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Research on the feasibility of distributed vibration sensing technology for leakage detection in diaphragm wall joint

Lingyan Zhou[1], Mingyin Chen[2]* and Yayong Zhang[1]

[1]Suzhou Rail Transit Construction Co., Ltd., Suzhou, Jiangsu, China, [2]Suzhou NanZee Sensing Technology Co., Ltd., Suzhou, Jiangsu, China

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EDITED BY
Rubin Wang,
Hohai University, China

REVIEWED BY
Mengya Sun,
Hohai University, China
Mengfen Shen,
Zhejiang University of Technology, China

*CORRESPONDENCE
Mingyin Chen,
✉ 920666220@qq.com

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The integrity of diaphragm walls is of paramount importance to the safety of foundation pits; leakage can readily induce issues such as instability and heave, necessitating efficient and precise detection. This study conductsl aboratory model tests based on Distributed Acoustic Sensing (DAS) technology to investigate the applicability of active and passive methods in leakage identification, as well as the effects of leakage magnitude, sensing optical cable layout positions, and boundary conditions. The results indicate that DAS can effectively identify leakage through acoustic vibration characteristics: the passive method exhibits distinct leakage characteristic signals at 10.25 Hz and 20.25 Hz, with leakage velocity showing a linear positive correlation with peak amplitude; the active method identifies leakage via an external vibration source, and when the spacing between the sensing optical cable and the leakage channel exceeds 50 cm or the channel depth is less than 5 cm, signal attenuation occurs and distinguishability decreases. This study validates the feasibility of DAS technology, providing a scientific basis for real-time distributed leakage detection in foundation pit engineering.

KEYWORDS

distributed acoustic sensing technology, diaphragm wall, leakage detection, passivemethod, active method

1 Introduction

The diaphragm wall is the core structure of foundation pit support, undertaking key functions such as load-bearing, water cutoff, and leakage prevention [1]. Due to its convenient construction and high cost-effectiveness, this technology is widely applied in various underground projects [2]. However, with the increasing national requirements for the construction safety of infrastructure projects, the quality inspection of diaphragm walls has become particularly crucial. Especially in complex environments such as soft soil areas and regions close to rivers, lakes, and seas, diaphragm wall leakage issue during foundation pit construction have emerged as pressing technical challenges to be addressed [3]. The diaphragm wall joints are the primary weak link for groundwater leakage. Once leakage occurs, it may trigger water or sand gushing during foundation pit excavation, increasing construction difficulties and even leading to serious safety accidents. Therefore, efficient and accurate diaphragm wall joint leakage detection technology is of great significance for ensuring the safety of foundation pit construction [4].

In China, research on leakage detection of diaphragm walls is extensive and has yielded numerous achievements. Gao et al. [5] took a diaphragm wall of Harbin Metro Line 3 as an example, applied electrical resistivity tomography technology for leakage detection, detailed the detection process, monitored and comparatively analyzed the leakage situation of the diaphragm wall after earth excavation, and verified the accuracy, rapidity and effectiveness of this method in leakage control. Fang et al. [6] comprehensively employed high-density electrical method, water pressure test, and ground-penetrating radar to successfully identify leakage hazards in the risk elimination and reinforcement project of a core wall dam in a deep canyon area. Bai et al. [7] used ground-penetrating radar technology to detect and analyze the quality of plastic concrete diaphragm walls, providing a scientific basis for the reinforcement of the anti-leakage wall of a plain reservoir and demonstrating good application prospects of this method in diaphragm wall detection. Although these methods can reflect the leakage situation of diaphragm walls to a certain extent, they still have certain limitations: limited detection coverage, low detection efficiency, high cost; limited detection accuracy and high misjudgment for deeper diaphragm walls [8]. Furthermore, most traditional methods struggle to achieve distributed measurement and meet significant challenges in long-term continuous detection. Therefore, further optimizing leakage detection technologies, improving detection accuracy and efficiency, and enhancing long-term detection capabilities will be an important direction for future research.

In recent years, with the development of sensing technology, Distributed Acoustic Sensing (DAS) technology has gradually become an important research direction for leakage detection of diaphragm walls. DAS technology features distributed detection capabilities, enabling comprehensive coverage of the entire diaphragm wall. By detecting micro-acoustic vibrations caused by leakage, it achieves high-sensitivity detection and provides real-time, long-term continuous detection data [9, 10]. This technology adopts a non-intrusive approach that requires no additional drilling or destructive operations, does not affect construction progress, and can adapt to complex environmental conditions [11, 12]. Compared with traditional methods, DAS technology not only improves detection accuracy but also identifies leakage risks earlier, providing more efficient and precise technical support for foundation pit construction safety [13, 14].

This study, based on laboratory model tests and combined with distributed optical fiber sensing technology, adopts a vibration detection method integrating passive and active approaches to explore the identification of diaphragm wall leakage. Focus is placed on analyzing the influence of leakage velocity, the distance between the sensing optical cable layout position and the leakage channel, and changes in the height of the leakage channel on detection applicability and accuracy.

The results of this study can provide a scientific basis and technical support for the health detection of diaphragm walls, and a reference for the future development of safety management and detection technology in underground engineering.

