# Research Progress on Monitoring and Reinforcement of Prestressed Concrete Cylinder Pipe

## Abstract

Prestressed Concrete Cylinder Pipe (PCCP), as a composite pipe material with high strength and good durability, is widely used in urban long-distance water transmission projects in China. Its main structure includes the steel cylinder, concrete, prestressed steel wires, and a mortar protective layer. However, over the long-term use of PCCP, problems such as cracks in the cement mortar protective layer, longitudinal cracks in the concrete wall, corrosion of circumferential prestressed steel wires, and wire breakage gradually emerge, leading to the degradation of pipe performance and even rupture accidents. Therefore, the safe operation of PCCP during its service life has attracted widespread attention from researchers. This paper provides a detailed review of the wire breakage monitoring technologies and reinforcement methods for PCCP, focusing on the wire breakage monitoring methods based on electromagnetic principles and distributed optical fiber sensing technology, and their applications in PCCP. In addition, this paper also introduces CFRP reinforcement technology and external prestressed reinforcement methods for PCCP pipe wire breakage issues. External prestressing has particular advantages over CFRP, which is commonly used for internal reinforcement, for in-service long-distance pipelines. Research shows that the use of modern non-destructive testing technologies and reinforcement methods can significantly enhance the safety and service life of PCCP pipes, especially in emergency repairs.

**Keywords:** PCCP, Monitoring wire breakage, Reinforcement and repair.

## Introduction

Prestressed Concrete Cylinder Pipe (PCCP) is a composite structure composed of a steel cylinder, concrete, prestressed steel wires, and a mortar protective layer. To resist the corrosion of harsh soil environments, cathodic protection and anti-corrosion coatings are often added, as shown in Figure 1.

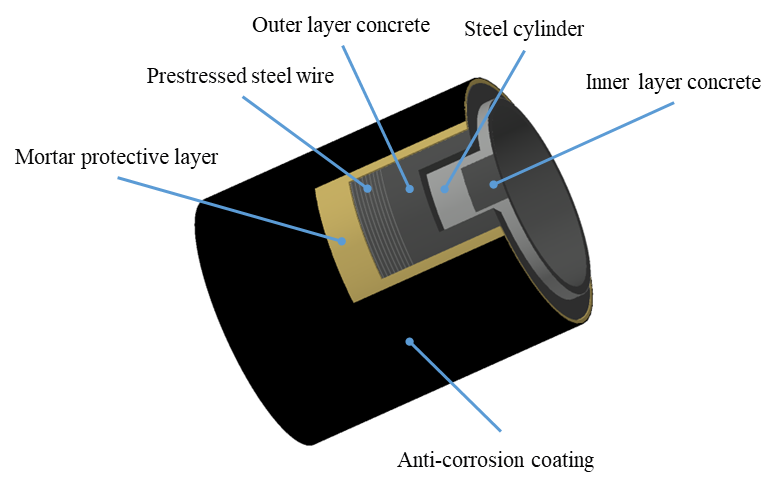


Figure 1: Schematic Diagram of PCCP Structure

This composite structure is made by welding thin steel plates and socket joint steel rings to form a cylinder, then pouring concrete into the inside and outside of the cylinder using a vertical vibration method to form the pipe core (PCCPE). PCCPL, on the other hand, uses a horizontal centrifugal method to pour concrete inside the cylinder to form the pipe core. After curing, circumferential prestressed steel wires are wound around the outer surface of the pipe core, creating circumferential prestress in the concrete wall. Finally, a mortar protective layer is sprayed onto the outer surface of the wound wire pipe core to form a new type of composite pipe material [1]. With its high strength, high impermeability, high sealing performance, good durability, precise interface dimensions, low maintenance costs, and wide range of pipe diameters, PCCP has become the primary pipeline material for urban long-distance water transmission projects in China. PCCP has been widely applied in key water transmission projects in China, such as the Hohhot Yellow River Diversion Project, Shanxi Wanjiazai Water Diversion Project, Harbin Mopanshan Water Transmission Project, Guangxi Xijiang Water Diversion Project, South-to-North Water Diversion Project, Liaoning Dahuofang Reservoir Water Diversion Project, and many other major water resource projects [2,3].

