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Advances and Challenges in Non-Destructive Testing (NDT) Methods for Underwater Concrete Structures

Shamima Akter Shimky[1], Minhajul Islam Mim[2], Fei Yao[1]

[1]College of Civil Engineering and Transportation, Hohai University, Nanjing, China
[2]Department of Information and Communication Engineering, Hohai University, Nanjing, China
Email: shamimaakter3493@gmail.com, minhajulislam435@outlook.com, yaofei215@hhu.edu.cn

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Abstract

The underwater concrete structures are one of infrastructure facilities to secure the underwater environment safely, in which, the dam, the offshore platform, and under water bridge element are representative cases. They are all subject to extremely severe marine climatic conditions and routine condition assessment is necessary to ensure the safety and performance of the spillway over the long term. Structural health conditions of these application parts are commonly inspected based on Non-Destructive Testing (NDT) methods. This review introduces the progresses and challenges of four common, nondestructive testing (NDT) techniques (impact-echo, ultrasonic testing, acoustic emission, hybrid method) of underwater concrete. The basic principles, applicators, limitations, and recent technological developments for each approach are described. In this paper, we consider advances in underwater diagnostics, in particular recent advances, such as the use of artificial intelligence (AI) for defect detection, advanced signal processing, sensor fusion and robotics inspection systems, and how these may benefit from technologies previously available in diagnostics. There are limitations such as bounding signal degradation, environmental pollution, easy installation. There is no universal application of the operation. The paper ends, with identifying the future research directions focused beam for improving real-time monitoring, the integration of AI and IoT and development of ruggedized automated underwater NDT systems. For engineers and researchers and asset managers and those within inspection and maintenance of underwater concrete structures, the review serves as an excellent reference.

Keywords

Underwater Concrete Structures, Non-Destructive Testing (NDT), Impact-Echo, Ultrasonic Testing, Acoustic Emission, Hybrid Techniques, Structural Health Monitoring, Signal Processing, Corrosion Detection, Sensor Fusion, Machine Learning, Real-Time Monitoring

1. Introduction

The underwater concrete structures of dams, piers, quay walls, tunnels, oil platforms etc., under the sea are the basic structures on which the life of human beings all over the world depends. These structures are continuously under aggressive conditions due to factors like entrance of chlorides, sulphates, hydrostatic pressure, thermal cycles and wave and current loading in the submerged environment [1]. Over time, these factors result in failure mechanisms, such as cracking, corrosion of reinforcement, delamination, and loss of material strength and threaten the safety and service life of these structures. Many of these installations are old and located in remote or hostile areas, so early detection of degradation is crucial to avoid catastrophic failure and reduce maintenance costs [2]. It is within this context that certain Non-Destructive Testing methods are used in structural monitoring, in which the engineer can examine the inner and surface conditions of the structure without affecting its integrity. Conventional visual testing (VT) is inadequate for underwater or large elements, and destructive tests are too intrusive to be conducted in the maritime environment. As such, advanced NDT techniques are critical for successful piecewise examination. The review paper thus investigates the four major NDT techniques, namely Impact-Echo, Ultrasonic Testing, Acoustic Emission, and Hybrid Techniques as prominent simulators used for UWC structure evaluation [3]. For each of these potential simulators, we discuss their modes/behaviors, working principles, competence in underwater applications, constraining factors, and mitigation methodologies. The inclusion of artificial intelligence, sensor technology, signal processing, and automation are also new trends driving the future of subsea NDT. This review might offer the practicing engineer, professional, and researcher an insightful perspective on the existing technologies.

2. Fundamentals of Underwater NDT Methods

2.1. Classification of NDT Methods

- NDT methods for underwater concrete structures can generally be divided, according to the physical principle utilized and with respect to their testing capabilities DivineMadhoorandSolomon2014, into two main categories: 1) (physical principle) and 2) (defect detection). Two broad categories of LD are pertinent to this report [4].

2.1.1. Acoustic-Based Methods

Acoustic NDT methods evaluate the interior of concrete using stress waves (mechanical vibrations). These techniques are very sensitive to the presence of internal anomalies such as voids, delamination's and cracks [5]. Typical techniques based on acoustic include the following:

Impact-Echo (IE):

- Applies a short-term mechanical impact to generate stress waves within a structure [6].
- Analyzes reflected waves from internal defects to identify anomalies.
- Commonly used for measuring thickness, detecting voids, and mapping delamination.