2 Principle of DAS leakage detection in diaphragm wall

DAS technology is a fiber-optic-based distributed sensing technology capable of sensing and analyzing acoustic signals over a continuous spatial range [15]. Its core principle is based on phase-sensitive Optical Time-Domain Reflectometry (ϕ-OTDR). When the optical fiber embedded in the diaphragm wall is subjected to external disturbances, minor changes occur in physical properties such as the refractive index and length of the fiber, which in turn causes changes in the phase and intensity of the backscattered light (RBS) [16], principle of DAS leakage detection is shown in Figure 1. This change can be described by the phase delay formula (Equation 1) [17]:

$$\phi = \frac{4\pi n x}{\lambda} \tag{1}$$

Where ϕ represents the phase difference (rad); n represents the refractive index of the medium (dimensionless); x represents the propagation length of light in the medium (m); λ represents the wavelength of light wave (m).

There exists a linear relationship between the phase change of the sensing channel and the dynamic axial strain caused by vibration, and the specific calculation formula is as follow Equation 2 [18]:

$$\Delta\phi = \frac{4\pi n L_g \psi}{\lambda} \varepsilon_{xx}(x,t) \tag{2}$$

Where l is the effective length of the optical fiber, g is a sensor-related constant, ψ is the sensitivity of the sensor, and $\varepsilon(x,t)$ is the axial strain at position x and time t.

3 Diaphragm wall leakage detection scheme and platform

3.1 Diaphragm wall leakage detection scheme

Figure 2 shows the experimental scheme diagram for leakage detection of diaphragm walls. The figure includes two schemes: passive method and active method. Passive leakage detection passively senses the vibration characteristic signals during leakage through distributed vibration sensing optical cables. The distributed vibration sensing fibers are vertically laid along the excavation side of the diaphragm wall, with installation positions generally selected at locations prone to leakage such as diaphragm wall joints. Data collection is performed using a distributed optical fiber vibration demodulator. Active leakage detection excites vibration signals of fixed frequency at different layers inside the diaphragm wall. It monitors diaphragm wall leakage by evaluating the amplitude and frequency variation characteristics of vibration waves. Distributed vibration sensing optical cables are vertically laid at the joints on the excavation side, and vibration excitation tubes are installed on the other side of the joints for vibration source excitation.

3.2 Test platform

As shown in Figure 3, for passive leakage detection, the dimensions of the diaphragm wall are set to 6 cm × 5 cm × 5 cm

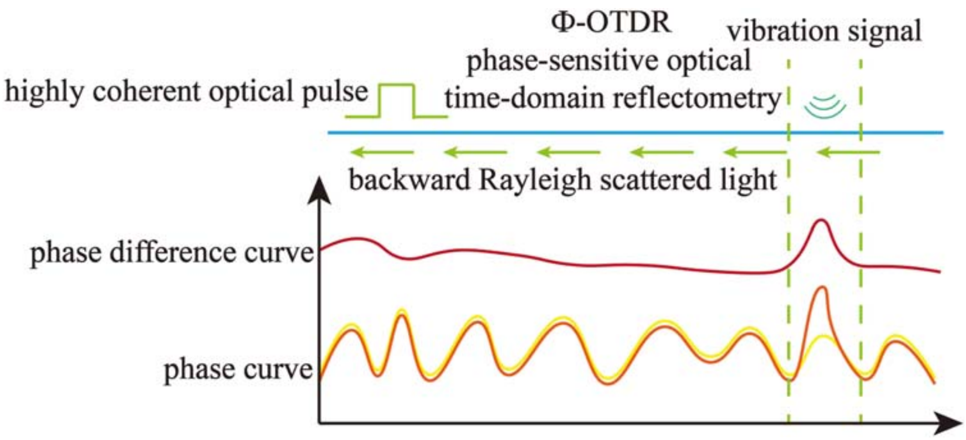

FIGURE 1
Principle of DAS leakage detection.

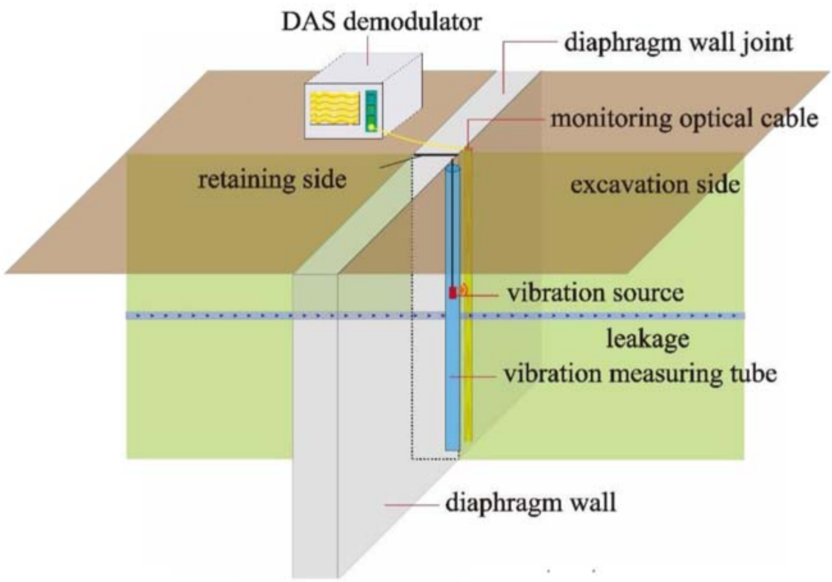

FIGURE 2
Experimental setup.

