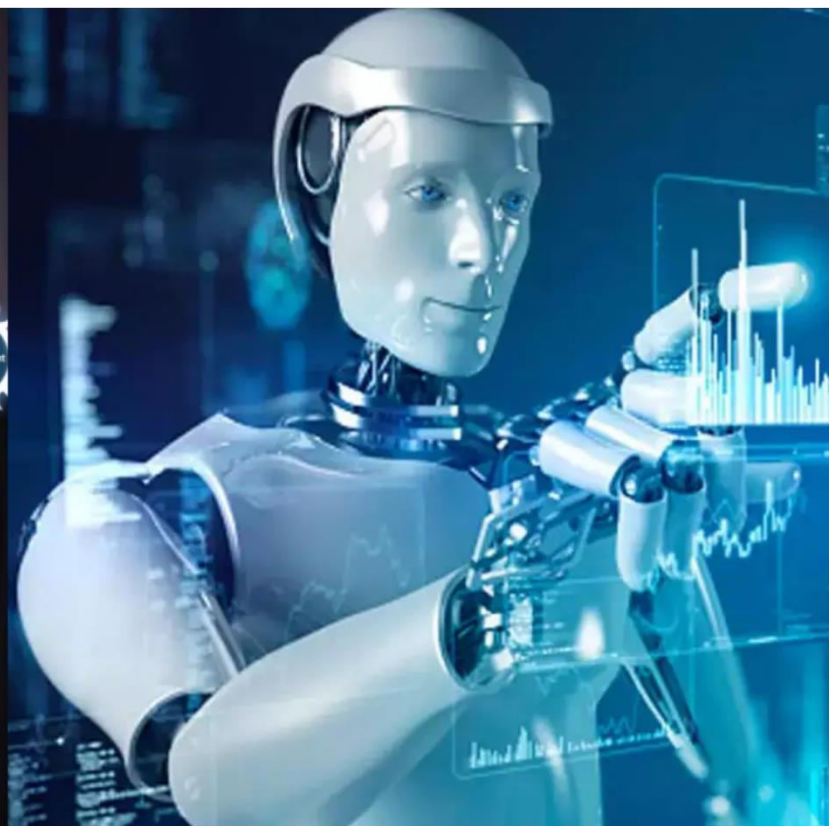




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Discussion on Identification Methods of Hydraulic Concrete Cracks in Complex Environments

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ABSTRACT: Facing challenges in hydraulic concrete crack identification such as severe environmental interference, difficulty in capturing microcrack, omission of hidden cracks, and large scale spans, this paper adopts literature review, technical analysis and engineering verification to compare the principles, advantages and disadvantages of three mainstream technologies: traditional non-destructive testing, intelligent sensor monitoring and deep learning. A three-level integrated system of "surface screening — deep detection — precise quantification" is constructed. Environmental adaptability improvement measures are proposed from the aspects of equipment, algorithms and data processing, which have been verified by engineering cases. The results show that the system realizes precise positioning of 0.1 mm microcracks with an identification accuracy over 90% under complex conditions, greatly improving detection accuracy and efficiency. The research findings provide technical support for the safe operation and maintenance of hydraulic structures, and possess important application value for enhancing the risk resistance of water conservancy projects and promoting the intelligent development of crack identification technology.

KEYWORDS: hydraulic concrete; crack identification; non-destructive testing; composite recognition
Introduction

I. INTRODUCTION

1.1 Research Background and Significance

Hydraulic concrete structures serve as the core of key water conservancy and hydropower facilities, such as dams and spillways. Their operational safety is directly tied to engineering functionality and public interest. Over 80% of hydraulic concrete structures in China are subjected to the coupled effects of multiple physical, chemical, and mechanical factors over the long term, including freeze-thaw cycles, chloride ion erosion, and water flow abrasion. These factors lead to varying degrees of cracking. Such defects compromise the structural integrity and durability, and in severe cases, can trigger safety incidents like leakage and structural instability [1]. Traditional crack identification relies primarily on manual inspections, which suffer from low efficiency, strong subjectivity, and inadequate coverage of concealed areas. Moreover, they have limited capability in detecting micro-cracks with widths less than 0.15 mm, and pose safety risks in harsh environments, making them ill-suited for the refined and intelligent operation and maintenance (O&M) demands of modern water conservancy projects[2]. Therefore, developing high-precision crack identification technologies for hydraulic concrete under complex environments to achieve early detection, precise quantification, and dynamic early warning holds significant scientific value and practical engineering significance for ensuring long-term operational safety, reducing O&M costs, and extending the service life of these structures.