With the widespread use of PCCP pipelines in China, some issues have emerged, such as cracking of the cement mortar protective layer, longitudinal cracks in the concrete pipe wall, corrosion and wire breakage of the circumferential prestressed steel wires, and occasional pipe bursts. Hassi et al. [4] presented the investigation results of PCCP failure accidents in the Tafilalet and Greater Agadir regions of Morocco, pointing out that chloride ion corrosion of prestressed steel wires and water hammer effects are the main causes of PCCP degradation. In addition to localized corrosion in corrosive burial zones, manufacturing defects (such as irregular mortar coating thickness, inconsistent prestressed steel wire spacing, and low mortar coating porosity), improper methods, and designs also significantly affect the degradation of PCCP pipelines. Among these, wire breakage is a major cause of concrete failure [5,6]. Therefore, the safe operation of PCCP during its service life has attracted widespread attention from researchers. In recent years, significant research has been conducted in our country on wire breakage monitoring [7-10] and reinforcement repair [11-15] of PCCP. The purpose of this paper is to analyse and summarise the current research hotspot of PCCP - monitoring and reinforcement.

## Overview of PCCP

### Development History of PCCP

As early as 1893, Paris chief engineer Bonna designed and manufactured the concrete cylinder pipe, with a diameter of 1800mm and an internal pressure of 0.35MPa. It was first laid in the Colombes water diversion pipeline network in Paris, with a length of 1500m. The first attempt at prestressed concrete was in Germany in 1888. The experiment failed because the mortar concrete used did not have sufficient strength to form adequate bonding between the concrete and the steel reinforcement. Twenty years later, in prestressed concrete beams, success was achieved by anchoring lightweight steel bars on the end plates to prevent slippage caused by bond failure. In 1927, France first used high-strength steel wires and ultra-high-strength concrete, marking a significant development in the design of prestressed concrete. Since then, prestressing has been successfully applied to piles, railway struts, electric poles, floor slabs, arches, beams, and many other reinforced concrete structures. In 1939, Bannon Company successfully manufactured the Prestressed Concrete Cylinder Pipe (PCCP) using the discovered principle of prestressed concrete and laid it in the suburbs of Paris. In 1942, the United States developed the prestressed concrete cylinder pipe and applied it to commercial manufacturing for the first time [16,17].

The development, research, and production of PCCP in China started later, with efforts beginning only in the 1980s. In 1984, the Suzhou Concrete Cement Products Research Institute collaborated with the Yantai City Waterworks Pipe Factory in Liaoning Province to develop a φ600mm PCCP using simplified methods, and it was tested on water transmission pipelines. In 1985, the Nanjing Cement Pipe Factory in Jiangsu Province cooperated with the Beijing Municipal Engineering Research Institute to manufacture prototype PCCPs with diameters DN600mm and DN1200mm using self-stressed concrete, which were installed in the Fujian Jianyang Hydropower Station and Nanjing city water supply pipelines for testing. Although these pipes were small in diameter and produced in small quantities using simplified methods, they successfully explored the potential for PCCP development. In 1989, Shandong Power Pipeline Engineering Company introduced PCCP manufacturing technology and key equipment (steel cylinder spiral welding machine, socket steel ring equipment, pipe molds, vibrators, etc.) from the American Amerren Company and domestic auxiliary equipment (such as winding machines and roller machines), establishing a production line. This marked the beginning of PCCP production in China [18].