(length × width × thickness). Both sides of diaphragm wall are filled with fine sand, with a uniformity coefficient Cu = 1.54, and are saturated. A peristaltic pump is used to simulate diaphragm wall leakage, with leakage volume adjusted by regulating the rotation speed. Vibration detection relies on distributed single-mode optical fibers (NZS-DSS-C07), and a distributed optical fiber vibration demodulator (NZS-DAS-A01) is used to collect data. Specifications of sensing optical cables and interrogator are shown in Table 1. Due to the spatial resolution limitations of the demodulator, the sensing optical cable is spirally wound to enhance spatial resolution. The test tool is shown in Figure 4 and the parameters of the spiral sensing optical cable are shown in Table 2. For active leakage detection, the model is basically consistent with active detection. The main difference is that a PVC pipe with a diameter of 7 cm is installed on the opposite side of the leakage point to facilitate the excitation of the vibration source at different heights. The excitation frequency of the vibration source is 100 Hz, which is far from general engineering interference frequencies.

4 Test results and analysis

4.1 Passive vibration detection of diaphragm wall leakage

As shown in Figure 5, the experimental results of passive leakage method are presented. From Figures 5a,b, it can be observed that when leakage occurs in the diaphragm wall, there is a significant

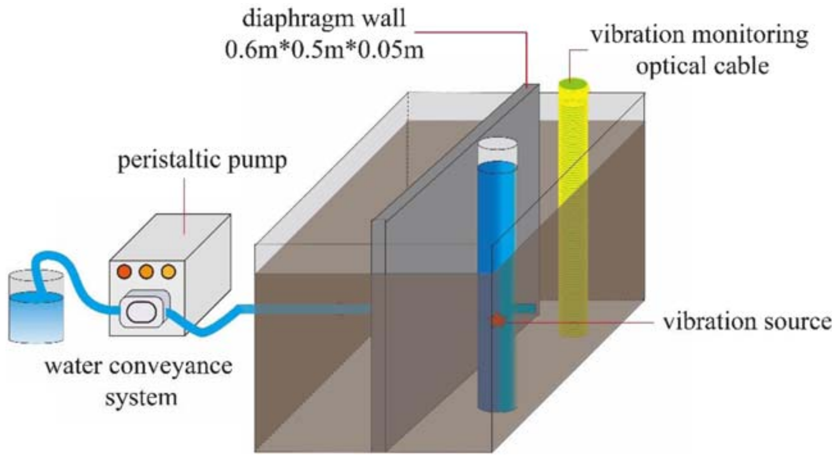

FIGURE 3
Test setup.

TABLE 1 Specifications of sensing optical cables and interrogator.

Item	Parameter
Sensing optical cable type	NZS-DSS-C07 (0.9)
Optical fiber core count	1
Diameter of sensing optical cables	0.9 mm
Work temperature	−20 ℃–80 ℃
Demodulator name	DAS(NZS-DAS-A01)
Detection distance	0–20 km
Maximum spatial resolution	0.5 m
Sampling frequency ($\times 10^3$)	0–50 Hz

TABLE 2 Parameters of the spiral sensing optical cable.

Item	Parameter
Material	Polyvinyl chloride tube
External diametert	50 mm
Wall thickness	1 mm
Effective length of measuring section	150 mm
Diameter of sensing cable	0.9 mm
Spiral pattern	Tight spiral winding
Total number of spiral coils	≈167
Spiral angle	≈0.33
Length of each round of sensing optical cable	≈0.160 m
Total sensing optical cable length	≈26.7 m

FIGURE 4
Test tool for spiraling sensing optical cable.

increase in the signals sensed by the sensing optical cable. This phenomenon indicates that leakage enhances the disturbance effect on the sensing optical cable. From Figures 5c,d, it can be observed that the frequency spectra under no-leakage and leakage conditions show significant differences. In the absence of leakage interference, the vibration signals recorded by the sensing optical cable are mainly background environmental noise. However, when leakage occurs, the signals exhibit obvious main frequencies, concentrated at 10.25 Hz and 20.25 Hz. The above results show that when leakage occurs in the diaphragm wall, the time-domain and frequency-domain signals of the sensing optical cable undergo significant changes. By comparing the differences in time-frequency domains at different positions of the diaphragm wall, the evaluation of the leakage status of the diaphragm wall can be achieved.

Figure 6 shows the correlation between leakage flow rate and phase velocity. It can be observed that as the leakage flow rate increases from 2.5 mL/s to 15 mL/s, the vibration amplitude increases linearly from 0.2 rad/s to 0.8 rad/s. This result indicates that there is a proportional relationship between leakage flow rate and phase velocity. The leakage size of the diaphragm wall can be

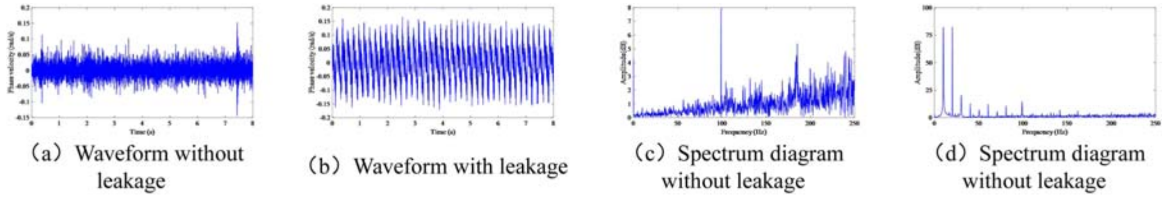

FIGURE 5
Feasibility study of DAS detection using passive method. **(a)** Waveform without leakage. **(b)** Waveform with leakage. **(c)** Spectrum diagram without leakage. **(d)** Spectrum diagram without leakage.