Ultrasonic Testing (UT):

- Employs high-frequency sound waves that pass-through concrete.
- Can be utilized in various scanning modes, including pulse-echo, through-transmission, and phased array.
- Ideal for assessing concrete quality, searching for voids, and determining material homogeneity [7].

Acoustic Emission (AE):

- Monitors real-time elastic waves emitted by active defects such as crack growth or corrosion.
- AE sensors capture the released energy, which is analyzed to locate the source of damage.
- Particularly effective for tracking the structural health over time [8].

Advantages:

- Internal defects are easily detectable.
- Provides an objective means of collecting both quantitative and qualitative data.
- Can be adapted for underwater applications by selecting appropriate sensors.

Limitations:

- Sound signal propagation can be attenuated in water.
- Interpretation of results may be complicated by noise and the heterogeneity of concrete.

2.1.2. Hybrid NDT Techniques

Hybrid Non-Destructive Testing (NDT) methods are created by combining two or more individual modalities to enhance diagnostic reliability, sensitivity, and coverage. The integration of complementary physical principles enables a more comprehensive structural characterization [9].

Common Hybrid Approaches:

- **Acoustic Emission (AE) + Review + Electrochemical Sensor:**

This approach is used for corrosion monitoring. AE detects cracks caused by corrosion, while electrochemical sensors measure chloride ingress and half-cell potential [10].

- **Ultrasonic Testing (UT) + Infrared Thermography (IR):**

Currently applied in monitoring systems for thick-walled welds, this combination utilizes non-contact detection and temperature measurement. UT identifies internal flaws, while IR detects variations in surface temperature indicative of subsurface defects or moisture ingress [11].

- **Drones + Multi-Sensor Vehicles (MSVs):**

Utilizing remotely operated vehicles (ROVs) or drones equipped with ground-penetrating radar (GPR), sonar, visual, and imaging sensors, this approach facilitates extensive underwater inspections [12].

Advantages:

- Mitigates the limitations of individual methods.
- Enhances confidence in defect characterization.
- Reduces false positives and increases coverage area.

Limitations:

- Challenges in data fusion and interpretation.
- Higher costs due to the complexity and number of sensors required.
- Necessitates advanced software and skilled operators.

2.2. Challenges in Underwater Environments

Applying Non-Destructive Testing (NDT) methods to underwater concrete structures presents unique technical and operational challenges that differ significantly from those in dry or above-water conditions. These challenges impact the reliability, accuracy, and feasibility of inspection procedures [13].

2.2.1. Signal Attenuation due to Water and Marine Growth

- **Underwater Interface:**
    - Acoustic signals, especially high-frequency waves, experience rapid attenuation in water and concrete during transmission.
    - This attenuation is influenced by factors such as depth, temperature variations, salinity differences, and the presence of suspended particles.
    - As a result, the distance for effective defect inspection is limited, and the signal strength diminishes, making it challenging to detect small defects [14].
- **Marine Growth:**
    - Biofouling organisms, including barnacles, algae, and mollusks, create inhomogeneities on the concrete surface, impacting signal propagation [15].
    - The presence of marine life forms an insulating barrier between the sensor and the concrete surface, disrupting effective coupling.
    - This can lead to deflection or absorption of acoustic signals, resulting in distorted readings and inaccurate measurements [16].

2.2.2. Challenges in Sensor Placement and Data Collection

- **Limited Accessibility and Stability:**
    - Underwater structures are often located in hard-to-reach or hazardous areas, such as submerged pier supports and offshore platforms.
    - The manual deployment of sensors by divers is time-consuming, labor-intensive, and poses safety risks.
    - Maintaining sensor contact with the structure's surface is challenging due

to water currents and poor visibility [17].

- **Surface Preparation:**
  - Effective non-destructive testing (NDT) relies on clean, flat surfaces for optimal signal transmission.
  - Cleaning surfaces underwater is difficult, often requiring mechanical tools or abrasive blasting, depending on the situation.
- **Equipment Movement Restrictions:**
  - The movement of equipment is limited, complicating the installation of heavy and delicate devices in aquatic environments.
  - Constraints related to tethering, power availability, and diver time further impede data collection efforts [18].

2.2.3. Environmental Noise and Signal Clarity

- **Background Noise:**
  - Underwater environments are rich in sound, filled with waves, marine organism calls, ship traffic, pumps, and turbines.
  - These diverse frequencies can interfere with NDT signal frequencies, obscuring data clarity [19].
- **Signal-to-Noise Ratio (SNR) Challenges:**
  - The SNR, defined as the ratio of signal power to noise power, is crucial for detecting weak or subtle signals, particularly in Acoustic Emission and Ultrasonic techniques.
  - Low SNR can mask early signs of damage, delaying necessary interventions [20].
- **Interference from Electronic Devices:**
  - Underwater facilities may introduce electromagnetic or acoustic interference, complicating interactions with sensitive sensors.

