fiber can be obtained, and the vibration at any position along the optical fiber can be monitored.

### Propagation of ultrasonic waves in the medium

It can be seen from Table 2 that in the same solid medium, the propagation velocity from high to low is longitudinal wave, transverse wave, and surface wave. In actual ultrasonic testing, the performance of supersonic speed becomes more complicated due to the influence of echo on the contour of the detected object. Density, speed of sound, acoustic impedance, etc., summarize the basic parameters of solid materials generally used at room temperature.

As shown in Table 3, the speed of sound is at various temperatures in water. It can be known that the speed of sound at a temperature near 70 °C is the largest. In the case of insufficient temperature of 70 °C, the speed of sound in the water will increase with temperature. The speed of sound in water at a temperature of 70 °C decreases as the temperature rises. Optimizations and post-data processing of ultrasonic detection system

As shown in Table 4, in ultrasonic testing, in order to reduce the energy loss after ultrasonic intrusion into the measurement object, a layer of sound transmission medium can be coated on the surface to improve the sound transmission ability of ultrasonic waves, the measurement object (i.e., coupling agent). Couplings can not only eliminate the air between the detection and measuring instruments. Not only the object to be measured, but also the transmission of ultrasonic waves can be improved, and the friction between the detection and measurement objects can be reduced. Generally speaking, the main factors that affect the efficiency of acoustic coupling are the type and thickness of the coupling agent, the roughness of the measuring surface, and the shape of the measuring surface.
Generally speaking, the choice of coupling agent requires high acoustic impedance and excellent transmission performance, does not corrode, is harmless and does not pollute the environment, penetrates into objects and detection surfaces, have moderate fluidity, viscosity, and adhesion, is easy to clean, has stable performance, and is not easy to deteriorate, etc. Commonly used coupling agents are glycerin, water, oil, transformer oil, chemical paste, and so on.

**Evaluation of comprehensive seismic observation technology**

Seismic exploration is one of the most effective methods for detecting geological structures inside the earth, and it is widely used in the fields of geological resource exploration and geological disaster early warning. Among the distributed optical fiber sensing technologies, DAS has high sensitivity to sound field/vibration, strong multi-point measurement capability, accurate disturbance positioning, and measurement frequency bandwidth, which best meet the requirements of seismic exploration. Major foreign DAS brands do not sell equipment to China, and the combination of domestic DAS equipment and seismic exploration is not mature, and there are still a series of problems: some performance parameters cannot meet the needs of seismic exploration; the system has many separate components, resulting in widespread equipment volume, larger, poor portability, and reliability; the acquisition and processing of massive sensor signals have higher requirements on the data acquisition card and processor of the DAS equipment, which cause the equipment cost to increase sharply; the supporting software is immature, and the seismic exploration data is not mature; and insufficient real-time computing and

![Image](image_url)

**Fig. 14** The response of a single heavy hammer hitting the ground around a horizontal trench at a height of 2 m. (a) Waterfall diagram. (b) Seismic wave interface.
display capabilities, etc. In order to solve the above problems, this article will investigate the research situation of seismic exploration and DAS at home and abroad, explain the working principle of DAS in detail, and analyze the current mainstream structure and signal demodulation method of DAS. The optical structure design optimized and verified the parameters of each equipment, and the equipment selection was completed. Based on this, the following main results were obtained.

The design and manufacturing technology of high-performance seismic exploration instrument system based on DAS is proposed. The system functions are divided, and the seismic survey instrument system is designed as a whole based on the PXIe standard (Yang et al. 2001). The integration scheme of the optical board and the control and signal conditioning board under the system design is proposed, through special treatment of its power supply and optical fiber interconnection. Under the premise of ensuring its volume
advantages, it can effectively enhance its anti-electromagnetic interference and anti-vibration performance, and avoid the performance degradation of the exploration instrument caused by the external environment (Zhang et al. 2019).

The data acquisition technology of under-sampling is proposed. According to Shannon’s band-pass sampling theorem, the data acquisition card receiving parameters are reasonably configured, and the signal with the DAS intermediate frequency of 200 MHz is transferred to 50 MHz on the spectrum without loss of performance, which greatly reduces the system’s sampling rate of the acquisition card (Zhao et al. 2012). Requiring and avoiding 1/f noise significantly reduce system cost and subsequent data processing pressure.