1.2 Review of Research Status

Scholars both domestically and internationally have established three main technical pathways for crack identification in hydraulic concrete: traditional non-destructive testing (NDT), intelligent sensing monitoring, and deep learning.

Although each technology demonstrates high accuracy in specific scenarios, their adaptability under complex environments still requires optimization.

1. **Traditional NDT:** These techniques are mature and widely applied. Ultrasonic testing offers precise localization (error < 4.7%) but limited penetration depth (< 50 cm). Surface wave methods are suitable for deep or inclined cracks but depend heavily on surface flatness. Infrared thermography can screen for concealed cracks but is highly susceptible to temperature and light interference.
2. **Intelligent Sensing Monitoring:** This approach enables dynamic early warning. The integration of Fiber Bragg Grating (FBG) and Acoustic Emission (AE) technologies allows for high-precision dynamic identification, though it involves high deployment and maintenance costs alongside complex, redundant data. Coupling AE with damage mechanics can simulate crack evolution, achieving diagnostic accuracy exceeding 90%.
3. **Deep Learning:** This provides a new intelligent paradigm. Improved models (e.g., Mask R-CNN) can achieve segmentation accuracy of over 82%, enabling precise quantification of crack parameters. However, under complex conditions such as high humidity and low light, their robustness and accuracy are limited by the signal-to-noise ratio.

Current research gaps include: the inability of single methods to meet full-scale crack detection requirements; inadequate mechanisms for suppressing interference in complex environments; and low efficiency in cross-scenario adaptation and multi-source data fusion. This paper will systematically analyze the characteristics of each technology and explore multi-technology fusion solutions to provide practical references for precise identification under complex environments.

II CRACK FORMATION MECHANISMS AND IDENTIFICATION CHALLENGES IN HYDRAULIC CONCRETE UNDER COMPLEX ENVIRONMENTS

2.1 Multi-field Coupling Mechanism of Crack Formation

The initiation and propagation of cracks in hydraulic concrete result from the multi-field coupling of physical, chemical, and mechanical factors. The synergistic evolution of these factors imparts nonlinear and time-varying characteristics to the cracks, significantly increasing the difficulty of identification and monitoring.

Under physical effects, freeze-thaw cycles in the Tibet region cause pore water in concrete to freeze and expand, generating internal stresses up to 200 MPa. Repeated action promotes the transition from micro-cracks to macro-cracks. In high-velocity flow areas, water flow abrasion and cavitation strip away the surface mortar, reducing surface strength by over 20% and providing pathways for the intrusion of corrosive media, thereby accelerating crack propagation.

Chemically, sulfate erosion reacts with concrete hydration products to form expansive substances, causing internal stress concentration that connects micro-cracks. Chloride ion intrusion destroys the passivation film of reinforcing steel, and the expansion of rust products causes the protective cover to crack. The synergistic effect of these two processes can reduce the mechanical properties of concrete by over 30%.

Mechanically, mechanical stresses generated by structural self-weight and water pressure superimpose with thermal stresses induced by temperature gradients, forming crack tips in stress concentration zones and accelerating their propagation. Additionally, micro-cracks caused by concrete drying shrinkage and creep can develop into macro-cracks under external loads. Under multi-field coupling, increased frequency of temperature and humidity fluctuations significantly raises the peak internal stress of the concrete, shortening the structural fatigue life by approximately 25%, further complicating crack evolution.

2.2 Challenges in Crack Identification Under Complex Environments

Crack identification in hydraulic concrete under complex environments is constrained by environmental interference, crack morphology, and scale factors, limiting detection accuracy and efficiency. The core challenges are reflected in four aspects:

Severe Environmental Noise Interference: Mechanical noise from water flow and vibrations can mask acoustic emission signals. Lighting conditions and water stains reduce the signal-to-noise ratio in image recognition. Temperature fluctuations interfere with the temperature difference signals in infrared thermography, easily leading to missed detections and false positives.

Complex Crack Morphology and Easy Missed Detection in Concealed Areas: Multi-field coupling forms complex cracks, such as intersecting and turtle-shell patterns, which are difficult to fully identify using traditional methods. Detection coverage is insufficient in concealed areas like beam-column corners, the back faces of structures, and underwater zones, resulting in a missed detection rate of up to 42%.

Wide Crack Scale Span and Poor Adaptability of Single Methods: Structures contain both micro-cracks at the 0.1 mm level and wide, deep cracks exceeding 15 mm. Different detection methods have their own limitations, making it difficult to accommodate full-scale crack detection requirements.