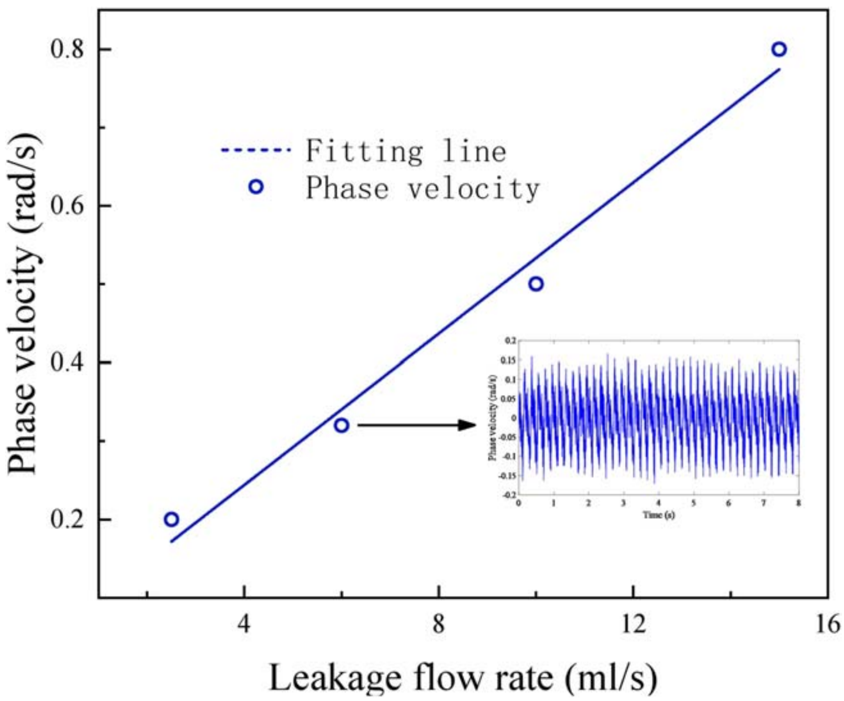

FIGURE 6
Correlation between leakage flow rate and phase velocity.

semi-quantitatively evaluated through the measured phase velocity of the sensing optical cable.

4.2 Active vibration detection of diaphragm wall leakage

Figure 7 shows the experimental results of detection leakage using the active method. Under no leakage condition, the signal received by the sensing optical cable mainly manifests as a sinusoidal wave excited by the excitation source, with a vibration frequency of approximately 100.51 Hz, and the waveform is regular and stable. In contrast, when leakage occurs, the waveform amplitude measured by the sensing optical cable increases significantly, accompanied by obvious changes in waveform shape, indicating that leakage has a substantial impact on the vibration signal. From the spectrograms shown in Figures 7c,d, it can be further observed that the frequency distribution under leakage conditions has changed, with more interference frequency components appearing in the signal, indicating that leakage has introduced additional vibration disturbances. Further analysis combined with time-frequency diagrams reveals that in the initial stage of leakage, the vibration frequency remains basically unchanged. Only when the leakage path is gradually formed and continuously affects the propagation path of surrounding groundwater can the leakage of the diaphragm wall be detected. This is because the formation of the leakage channel changes the transmission path and reflection interface of vibration waves. The above phenomena indicate that this technology can only realize the identification of diaphragm wall leakage when the leakage channel is formed and affects the vibration propagation path.

Figure 8 shows the results of the influence of the layout spacing of sensing optical cables on the perception of diaphragm wall leakage. As shown in Figures 8a,b, when the sensing optical cabless are placed close to the leakage channel, the vibration signals

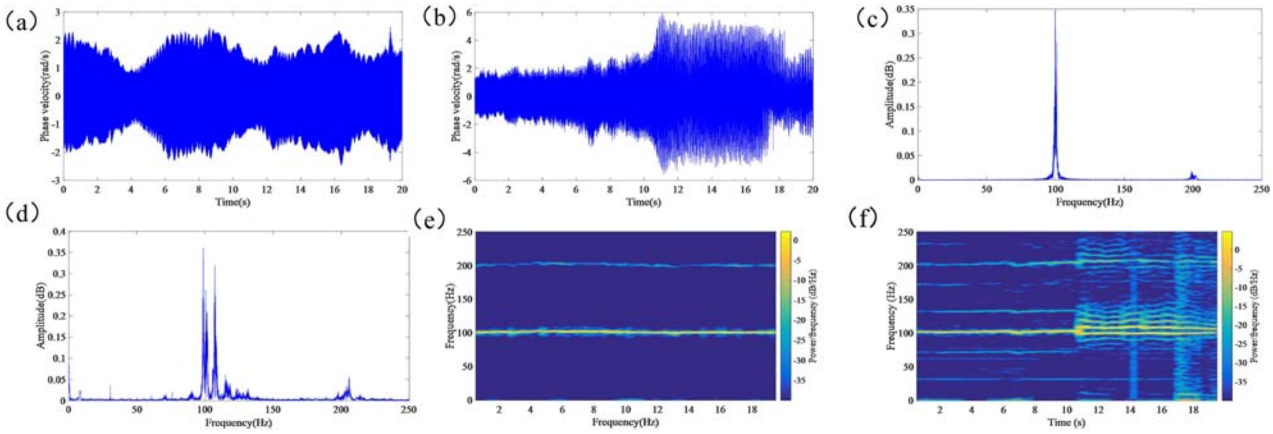

FIGURE 7
Feasibility study of DAS detection using active method. **(a)** Waveform without leakage condition. **(b)** Waveform with leakage condition. **(c)** Spectrum diagram without leakage condition. **(d)** Spectrum diagram with leakage condition. **(e)** Time-frequency diagram without leakage condition. **(f)** Time-frequency diagram with leakage condition.