### Structure of PCCP Pipes

Prestressed Concrete Cylinder Pipe (PCCP) is classified into two types based on its structure: internally lined prestressed concrete cylinder pipe (PCCPL) and embedded prestressed concrete cylinder pipe (PCCPE). According to the type of pipe joint sealing, they are further divided into single-gasket prestressed concrete cylinder pipes (PCCPSL, PCCPSE) and double-gasket prestressed concrete cylinder pipes (PCCPDL, PCCPDE). The difference between the internally lined and embedded structures lies in the position of the steel cylinder within the core. The internally lined structure consists of a steel cylinder and a concrete lining; the embedded structure consists of a steel cylinder with concrete layers on both the inner and outer sides of the cylinder. PCCP has a wide range of diameters (nominal internal diameter DN400 to DN4000), with a maximum working pressure of up to 2.0 MPa and a maximum burial depth of over 10 meters. The nominal internal diameter of PCCPL is generally DN400 to DN1400, while PCCPE’s nominal internal diameter typically ranges from DN1000 to DN4000 [19].

## Research Progress in Monitoring Wire Breakage of PCCP

### Wire Breakage Detection Based on Electromagnetic Principles

Eddy current testing based on electromagnetic induction principles is a detection method used to evaluate the properties of conductive materials or near-surface defects by measuring changes in the impedance of a detection coil caused by induced eddy currents in the specimen. It is commonly used for surface crack detection in medium and small-diameter metal pipes. Xu Jin et al. [20] utilized far-field eddy current transformer coupling technology to detect wire breakage in prestressed concrete cylinder pipes (PCCP). The basic principle of wire breakage detection was introduced, where the occurrence of wire breakage in the prestressed concrete cylinder pipe causes distortions in the amplitude and phase of the far-field eddy current signal that penetrates the pipe wall twice. This phenomenon can be used to determine the number and position of wire breakages in the prestressed steel wires of PCCP. The method was validated through experiments. Hu Shaowei et al. [7] proposed a non-destructive testing method for PCCP wire breakage based on eddy current principles. The PCCP is viewed as an enlarged metal pipe, with prestressed steel wires forming the main structure. During detection, a probe with an internal coil generates eddy currents inside the pipe, and the magnetic field generated by the eddy currents reacts with the probe's magnetic field, causing changes in the probe's magnetic flux. By collecting impedance fluctuations from the probe, the change in magnetic flux can be obtained, and the damage condition of the prestressed steel wires in the PCCP can be inferred. An associated equation was established using electromagnetic induction and equivalent circuits, and the impedance fluctuation formula was derived. The feasibility of this method was preliminarily demonstrated based on experimental methods.

Li Runbin et al. [21] constructed a simulation model using finite element analysis to study the principle of orthogonal electromagnetic detection for PCCP wire breakage. They analyzed the impact of axial and circumferential positions of wire breakage on detection signals, providing theoretical guidance for practical detection. Finally, the model was experimentally validated on a PCCP DE3000×5000 pipeline, and the model accurately simulated real-world conditions.

### Wire Breakage Detection Based on Distributed Optical Fiber Sensing

Compared to traditional methods, distributed optical fiber sensing technology for PCCP wire breakage monitoring has significant advantages in terms of sensor deployment convenience and event recognition accuracy. Zhang Xuping et al. [22] compared various existing methods for PCCP wire breakage detection and introduced a real-time online monitoring scheme based on the integrated DAS (Distributed Acoustic Sensing) principle, which has emerged in recent years. Zhang Ye et al. [9] analyzed prototype experimental signal characteristics and classified wire breakage types using an intelligent learning model. They conducted prototype experiments on embedded PCCP with an internal diameter of 3.4 m and length of 5 m. The distributed optical fiber sensor was used to monitor real-time signals of cut wires, corroded wires, and tapping noise. Based on short-time Fourier transform and deep learning models, they reconstructed wire breakage signals and finally developed a wire breakage signal recognition model using support vector machines. The wire breakage recognition model, based on Inception-ResNet-v2 for signal reconstruction, achieved a minimum accuracy of 92.9% and a maximum accuracy of 100%. The effectiveness of signal reconstruction was subsequently validated using *t*-SNE. Yang Guang et al. [10], to enhance the real-time detection capability of the distributed optical fiber monitoring system for PCCP wire breakage signals, developed an analytical model based on a packaging strategy to extract effective feature parameters conducive to vibration mode recognition. A phase-sensitive optical time-domain reflectometry (Φ-OTDR) based distributed optical fiber monitoring system was used to collect vibration signals. Raw feature parameter sets were established for time domain, frequency domain, and time-frequency domain analysis. Nonlinear convergence factors, nonlinear adaptive weights, Gaussian perturbation, and Tent chaotic perturbation were introduced to improve the whale optimization algorithm (WOA). Based on this, the improved WOA (IWOA) and hierarchical clustering (HC) were used to propose the IWOA-HC effective feature extraction model. This model provides technical support for the health diagnosis and disaster early warning of in-service PCCP projects.