Operational Restrictions in Harsh Environments and Low Automation: In environments such as high altitudes, severe cold, and underwater, manual inspections and traditional detection methods suffer from low safety and poor efficiency, making it impossible to conduct continuous, large-area inspections.

III. MAINSTREAM METHODS FOR CRACK IDENTIFICATION IN HYDRAULIC CONCRETE UNDER COMPLEX ENVIRONMENTS

3.1 Traditional Non-Destructive Testing Methods

Traditional NDT serves as the fundamental means for crack identification in hydraulic concrete. Characterized by technological maturity, ease of operation, and low cost, it is suitable for rapid on-site testing and preliminary screening. Each method has its specific principles and applicable scenarios, allowing for selection based on specific needs.

3.1.1 Ultrasonic Testing Technology

Ultrasonic testing is employed to detect internal defects in concrete structures. When ultrasonic waves propagate to defects such as cracks and voids, the wave velocity decreases significantly, accompanied by waveform distortion. According to the concrete quality classification standards specified in SL/T 352—2020, the internal quality condition of the structure can be determined[3], as shown in Table 1.

Table 1 Standard for Ultrasonic Testing of Concrete Quality Classification

quality grade	Wave Velocity Range/ (km/s)	attenuation coefficient/ (dB/m)	estimation of quality
I 级	≥ 4.5	≤ 8.0	excellent
II 级	4.0~4.5	8.0~10.0	all right
III 级	3.5~4.0	10.0~12.0	just like
IV 级	< 3.5	> 12.0	range

3.1.2 Surface Wave Testing Technology

By exciting Rayleigh waves to propagate along the concrete surface, this method identifies crack locations and depths by analyzing changes in wave velocity and waveform, with a detection range exceeding 1 m. Its accuracy for detecting vertical cracks approximately 40 cm deep surpasses that of ultrasonic methods; detection errors decrease significantly with lower crack depths, demonstrating notable advantages in identifying medium-deep and complex-shaped cracks[4]. The technique is suitable for detecting deep cracks in large-volume concrete structures but requires high surface flatness, necessitating prior removal of surface contaminants, floating slurry, and water stains.

3.1.3 Infrared thermal imaging technology

The system employs a 640×512-pixel uncooled vanadium oxide focal plane detector to capture thermal radiation differences between cracks and the substrate for crack identification. By processing the temperature difference signals at crack locations, the thermal image achieves a signal-to-noise ratio of up to 38 dB, enabling the construction of three-dimensional visual models of cracks through 3D laser scanning. This method is non-contact, capable of large-scale applications, and offers rapid screening, making it suitable for preliminary inspection of extensive structures such as dam surfaces and spillways. However, its performance is susceptible to factors like sunlight exposure, temperature/humidity conditions, and surface contaminants, with identification accuracy declining in environments with weak temperature gradients.

3.2 Intelligent Sensing and Monitoring Methods

Smart sensing monitoring overcomes the limitations of traditional non-destructive testing, which is static and offline, enabling dynamic, online, and continuous crack monitoring and early warning. It can capture the initiation and propagation process of cracks in real time, serving as a core technology for early crack detection and suitable for long-term monitoring of critical engineering components[5].

3.2.1 Multi-source Sensing Network Technology

This approach establishes a multi-source network integrating fiber Bragg grating (FBG), acoustic emission (AE), and electrochemical sensing to achieve full lifecycle monitoring of cracks: FBG sensors provide measurement accuracy of $\pm 2 \mu\text{m}$ while real-time recording strain and temperature variations; AE sensors capture elastic wave signals associated with crack propagation to assess crack activity; electrochemical sensors monitor chloride ion concentration and pH levels, enabling early warning of cracks induced by steel bar corrosion. Data are preprocessed using techniques such as wavelet denoising and integrated with a visualization platform for real-time structural health assessment. While this method enables early crack detection and dynamic alerts, it faces challenges including complex sensor deployment and wiring requirements, high maintenance costs, significant data redundancy, and substantial demands on data processing and analysis capabilities.

3.2.2 Coupling Method Between Acoustic Emission and Damage Mechanics

By integrating the time-domain and frequency-domain characteristics of acoustic emission signals with damage mechanics theory, a crack evolution model was developed to enable dynamic tracking and quantitative analysis. Characteristic parameters of acoustic emission signals were extracted, and CNN was employed for automatic identification of crack types and damage severity, achieving a diagnostic accuracy of $\geq 90\%$. The damage variable D was introduced, and the stress-strain relationship coupled with the damage evolution equation was established to simulate the entire process from crack initiation to instability, with simulation results deviating by $\leq 10\%$ from experimental measurements. This method enables dynamic simulation and quantitative evaluation of crack evolution, providing a theoretical basis for safety early warning; however, it requires optimal sensor placement and ensures complete and reliable signal acquisition.