collected by the sensing optical cables have a larger vibration amplitude, and the vibration frequency evolves from a single fixed frequency to multiple frequencies, allowing clear capture of leakage signals. As the distance between the sensing optical cable and the leakage channel increases to 25 cm (Figure 8c), the peak-to-peak vibration amplitude exhibits an attenuation of approximately 7 rad/s. The main reason is that the increase in vibration propagation distance leads to a longer propagation path and more reflection interfaces of the waves. However, under the influence of water flow disturbance, the signal frequency still shows diffraction phenomena caused by the interference of water flow signals, and the leakage of the diaphragm wall can still be effectively monitored. When the distance of the sensing optical cable is further increased to 50 cm (Figures 8e,f), due to the low leakage velocity, there is no significant change in the vibration propagation path near the sensing optical cable, and the time-frequency domain signals of vibration do not show significant differences from the excited time-frequency domain signals. To further quantify the influence of leakage on the vibration signals collected by the sensing sensing optical cables, the short-time energy of the signals in the 80–120 Hz range was calculated, and the results are shown in Table 3. The results show that as the distance between the sensing optical cable and the leakage channel increases, the short-time energy of the sensed signal decreases. This change indicates that the layout position of the sensing optical cable has a significant impact on the active detection of leakage signals by DAS.

To ensure the accuracy of detection, sensing optical cables should be laid in areas prone to leakage such as diaphragm wall joints, so as to improve the identification capability of diaphragm wall leakage.

Figure 9 shows the influence of leakage channels at different depths in the soil layer on the detection effect of leakage signals. As shown in Figures 9a,d, when the leakage channel is located 25 cm from the soil surface, the distributed optical fiber acoustic sensing (DAS) system can clearly capture the leakage signal, specifically manifested by a significant increase in waveform amplitude and obvious changes in waveform shape, indicating that leakage events can be effectively identified within this depth range. As the leakage channel moves up to 15 cm from the surface (as shown in Figure 9b), although the signal changes caused by water flow disturbance are not as significant as those at 25 cm, the frequency of the vibration signal still exhibits a certain degree of irregular fluctuation, indicating that there is still a certain leakage identification capability at this depth. As shown in Figure 9e, it is worth noting that compared with the 25 cm case, the peak frequency amplitude of the signal attenuates by approximately 8 rad/s. The main reason is that when the leaking water is close to the surface, part of the water spreads horizontally and the other part infiltrates downward, resulting in a weakening of the horizontal component in the signal; while in deeper soil layers, the horizontal component of the signal dominates, which helps to enhance the signal strength. As the leakage channel moves further upward to only 5 cm from the soil surface (Figures 9c,f), the impact of the initial leakage on the soil causes short-term frequency changes, and the waveform amplitude also increases significantly but then attenuates rapidly. As the leakage gradually penetrates the surface and forms a stable flow channel, the fluctuation of the signal amplitude tends to become regular, and the characteristics of the leakage signal gradually become indistinguishable. As this indicates, when the leakage channel is too close to the surface, although the DAS system still has a certain detection capability, its accuracy and reliability are easily affected by the leakage evolution process. To further quantify the impact of leakage on the vibration signals collected by the sensing optical cable, this paper has calculated the centroid frequency of the signals under various working conditions, and the results are shown in Table 4. The results indicate that as the distance between the leakage channel and the soil surface increases, the centroid frequency of the collected signals shows a gradually decreasing trend. This regularity suggests that in practical detection, the possible depth of leakage and signal propagation characteristics should be comprehensively considered, and the burial position of the sensing optical cable should be optimized to improve the accuracy and stability of leakage detection.

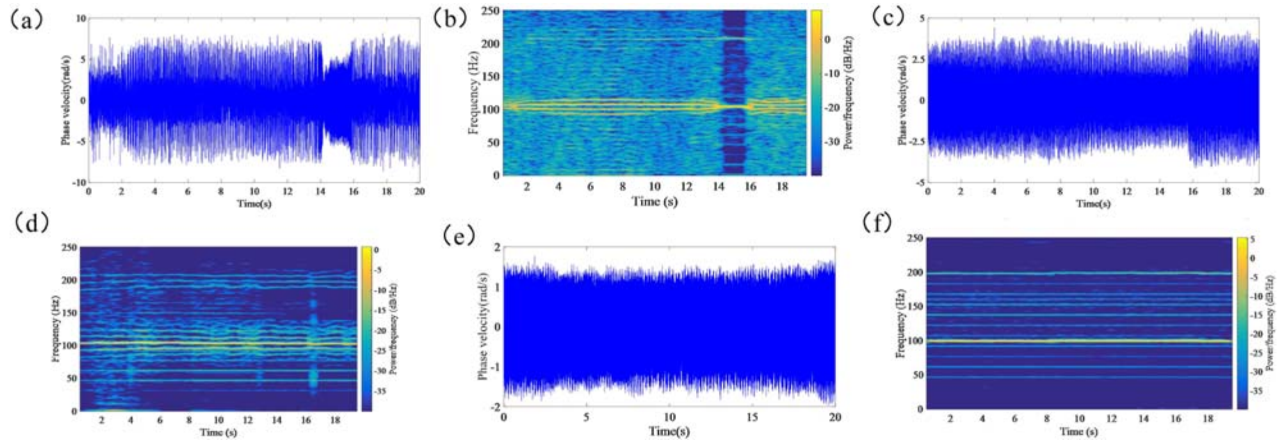

FIGURE 8
Effect of varying the distance between receiving fiber and leakage path in active DAS method. **(a)** Waveform Diagram at 0 cm from the Soil Surface. **(b)** Time-Frequency Diagram at 0 cm from the Soil Surface. **(c)** Waveform Diagram at 25 cm from the Soil Surface. **(d)** Time-Frequency Diagram at 25 cm from the Soil Surface. **(e)** Waveform Diagram at 50 cm from the Soil Surface. **(f)** Time-Frequency Diagram at 50 cm from the Soil Surface.