## Research Progress in Reinforcement and Repair of PCCP

Wire breakage is currently the most common defect in PCCP, and if reinforcement is not performed in time, it can easily lead to pipe bursts and other accidents. The repair methods for PCCP with wire breakage depend on the on-site conditions, materials, load, and the degree of damage to the pipe. Reinforcement methods include pipe replacement, internal reinforcement, and external reinforcement.

### CFRP Reinforcement

Bonding carbon fiber reinforced polymer (CFRP) lining to the inner wall of the pipe core is a common reinforcement method. Due to CFRP's high tensile strength, corrosion resistance, light weight, and ease of construction, CFRP lining can significantly enhance the load-bearing capacity of PCCP pipes with wire breakage, and can repair PCCP pipes from the inside without excavation. Dou Tiesheng et al. [11] verified the effectiveness of CFRP in repairing PCCP with wire breakage by comparing the reinforced pipe with CFRP applied to the inner surface of the concrete core and the original pipe. They performed wire breakage tests under different internal pressures to study the damage characteristics of PCCP wire breakage under the most unfavorable conditions. The test results showed that the CFRP applied to the inner wall of the concrete core, when combined with the PCCP structure, contributed to load-bearing. After microcracks appeared in the concrete core, the CFRP participated in stress redistribution, limiting the development of cracks in the concrete core and adjusting the stress state of the pipe structure. The CFRP reinforcement had a clear effect on strengthening PCCP with wire breakage. Lv Kangwei et al. [23] proposed an internal circumferential prestressed carbon fiber reinforced polymer (CFRP) plate reinforcement method to fully utilize the tensile properties of CFRP and enhance the bearing capacity of PCCP with broken wires. Through analysis of circumferential stresses in CFRP and concrete, it was demonstrated that the mechanical model calculations based on Lamé's formula aligned well with finite element analysis results, with a maximum discrepancy of only 9.3%. Computational studies on different wire breakage distributions under identical breakage rates revealed that concentrated wire breaks at the same location represented the most critical scenario. When wire breaks occur, concrete damage progresses from minor to severe from the inner to outer surfaces at the breakage location. A focused comparison of pre- and post-reinforcement performance at 10% wire breakage rate showed that under normal operating water pressure, stress-strain in PCCP concrete and steel cylinders at breakage locations significantly decreased, confirming CFRP's effective reinforcement. Higher wire breakage rates amplified CFRP's beneficial effects prior to inner wall concrete damage. This method also features short construction cycles, minimal environmental impact, trenchless operation, and ease of implementation, making it highly valuable for emergency PCCP repairs.

Wei Haonan et al. [24] investigated the effects of pipe diameter and high-compression elastic cushion layer thickness on composite CFRP-reinforced PCCP by developing finite element models with 6 pipe diameters and 4 cushion thicknesses. Strain responses under various internal water pressures and prestressed wire breakage conditions revealed that increased cushion thickness substantially enhanced CFRP circumferential strain while significantly improving concrete circumferential strain distribution.

Zhai Kejie et al. [13] proposed a repair method using externally bonded Carbon Fiber Reinforced Polymer (CFRP) to address the issue of difficult shutdown maintenance for long-distance PCCP water transmission pipelines. To investigate the effectiveness of externally bonded CFRP in repairing broken strands in PCCP, a full-scale internal water pressure test was conducted on a PCCP pipeline with an internal diameter of 2.8 m. The strain responses of the PCCP structure before and after the repair were compared and analyzed. The results showed that, due to the "hooping" effect of CFRP, the material strain in the middle section of the broken strand area decreased after the repair, which is beneficial for the load-bearing capacity of the PCCP. Zhai Kejie et al. [25] proposed a technique for reinforcing damaged PCCP using externally wrapped prestressed carbon fibre reinforced polymer (CFRP). When a PCCP reaches the serviceability limit state, prestressed CFRP repair and non-prestressed CFRP repair can increase the bearing capacity of the pipe by 87.3% and 34.9%, respectively.