IV. OPTIMIZATION AND INTEGRATED APPLICATION OF CRACK IDENTIFICATION METHODS UNDER COMPLEX ENVIRONMENTS

4.1 Multi-method Integration and Optimization Strategy

To address the limitations of single identification methods, this study proposes a three-tier multi-method integration and optimization strategy of "surface screening - deep detection - precise quantification" by combining the technical advantages and applicable scenarios of various methods. This strategy achieves complementary advantages of different technologies, thereby improving the accuracy and efficiency of crack identification in hydraulic concrete under complex environments.

Tier 1: Large-area rapid surface screening to identify potential crack zones. Infrared thermography is utilized for non-contact, large-scale, and rapid detection of hydraulic concrete structures. Leveraging its high detection efficiency and broad coverage, this method quickly identifies potential and concealed crack zones in large-area structures such as dam faces and spillways. The screening efficiency is improved by more than 10 times compared to manual inspections, effectively delineating the scope for subsequent precise detection and reducing the workload of invalid testing.

Tier 2: Deep precise detection of suspected zones to determine crack depth and distribution. For suspected crack zones identified via infrared thermography, the surface wave method is employed for deep crack detection to determine the depth, orientation, and distribution characteristics of the cracks. For shallow surface cracks, the ultrasonic method is combined for cross-validation. Through the synergistic detection of these two methods, the error in crack depth detection is controlled within 8%, achieving precise spatial localization of the cracks.

Tier 3: Precise quantification of crack geometric parameters to evaluate propagation trends. For localized crack zones, deep learning-driven image recognition methods are used to achieve pixel-level precise quantification of geometric parameters such as crack length, width, and area. Concurrently, by integrating real-time monitoring data from multi-source sensor networks, the strain and vibration characteristics of the cracks are analyzed to construct a crack propagation trend model. This evaluates the crack's activity and development trend, providing accurate data support for

engineering operation and maintenance (O&M) decision-making.

This three-tier integration strategy realizes a full-process detection workflow ranging "from large-scale screening to precise localization, from qualitative identification to quantitative analysis, and from static detection to dynamic early warning." It effectively resolves the issue that single methods struggle to accommodate cracks of different scales and morphologies, significantly enhancing identification accuracy under complex environments.

4.2 Improvement Measures for Complex Environment Adaptability

Targeting the characteristics of complex environments such as high humidity, low illumination, freeze-thaw cycles, and high-velocity flows, targeted improvement measures are implemented across detection equipment, algorithm models, and data processing to enhance the environmental adaptability and anti-interference capabilities of crack identification technologies.

First, optimize the weather resistance of detection equipment. During sensor deployment, waterproof, anti-corrosion, and freeze-thaw resistant encapsulation materials are selected to extend the service life of sensors, such as Fiber Bragg Grating (FBG) and acoustic emission sensors, in complex environments. Weather-resistant image acquisition equipment equipped with waterproof and anti-fog lenses is utilized to minimize the impact of water stains and fog on image acquisition quality, making it suitable for underwater and high-humidity environments.

Second, improve the anti-interference capability of algorithm models. For low-light environments, image enhancement techniques such as histogram equalization and the Retinex algorithm are applied to improve image brightness, contrast, and overall quality. To address issues with water stains and dirt coverage, adaptive threshold segmentation and morphological processing are employed to eliminate background interference and highlight crack features. For areas frequently subjected to freeze-thaw cycles, the frequency filtering range of acoustic emission signals is optimized to 100 kHz–500 kHz to emphasize effective signals of crack propagation and suppress noise interference caused by temperature fluctuations[6].

Third, refine data preprocessing techniques. To tackle noise interference in detection data under complex environments, a combination of data preprocessing techniques—including wavelet denoising, adaptive filtering, and principal component analysis (PCA)—is applied. These techniques denoise and reduce the dimensionality of detection signals (ultrasonic, surface wave, acoustic emission) and image data, thereby improving the signal-to-noise ratio and mitigating the impact of noise on identification accuracy[7].

4.3 Engineering Application Case Study

Taking the Fengman Hydropower Station gravity dam as an example[8], this dam is located in a cold northern region and has long been subjected to complex environmental effects such as freeze-thaw cycles and water flow scouring. The concrete on the dam face exhibits varying degrees of crack defects. An integrated identification scheme comprising "infrared thermography + surface wave detection + deep learning image recognition + multi-source sensor monitoring" was implemented to conduct crack identification and monitoring.