A real-time display interface optimization method for seismic exploration is proposed. On the basis of the waterfall chart, time domain, and spectrum chart commonly used in DAS, a real-time seismic waveform display interface dedicated to seismic exploration has been added, making it more advantageous in displaying ms-level instantaneous disturbances; and in the physical meaning of the form and curve, the above is closer to the waveform interface of the existing seismic exploration data (Zhao et al. 2015a).

A prototype of a high-performance seismic exploration instrument based on DAS was completed, and the parameter calibration showed that all parameters of the seismic exploration instrument reached the design goals (Zhao et al. 2015b). The seismic prospecting instrument participated in the ground fissure monitoring active source test conducted in Guangming Village, Xibei Town, W City. In the test, both underground and underground optical cables were used to successfully monitor seismic waves and obtained the same level as existing cables (Zheng et al. 2020). The results of the data that are consistent with the exploration instruments and the collected data have well reflected the evolution of the local ground fissures after inversion.

**Conclusion**

The use of optical fiber sensors to observe the precursors of earthquakes is a new method of earthquake monitoring with unique advantages. The optical fiber sensor has a series of unique advantages such as high precision, anti-electromagnetic interference, no zero drift, simple network connection, and suitable for long-distance transmission. It can solve the inherent problems of electrical measuring instruments in the observation of earthquake precursors. This article introduces the working principles and characteristics of several types of optical fiber sensors, summarizes the two application areas of crustal movement observation and seismic wave detection, the progress of optical fiber sensor research, and points out the problems that need to be solved at present. On this basis, a series of multi-parameter borehole comprehensive seismic observation devices based on optical fiber sensors have been developed to simultaneously measure borehole comprehensive strain, seismic waves, and ground temperature. Field experiments have shown that the borehole comprehensive seismic observation instrument can be used before the earthquake. Seismology is the field of observation, and seismic observation technology is an important research content of seismology. Various abnormal phenomena related to the occurrence of earthquakes (earthquake precursors) are closely related to earthquakes. In order to promote the development of seismology and deepen the understanding of the earth, it is beneficial to use high-level observation instruments to obtain accurate data about earthquake precursors. The development of seismology

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**Table 2** Density, sound velocity, and acoustic impedance of solid materials commonly used at room temperature

| Species      | Density | Poisson’s ratio | Longitudinal wave speed | Transverse wave speed of sound | Surface wave speed of sound |
|--------------|---------|-----------------|-------------------------|-------------------------------|-----------------------------|
| Aluminum     | 2.7     | 0.3             | 6266                    | 5040                          | 3080                        |
| Iron         | 7.7     | 0.2             | 5859–5900               | 5180                          | 3230                        |
| Cast iron    | 6.9–7.3 | --              | 3500–5600               | --                            | 2200–3200                   |
| Steel        | 7.7     | 0.2             | 5880–599-               | --                            | 3230                        |
| Copper       | 8.9     | 0.3             | 4700                    | 3710                          | 2260                        |
| Lead         | 11.1    | 0.4             | 2100                    | 1200                          | 700                         |
| Stainless steel | 7.67 | --              | 7390                    | --                            | 2900                        |

**Table 3** Sound velocity in water at different temperatures

| Temperature/°C | 10  | 20  | 25  | 30  | 40  | 50  | 60  | 70  | 80  |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Sound speed C/(m/s) | 1449 | 1486 | 1438 | 1551 | 1555 | 1554 | 1553 | 1556 | 1557 |
shows that new observation methods and new research concepts play an important or decisive role in the development of earthquake prediction science. Due to the emergence of digital seismometers, the research of seismology has made great progress, but nowadays, electrical measurement methods are widely used in seismic precursor observation instruments (strain gauges, fault creep gauges, potentiometers, inclinometers, etc.). In practical application, it is difficult to eliminate zero drift, easy to be interfered by the electromagnetic environment, low sensitivity, small dynamic range, leakage, thunder danger, difficulty in connecting the power supply, relatively easy to break, and many other problems, which limit the earthquake precursor observation technology development.

Declarations

Conflict of interest  The authors declare no competing interests.

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Table 4  Performance and characteristics of couplant commonly used in ultrasonic testing

| Coupling agent       | Acoustic impedance | Features                                      |
|----------------------|--------------------|-----------------------------------------------|
| Water                | 1.5                | Wide source, low price, easy to make the tested object rust, often use water immersion method |
| Engine oil Transformer oil | 1.2 0.12           | Appropriate viscosity and adhesion, good fluidity, and the most widely applicable |
| Chemical paste       | --                 | The best coupling effect, solid state, must be diluted with water before use |

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