3. Acoustic-Based NDT Techniques

3.1. Impact-Echo Method

Impact-Echo (IE) Method Overview

The Impact-Echo (IE) method is a widely used acoustic nondestructive testing (NDT) technique for evaluating the condition of concrete structures. It is particularly effective for non-destructive inspections aimed at identifying internal defects, and it can be applied in both wet and underwater environments [21].

3.1.1. Principle

- The IE technique operates by generating a brief impact on the concrete surface using a small hammer, steel ball, or solenoid plunger.
- This impact produces low-frequency stress waves—both compression and shear—that propagate through the material.
- When these waves encounter changes in the material, such as voids, delamination's, or boundaries, they are reflected back to the surface.
- A receiver (transducer or sensor) captures the lateral vibrations at the sur-

face, which are then analyzed by performing a Fast Fourier Transform (FFT) to convert the time-domain signal into the frequency domain [22].

- The frequency spectrum reveals peaks that correspond to resonant frequencies, which are used to ascertain the depth and location of internal discontinuities based on known wave speeds [23].

3.1.2. Applications

The Impact-Echo method is versatile and applicable to various types of concrete elements. Key applications include:

- **Internal Voids:** Detection of issues such as honeycombing and inadequate compaction within concrete.
- **Delamination Mapping:** Identification of cracking between layers (e.g., concrete overlays) or between reinforcing layers and concrete covers [24].
- **Depth Measurement:** Measuring the depth of walls and structural members in situations where only one side is accessible [25].
- **Precast Inspection:** Evaluating precast units for structural integrity prior to installation.

The IE method can also be adapted for underwater conditions using submersible sensors and remote impact devices, enabling the evaluation of submerged piers, slabs, and offshore platforms [26].

3.1.3. Limitations

While the IE method offers several advantages, it also presents limitations, particularly in underwater scenarios:

- **Dependence on Surface Condition:**
  - Rough or uneven surfaces can scatter waves, complicating the interpretation of signals.
  - Marine growth or water layers may hinder sensor coupling, negatively impacting signal quality [27].
- **Interpretation Challenges:**
  - Differentiating multiple reflections in non-homogeneous concrete can be difficult.
  - Overlapping peaks and low signal-to-noise ratios can complicate the measurement of flaw depth and size [28].
- **Single Point Limitation:**
  - Conventional IE measurements are taken at specific sensor locations, which may result in missed local defects unless a dense grid of measurements is employed [29].

3.1.4. Recent Improvements

Recent advancements in the Impact-Echo method have been driven by innovative technologies:

- **Machine Learning and Adaptive Signal Analysis:**
  - These technologies facilitate pattern recognition, clustering algorithms, and neural networks for automated defect classification, reducing human

interpretation errors.

- They enhance the repeatability and precision of defect detection and measurement [30].

- **Multitransducer Devices:**
  - Multi-channel/beam IE systems can simultaneously measure over larger areas.
  - This capability leads to faster data acquisition and improved spatial resolution [31].
- **3D SIBIE Imaging (Stack Imaging of Spectral Amplitudes Based on Impact-Echo):**
  - This imaging technique provides a 3D visualization of internal concrete voids derived from multiple IE measurements.
  - It offers a more comprehensive analysis and better focus on flaws compared to conventional single-frequency methods [32].

3.2. Ultrasonic Testing

3.2.1. Types

Ultrasonic testing methods used for underwater concrete inspection can be broadly categorized into Pulse-Echo, Through-Transmission, and Phased Array Ultrasonic Testing (PAUT). The Pulse-Echo technique utilizes a single transducer that emits ultrasonic waves into the concrete and then receives the reflected echoes from internal flaws or interfaces. This method is particularly suitable for underwater environments where only single-sided access is available, such as in submerged piers or dam faces. In contrast, the Through-Transmission method requires a transmitter and a receiver to be placed on opposite sides of the structure. A decrease in received signal energy typically indicates the presence of internal defects. However, due to the need for dual-sided access, this method is less practical for underwater applications. Finally, Phased Array Ultrasonic Testing (PAUT) employs an array of transducers that can emit synchronized ultrasonic pulses, allowing for beam steering, focusing, and real-time imaging. This technique provides high-resolution inspections and is highly suitable for underwater use, especially when integrated with Remotely Operated Vehicles (ROVs) or Autonomous Underwater Vehicles (AUVs) for automated and extended coverage of submerged structures [33].