First, infrared thermography was used for large-area rapid screening of a 120,000 m² dam face area, identifying 32 suspected crack zones and achieving rapid localization of potential defects. Second, the surface wave method was applied to the 32 suspected zones for deep detection, combined with ultrasonic cross-validation. This revealed two deep, hazardous cracks exceeding 80 cm in depth and clarified the depth, orientation, and distribution characteristics of all identified cracks. Third, deep learning image recognition was utilized to precisely quantify all crack zones, obtaining geometric parameters including length, width, and area, with a minimum identifiable crack width of 0.1 mm. Finally, a multi-source sensor network was deployed in the hazardous crack zones to monitor strain and vibration characteristics in real time. A crack propagation trend model was constructed, predicting that the maximum crack width would expand from 0.3 mm to 0.5 mm within three months.

Based on the detection and monitoring results, the engineering authorities promptly implemented treatment measures, such as surface sealing and grouting reinforcement, effectively inhibiting further crack propagation and ensuring the safe operation of the dam. This engineering case demonstrates that the integrated identification scheme achieves a 92% accuracy rate in crack identification under complex environments, enabling precise capture of micro-cracks and effective detection of deep cracks. It provides accurate data support for O&M decision-making of hydraulic concrete

structures, validating the feasibility and practicality of the multi-method integration strategy.

V. CONCLUSION

5.1 Research Conclusions

Cracks in hydraulic concrete under complex environments are formed through the multi-field coupling of physical, chemical, and mechanical factors. Crack identification faces significant challenges, including severe environmental interference, complex crack morphologies, a wide span of crack scales, and a high susceptibility to missed detections in concealed areas. Consequently, single identification methods struggle to meet the refined and intelligent operation and maintenance (O&M) demands of engineering projects.

Traditional non-destructive testing (NDT) serves as the fundamental means for crack identification. Ultrasonic testing is suitable for shallow surface crack detection, surface wave methods excel in identifying deep cracks, and infrared thermography is ideal for rapid, large-area screening. Intelligent sensing monitoring enables dynamic, online, and continuous tracking of cracks, representing the core technology for early crack warning. Deep learning-driven image recognition achieves pixel-level precise quantification of crack geometric parameters, making it highly suitable for high-precision detection of cracks with complex surface morphologies. Each of these three methods possesses distinct technical advantages and specific application scenarios[9].

By constructing a three-tier multi-method integration strategy of "surface screening - deep detection - precise quantification," and incorporating environmental adaptability improvements across detection equipment, algorithm models, and data processing, complementary technical advantages can be realized. This effectively enhances crack identification accuracy under complex environments, achieving precise localization of micro-cracks at the 0.1 mm level and an identification accuracy rate exceeding 90%. The comprehensive solution framework of "mechanism analysis - technology selection - precise identification - dynamic warning" established in this study provides reliable technical support for the safe O&M of hydraulic concrete structures.

5.2 Future Perspectives

As water conservancy engineering advances toward intelligentization and digitalization, crack identification technologies for hydraulic concrete will evolve toward multi-source fusion, intelligent early warning, and digital twin applications. Future research can be deepened in the following three aspects[10]:

1. Optimize multi-source data fusion models: Delve into the fusion mechanisms of heterogeneous data from ultrasonic testing, infrared thermography, and sensor monitoring. Combine this with machine learning to extract crack evolution characteristics, thereby improving the comprehensiveness of identification and the accuracy of damage assessment.
2. Develop advanced sensing equipment: Research and develop low-cost, highly weather-resistant, and miniaturized sensors, such as Fiber Bragg Grating (FBG) and acoustic emission sensors. Concurrently, develop wireless sensor network technologies to enable lightweight equipment deployment and reduce O&M costs.
3. Integrate BIM and digital twin technologies: Construct digital twin models for hydraulic concrete structures to visualize crack characteristics by linking detection data. Combine this with evolution models to dynamically simulate and predict crack propagation, thereby building an intelligent early warning system. This will drive the transformation of crack identification from precise detection to intelligent warning and proactive prevention/control.

Additionally, it is essential to strengthen interdisciplinary integration across materials science, mechanics, and computer science to refine the theoretical and technological framework for crack identification. Establishing specialized datasets that cover diverse environmental conditions and crack morphologies will enhance the generalization and cross-scenario adaptability of deep learning models, providing stronger technical support for the full-lifecycle safe O&M of water conservancy projects.

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