TABLE 3 Correlation between the position of the sensing fiber and short-time energy.

Space (cm)	0	25	50
short-time energy (dB)	150,202	139,942	131,637

5 Verification of DAS leakage detection and discussion

To verify the effectiveness of DAS leakage detection technology in real diaphragm wall leakage detection, a concrete model with the same width as a real diaphragm wall was cast indoors to carry out relevant experiments. The DAS leakage detection technology verification is carried out using a concrete test block with length, width and height of 1.1 m × 0.4 m × 0.15 m. The experiment set up an experimental group and a reference group. In the experimental group, three different concrete test blocks were embedded with three PVC pipes with a length of 1.1 m and diameters of 1.5 cm, 1 cm, and 0.5 cm respectively to simulate leakage channels of different diameters, so as to explore the leakage identification performance effect of leakage channels with different diameters.

As shown in Figure 10, sinusoidal signals with excitation voltages of 5V and 10V (corresponding frequencies of 35.8 Hz and 71.6 Hz respectively) were applied to excite the test blocks with leakage channels and those without leakage channels (channel diameter 1.5 cm). The results showed no significant difference in vibration signals, and no obvious sinusoidal signals were observed in either case.

Figure 11 shows the Fourier transform of the test in Figure 12. As depicted, under the 5V excitation voltage, with a leakage channel, the symmetrical vibration measuring tube can detect the excited vibration frequency of 35.8 Hz, while it cannot be observed without a leakage channel. For the 10V excitation voltage, a similar signal can be observed: the external excitation signal of 71.6 Hz can be detected in the presence of a leakage channel, but it is difficult to obtain in the absence of a leakage channel.

Based on the test results, the DAS system can accurately identify leakage phenomena in diaphragm walls by detection the presence or absence of target excitation signals. Therefore, this method demonstrates the effectiveness of DAS technology in diaphragm wall leakage detection and shows its feasibility in practical engineering applications.

Figure 13 shows the frequency domain response curves recorded by the DAS system under 5 V vibration excitation of the motor for three different leakage channel diameters (1.5 cm in blue, 1.0 cm in red, and 0.5 cm in black), where the horizontal axis represents time and the vertical axis represents the power spectrum amplitude.

As can be seen from Figure 13, as the diameter of the leakage channel increases, the amplitude of the signal perceived by the DAS system increases significantly. The blue curve for the 1.5 cm diameter shows the most significant peak response, with an amplitude much higher than the background noise, indicating that larger channels can more effectively conduct vibration energy to the sensing optical cable sensing area. The red curve for the 1.0 cm diameter also shows a clear peak, but with a lower amplitude, reflecting a certain attenuation in the transmission process of medium-sized channels. In contrast, the black curve for the 0.5 cm diameter is close to the background noise and does not form a clear peak, indicating that the reduction in channel diameter may increase the number of reflections during vibration propagation, resulting in vibration energy attenuation.

Based on the comprehensive comparison results, the geometric size of the leakage channel is a key factor affecting the recognition ability of the DAS system. When the channel diameter is ≥ 1.0 cm, the system can reliably identify the enhanced signal; however, when the diameter is reduced to less than 0.5 cm, the recognition difficulty increases significantly, requiring compensation with higher sensitivity or stronger excitation.