### External Prestressed Reinforcement

External prestressing reinforcement actively compensates for prestress loss caused by wire breakage in PCCP, restoring original bearing capacity without pipeline drainage –particularly advantageous for non-interruptible water supply systems. Zhao Lijun et al. [14] conducted a comprehensive prototype test simulating PCCP loading-wire breakage-concrete cracking-pressure reduction-external prestressing application-reloading to design load. Analysis of mechanical behavior and deformation characteristics at each stage demonstrated that external prestressing with steel strands effectively closed pipe cracks, restored bearing capacity to the design internal pressure of 0.9 MPa, maintained strands in elastic state, and preserved watertightness.

## Conclusion and Prospects

As an efficient water conveyance material, PCCP inevitably experiences wire breakage failures during prolonged service. Analysis of monitoring technologies reveals that eddy current testing based on electromagnetic principles and distributed fiber optic sensing provide effective non-destructive detection solutions with high accuracy and real-time capability. CFRP reinforcement and external prestressing methods have proven effective in enhancing PCCP's load-bearing capacity and service life, with external prestressing showing particular advantages for in-service long-distance pipelines. Continued advancements in monitoring and reinforcement technologies will further ensure operational safety and reliability, providing robust support for secure water transmission infrastructure.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Option 2:

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1.

2.

3.