Pulse-Echo is favored in underwater inspections where only one side of the structure is accessible.

PAUT offers real-time defect imaging and is increasingly adopted for offshore concrete and steel-concrete composites.

3.2.2. Applications

Ultrasonic testing serves a range of diagnostic purposes in underwater concrete structures. It is widely used for flaw detection, enabling the identification of internal anomalies such as cracks, voids, honeycombing, and delamination. The method is also effective for thickness measurement, particularly when access is available from only one side of the structure, as in the case of submerged walls or piles. In addition, ultrasonic testing allows for material characterization, such as estimating the elastic modulus, density, and homogeneity of the concrete. Lastly, it plays a key role in bond integrity testing, helping to evaluate the effectiveness of overlays, grout injections, or the interface between steel reinforcements and concrete [34] (**Table 1**).

Table 1. Applications of ultrasonic testing in underwater concrete structures.

Application	Purpose
Flaw Detection	Cracks, voids, honeycombing, delamination
Thickness Measurement	Evaluation of slab/pile/wall thickness, especially in single-side access
Material Characterization	Estimation of elastic modulus, density, and homogeneity
Bond Integrity Testing	Evaluation of overlays, grout injections, or steel-concrete interfaces

3.2.3. Limitations

Ultrasonic testing faces several limitations when applied to underwater concrete structures. One major constraint is the need for an effective coupling medium; although water itself can act as a medium, marine growth, biofouling, or surface irregularity can hinder proper transducer coupling and reduce signal reliability [35]. Additionally, signal attenuation occurs due to the presence of coarse aggregates and water-filled pores, which diminish wave intensity and reduce the depth of penetration. The presence of heterogeneous materials, such as embedded steel reinforcements or large aggregates, further complicates signal interpretation by causing wave scattering and diffraction. Finally, access and alignment challenges arise because precise positioning of sensors underwater is difficult, especially without the assistance of robotic systems or positioning arms, which limits inspection coverage and repeatability [36].

3.2.4. Recent Improvements

Recent advancements have significantly enhanced the effectiveness of ultrasonic testing in underwater environments. The adoption of Phased Array Ultrasonic Testing (PAUT) allows for fast, steerable scanning and provides 2D or 3D imaging, which improves the detection and characterization of subsurface defects. In parallel, advanced signal processing techniques—such as Fast Fourier Transform (FFT), wavelet analysis, and AI-based classification algorithms—have improved the accuracy of flaw detection by enhancing signal clarity and enabling automated interpretation [37]. The development of smart underwater probes, including self-leveling sensors or those mounted on Remotely Operated Vehicles (ROVs), ensures better stability and precision during inspections in turbulent or inaccessible zones [38]. Finally, the hybrid integration of ultrasonic methods with other techniques like Impact-Echo or Acoustic Emission boosts diagnostic reliability by providing complementary insights from multiple NDT approaches [39] (**Table 2**).

Table 2. Recent improvements in ultrasonic testing for underwater concrete structures.

Improvement	Impact
Phased Array Ultrasonic Testing	Enables rapid, steerable scanning with 2D or 3D imaging of defect zones
Advanced Signal Processing	FFT, wavelet transforms, AI-based classification improve defect recognition
Smart Underwater Probes	Self-leveling or ROV-mounted probes allow stable underwater measurements
Hybrid Integration	Combined use with Impact-Echo or Acoustic Emission enhances reliability

Key Equations

1) Depth Estimation in Pulse-Echo Mode

Used to determine defect or back-wall location:

$$\boldsymbol{d} = \frac{\boldsymbol{Ct}}{2}$$

where:

- $\boldsymbol{d}$ = depth or thickness (m)
- $\boldsymbol{C}$ = ultrasonic wave velocity in concrete (typically 3500 - 4500 m/s)
- $\boldsymbol{t}$ = round-trip time-of-flight of the signal (s)

2) Material Characterization via Wave Speed

Determines compressional wave velocity:

$$C = \frac{L}{t}$$

where:

- C = wave speed (m/s)
- L = known distance between sensors (m)
- t = travel time of wave (s)

3) Dynamic Modulus Estimation

If density ρ is known:

$$E_d = \rho C^2$$

where:

- E_d = dynamic modulus of elasticity (Pa)
- ρ = concrete density (kg/m^3)
- C = wave velocity (m/s)

3.3. Acoustic Emission Monitoring

Acoustic Emission (AE) is a passive, non-destructive method used to observe transient elastic waves generated by the rapid release of energy from localized sources, such as crack formation, corrosion activity, or micro-damage within a structure. AE is increasingly advantageous for monitoring underwater concrete structures, enabling real-time assessment of degradation processes without interrupting service [40].