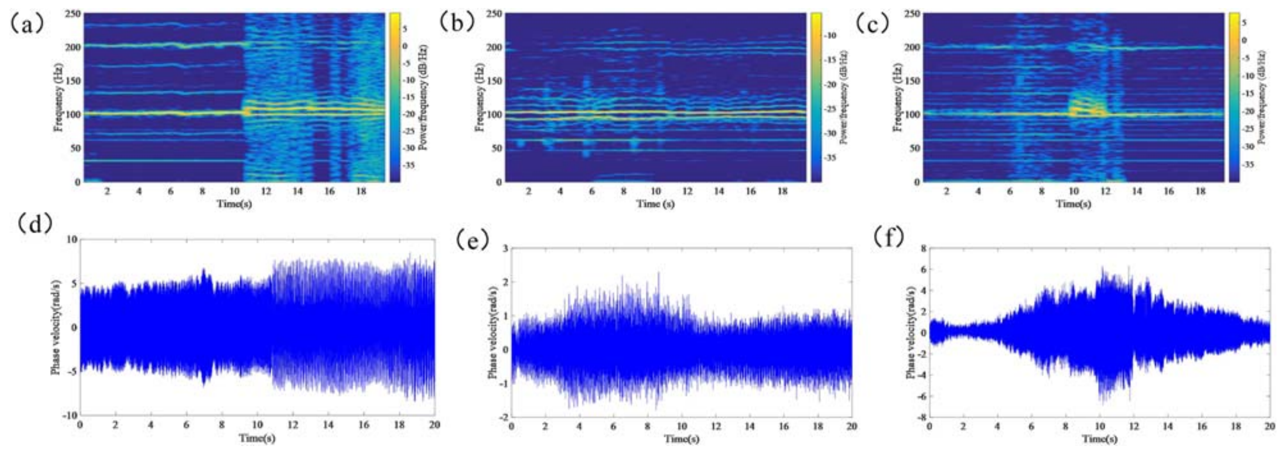

FIGURE 9
Correlation of leakage flow channel position variation differences in active DAS method. **(a)** Time-Frequency Diagram at 25 cm from the Soil Surface. **(b)** Time-Frequency Diagram at 15 cm from the Soil Surface. **(c)** Time-Frequency Diagram at 5 cm from the Soil Surface. **(d)** Waveform Diagram at 25 cm from the Soil Surface. **(e)** Waveform Diagram at15 cm from the Soil Surface. **(f)** Waveform Diagram at 5 cm from the Soil Surface.

TABLE 4 **Relationship between leakage flow channel position and the spectral centroid.**

Leakage flow channel distance from soil surface (cm)	25	15	5
Centroid frequency (Hz)	111.61	113.82	117.31

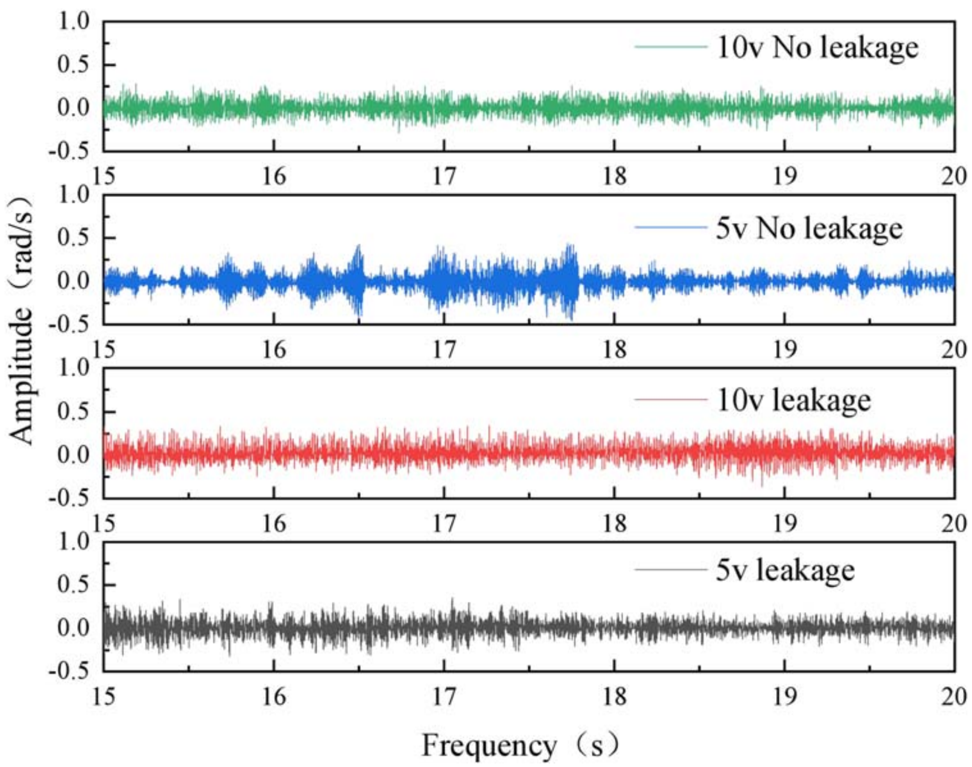

FIGURE 10
Vibration time domain diagram under different voltage conditions.

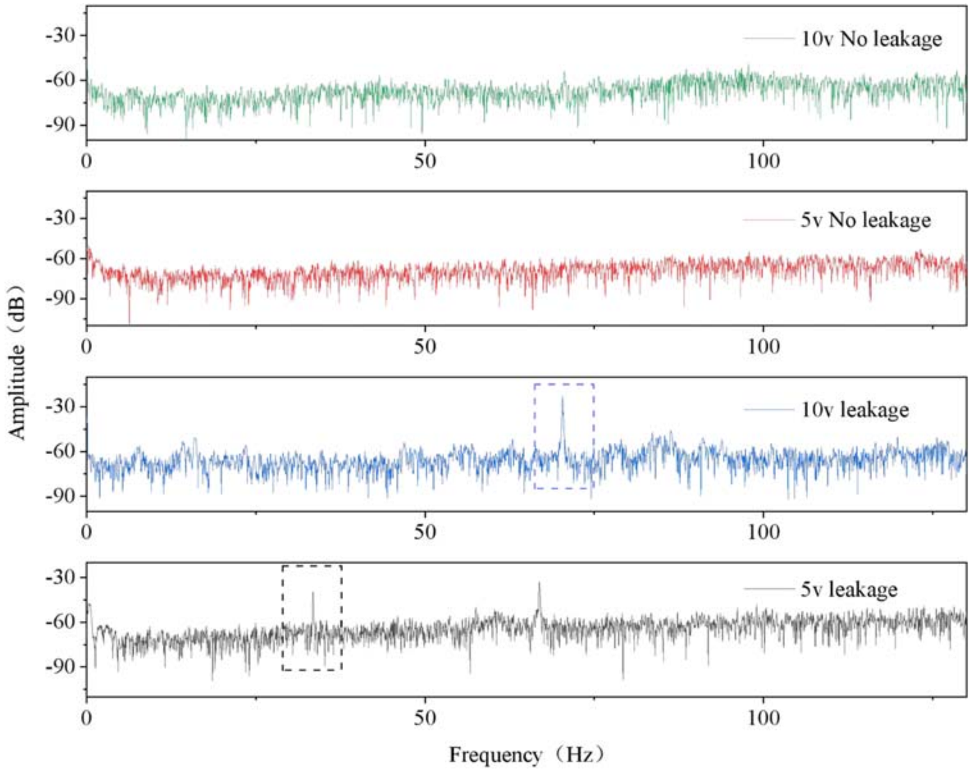

FIGURE 11
Vibration frequency domain diagram under different voltage conditions.