References

1. Zhang, S. K. (2007). Development review and future prospects of prestressed steel cylinder concrete pipe. Concrete and Cement Products, (02), 25-28. doi:10.19761/j.1000-4637.2007.02.008.
2. (2015). SL 702-2015. Ministry of Water Resources of the People's Republic of China. https://kns.cnki.net/kcms2/article/abstract?v=SmerkCJHUJltmI9eZPyQU3Z4TjJbRgPknw\_jd8MnrQftVfQlXEUpp0d2fVNYdLjKk9maLIB59ch4bO4-l0c0IpQGuKyRnTBy6vZ8H0pGITWhHVhnJqEd\_vKKNM8aCF6mBcI2rln9FgQhlFCfUKysdLeHPU7O4QbNw1fqpKfj1oSkpMKiluvJXwJLxU5jMRpA&uniplatform=NZKPT&language=CHS
3. Sun, Y. Y., Hu, S. W., Hu, D. X., Huang, Y. Q., & Wang, Y. (2023). Research progress of prestressed steel cylinder concrete pipe (PCCP). Yangtze River, (06), 162-168. doi:10.16232/j.cnki.1001-4179.2023.06.023.
4. Hassi, S., Ejbouh, A., Ebn Touhami, M., Berrami, K., Ech-chebab, A., & Boujad, A. (2021). Performance of prestressed concrete cylinder pipe in North Africa: Case study of the water transmission systems in the Tafilalet Region of Morocco. Journal of Pipeline Systems Engineering and Practice, 12, 05021002.
5. Hu, S. W., & Shen, J. (2011). Study on the influence of internal wire breaks in large-diameter PCCP on its load-bearing capacity. Water Resources and Hydropower Technology, (04), 41-44. doi:10.13928/j.cnki.wrahe.2011.04.013.
6. Hu, S. W., Lu, Y., Sun, Y. Y., & Huang, Y. Q. (2019). Study on the influence of wire breaks on the internal water pressure-bearing capacity of PCCP under actual buried conditions. Concrete and Cement Products, (10), 27-30. doi:10.19761/j.1000-4637.2019.09.027.04.
7. Hu, S. W., Hu, X., & Lu, J. (2016). Study on non-destructive detection method of PCCP wire breaks based on eddy current principle. Water Resources and Hydropower Technology, (02), 101-103+114. doi:10.13928/j.cnki.wrahe.2016.02.022.
8. Li, R. B., Feng, H., & Liu, X. (2020). Finite element simulation analysis of PCCP wire break detection based on orthogonal electromagnetic principle. Instrument Technology and Sensors, (07), 94-99. https://kns.cnki.net/kcms2/article/abstract?v=SmerkCJHUJl4rcxoGS\_3tPBsWAuxm-yxkLIhPPsLjRhBPQmN9g2lFV51v7htn5l-Kr5466hoM-rGYP8tI5BGehsT9AzkGHx2iaWVtP46lfi1X-lPDuEKEKGMvoBR9gQI7mm-VqNcDVKG4WtOaWoItSxJ8Qut0YeLHqOtE267Bu45-GQolRB323IDizVUFjC5sv68EouWVok=&uniplatform=NZKPT&language=CHS
9. Zhang, Y., Yuan, S. M., Li, Y. L., Wen, L. F., Si, Z., & Sun, K. Y. (2023). Intelligent recognition and analysis of PCCP wire break signals in water conveyance projects based on prototype tests. Journal of Hydraulic Engineering, (05), 587-598. doi:10.13243/j.cnki.slxb.20220913.
10. Yang, G., Luan, B. W., Li, B., Sun, J., Zhu, Z. H., & Zhang, J. W. (2024). Effective feature mining of PCCP wire break signals based on prototype tests and encapsulation strategies. Journal of Hydraulic Engineering, 1-11. doi:10.13243/j.cnki.slxb.20240128.
11. Dou, T. S., Cheng, B. Q., Hu, H., Xia, S. F., & Zhao, L. J. (2019). Experimental study on CFRP repair of PCCP pipes with wire breaks. Journal of the China Institute of Water Resources and Hydropower Research, (01), 68-74. doi:10.13244/j.cnki.jiwhr.2019.01.010.
12. Dong, X. N., Li, M., Sun, Z. H., & Ma, Y. (2019). Experimental and computational analysis of composite carbon fiber reinforcement for the inner wall of prestressed steel cylinder concrete pipes. Journal of Hydraulic Engineering, (06), 780-786. doi:10.13243/j.cnki.slxb.20190175.
13. Zhai, K. J., Fang, H. Y., Fu, B., Wang, F. M., Hu, B. Y., & Lu, X. H. (2019). Full-scale model test study on external CFRP repair of PCCP pipes with wire breaks. Journal of Geotechnical Engineering, (S1), 157-160. https://kns.cnki.net/kcms2/article/abstract?v=SmerkCJHUJmLnhkfrMfZbGZwDqemRD\_P\_pzpUoeIeMhchHI3SKBE3Qj0tZbGbV0x3o2nkSWua7Sh0XJHznRoWP9pqO-AjcVE4kLWuu4fSHdQFI0LRSi\_85aGNgGg5pYpncNsJhN4G8l1JxYM\_ThulluC8k1ucXAEt\_mnRTanmpHKVjrn6PQV6r2mZ\_Oh-0F2-cY0sOr6tV8=&uniplatform=NZKPT&language=CHS
14. Zhao, L. J., Dou, T. S., Cheng, B. Q., Xia, S. F., Zhang, T., & Bi, R. (2019). Experimental study on external prestressing reinforcement of prestressed steel cylinder concrete pipes. Journal of Hydraulic Engineering, (07), 844-853. doi:10.13243/j.cnki.slxb.20190224.
15. Zhang, X. J., Wu, J. Y., & Chen, J. F. (n.d.). Bearing capacity analysis of CFRP-lined PCCP under internal pressure. Industrial Construction, 1-17. http://kns.cnki.net/kcms/detail/11.2068.TU.20240223.1810.008.html.
16. Kennison, H. F. (1950). Design of Prestressed Concrete Cylinder Pipe. Journal (American Water Works Association), 42(11), 1049–1064. http://www.jstor.org/stable/41235360.
17. Sun, S. P. (2001). Analysis of some basic issues of prestressed steel cylinder concrete pipes. Special Structures, (03), 17-20+33. https://kns.cnki.net/kcms2/article/abstract?v=SmerkCJHUJlOlmYoXRJ\_J8GLgcW7ilkgceAIXcxWQ1S8WhSD0gLBNwwyGVwXVGyL3IRb1jz6RBcNz0AUK837nCe6sczim5XQaLsMs0z\_S-btez1llIAxgI6kwfROyhcmrlpa5nuBovdxYYHCzZv2b4ASR3Vn9qeCM\_8xrXG1subiq9PN5hnfBXfpLp\_cMAFNRumUs2Mv-SI=&uniplatform=NZKPT&language=CHS
18. Zhang, S. K. (2007). Late start, excellent performance, large market: A review of the current development status of prestressed steel cylinder concrete pipes (PCCP) in China. China Building Materials, (04), 37-40. doi:10.16291/j.cnki.zgjc.2007.04.009.
19. National Cement Products Standardization Technical Committee (SAC/TC 197). (2017). GB/T 19685-2017. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China; Standardization Administration of China. https://kns.cnki.net/kcms2/article/abstract?v=SmerkCJHUJnECnFFrHXcBNOypckT1-F8-rKanYuKItV2\_K36cPZ4kDL5MF16GAKVzbK1KOLik9jngokkU5bc0L0iKJyxugzFntIAyElmur7V8hhiinMKiazat-Ii4HAmK5A1uzmTdsZ-CCrY1nzI\_tneBpcROo1JhP7\_E40T0lJz9G8UTJTdGLqS95OgC9OR&uniplatform=NZKPT&language=CHS
20. Xu, J., Tian, H., Peng, Z. H., Zhu, J. X., & Wu, Y. M. (2014). Application of far-field eddy current technology in PCCP wire break detection. Concrete and Cement Products, (12), 32-34. doi:10.19761/j.1000-4637.2014.12.009.
21. Li, R. B., Feng, H., & Liu, X. (2020). Finite element simulation analysis of PCCP wire break detection based on orthogonal electromagnetic principle. Instrument Technology and Sensors, (07), 94-99. https://kns.cnki.net/kcms2/article/abstract?v=SmerkCJHUJki3k\_xScmcoXiRbrcsGU-IDYwmnbODUe-u\_6Z3xaIe6FfNHVDdX6UGooTzXBLSNaMaG12nao7vHMXw2Z4u\_0aqtd1cUKsQxOKjq07SfqEZgeKzSc3wuLAQRs1H37ERiN8UldssIxXnXzn59g-W-KIU0tRe6qeH0GRGfgx6Q86o7ubQvcXDTgvnLuV4srX99LI=&uniplatform=NZKPT&language=CHS
22. Zhang, X. P., Zhou, G. N., Wang, H. R., Wang, J., Liu, S. C., Zhang, D., ... & Zhang, Y. X. (n.d.). Research progress on PCCP wire break monitoring based on distributed fiber optic acoustic field sensing. Chinese Journal of Optics, 1-24. http://kns.cnki.net/kcms/detail/31.1252.O4.20231114.1516.082.html.
23. Lv, K. W., Lu, W. Y., Liu, H. X., Ke, M. Y., & Xu, M. F. (2021). Numerical analysis of hoop prestressed carbon fiber board reinforcement for PCCP pipes. Journal of Hydraulic and Waterway Engineering, (06), 133-141. https://link.cnki.net/urlid/32.1613.TV.20211217.1930.008
24. Wei, H. N., & Sun, Z. H. (2021). Strain impact analysis of composite carbon fiber reinforcement for PCCP with high-compression elastic cushion layer. Journal of the China Institute of Water Resources and Hydropower Research, (03), 301-307+312. doi:10.13244/j.cnki.jiwhr.20200120.
25. Zhai, K., Fang, H., Guo, C., Ni, P., Wu, H., & Wang, F. (2021). Full-scale experiment and numerical simulation of prestressed concrete cylinder pipe with broken wires strengthened by prestressed CFRP. Tunnelling and Underground Space Technology, 115, 104021.