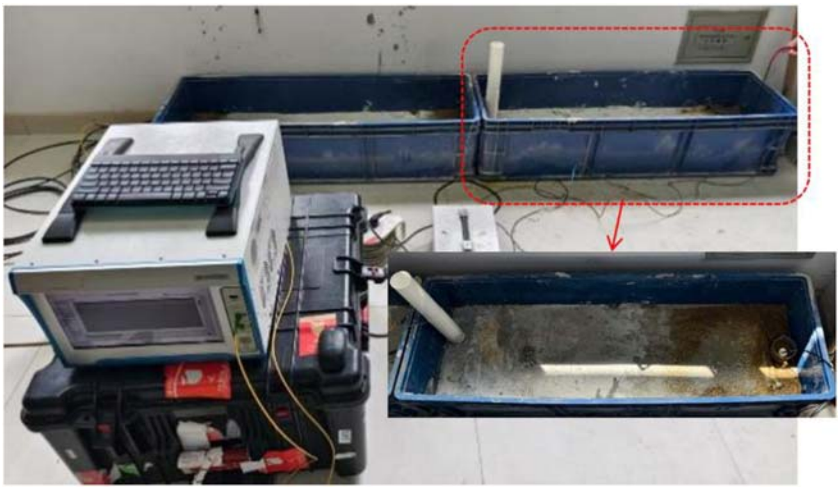

FIGURE 12
Photo of test device.

Future research should integrate practical engineering scenarios to further investigate the detection stability of DAS technology under the conditions of different soil layer media, multi-directional leakage channels, and multi-field coupling effects, thereby promoting its large-scale application in the leakage detection of underground structures.

6 Conclusion

This study systematically investigated the application effectiveness of DAS technology in leakage detection of diaphragm walls through indoor model tests, and the main conclusions are as follows:

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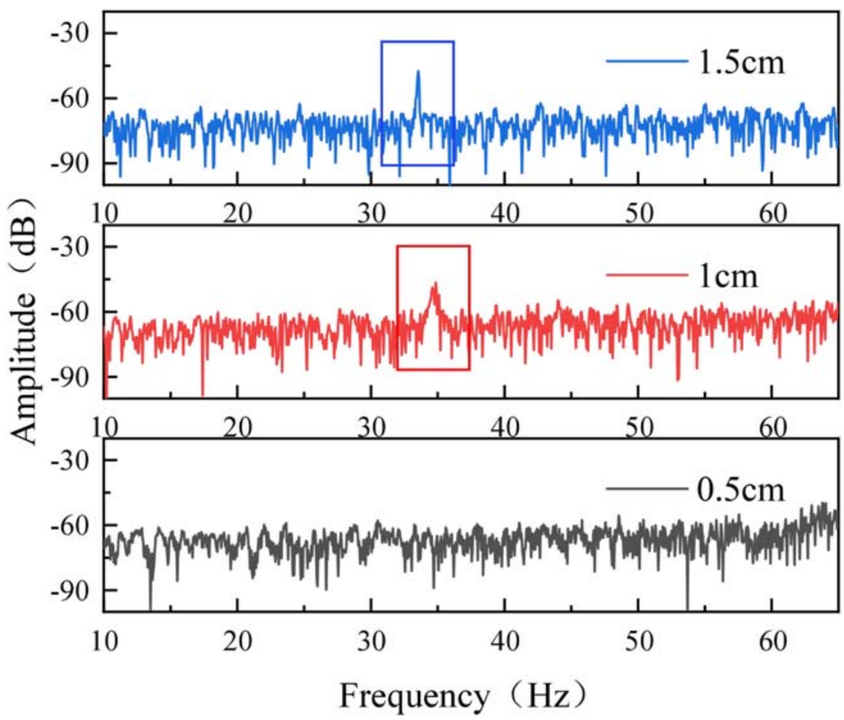

FIGURE 13
Frequency domain response curves for different leakage channel diameters.

1. Both passive and active vibration detection can effectively identify leakage in diaphragm wall, with significant changes in signals observed in both time and frequency domains, demonstrating strong detectability and identifiability.
2. Leakage flow rate is linearly proportional to vibration amplitude, with stronger signals detected when sensing optical cables are installed closer to leakage points. Priority should be given to deploying cables in sections prone to leakage
3. The depth of leakage channels affects signal detection: deeper leaks are more easily detectable, while shallow signals tend to attenuate. Sensing optical cable burial depth and layout should be optimized based on geological conditions

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

LZ: Writing – original draft, Writing – review and editing. MC: Writing – review and editing, Writing – original draft. YC: Writing – review and editing, Writing – original draft.

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Conflict of interest

Authors LZ and YZ were employed by Suzhou Rail Transit Construction Co., Ltd. Author MC was employed by Suzhou NanZee Sensing Technology Co., Ltd.

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