3.3.1. Principle

AE can detect stress waves produced by internal activities, such as micro-cracking or corrosion-induced rupture, within the material. These waves propagate through the concrete and are captured by sensors, which may be either surface-mounted or embedded within the material [41].

- The underlying principle is based on wave propagation theory, which states that local events (such as crack tips) emit elastic waves.
- In concrete, AE signals typically fall within the frequency range of 100 kHz to 1 MHz.
- Triangulation of the event source is achieved by analyzing the Time-of-Arrival (TOA) of signals detected by multiple sensors.

Key Equation: Source Location (Triangulation)

In 2D localization:

$$(x - x_i)^2 + (y - y_i)^2 = v^2 (t_i - t_o)^2$$

where:

- (x, y): source coordinates
- (x_i, y_i): sensor location
- v: wave velocity in concrete
- t_i: arrival time at sensor iii
- t_o: event occurrence time.

3.3.2. Applications

Acoustic Emission (AE) monitoring plays a vital role in the real-time evaluation of underwater concrete structures. One of its primary uses is in crack propagation monitoring, where it detects the release of energy during active crack formation, especially under conditions of mechanical loading or thermal variation. This provides valuable insight into the structure's response to environmental or operational stresses. Additionally, AE is effective in corrosion detection, as it can sense micro-events associated with rust-induced expansion or deterioration of steel-concrete bonds [42]. Another key application is in identifying leakage or cavitation, where sudden pressure changes or fluid turbulence in submerged pipelines or structures produce high-energy acoustic signals. Finally, AE is widely used in structural health monitoring, enabling long-term, continuous surveillance of concrete condition throughout its service life, which is essential for early fault detection and preventive maintenance planning [43] (**Table 3**).

Table 3. Applications of acoustic emission monitoring in underwater concrete structures.

Application	Description
Crack Propagation Monitoring	Detects active cracking in real-time, especially under loading or temperature change
Corrosion Detection	Captures micro-events caused by rust expansion or bond deterioration

Continued

Leakage and Cavitation	Identifies high-energy bursts caused by pressure loss in submerged pipes/structures
Structural Health Monitoring	Continuous condition assessment over the service life

3.3.3. Limitations

While Acoustic Emission (AE) monitoring offers real-time diagnostic capabilities, its application in underwater environments faces several limitations. One of the most significant issues is environmental noise interference, where marine traffic, wave activity, and biological sources such as fish or marine mammals can generate background noise that mimics or obscures true AE signals [44]. Another challenge is source localization, which requires accurate acoustic velocity models of the structure and often a dense array of sensors to triangulate the emission source—a requirement that is difficult to achieve underwater. Additionally, signal attenuation is a critical limitation; high-frequency AE waves are more rapidly absorbed in water compared to lower-frequency signals used in methods like ultrasonic testing, which reduces the detection range and sensitivity. Finally, complex data interpretation is a persistent issue due to waveform dispersion, overlapping events, and the need to distinguish between different types of signals, often requiring advanced filtering or machine learning techniques to improve reliability [45].

3.3.4. Recent Improvements

Recent technological advancements have significantly enhanced the performance and applicability of Acoustic Emission (AE) monitoring in underwater concrete structures. One major improvement is the development of fiber-optic AE sensors, such as Fiber Bragg Grating (FBG) sensors, which are highly resistant to corrosion, unaffected by electromagnetic interference, and capable of functioning reliably in high-pressure submerged environments [46]. In addition, machine learning algorithms—including neural networks and Support Vector Machines (SVMs)—have been applied to classify AE signals more accurately, reducing false alarms by distinguishing between structural emissions and background noise. Another advancement is the use of wavelet-based de-noising techniques, which help extract meaningful AE data from noisy underwater environments by isolating relevant signal components. Lastly, AE data is increasingly being integrated with structural models, such as finite element simulations, to correlate acoustic activity with predicted stress or damage zones, enabling predictive assessments and enhancing decision-making in maintenance planning [47].

Key Signal Parameters in AE Analysis

Parameter	Definition	Significance
Amplitude (dB)	Peak signal strength	Higher values indicate more intense events
Duration (μs)	Time from first to last threshold crossing	Indicates the nature of the emission source

Continued

Rise Time	Time from onset to peak amplitude	Helps differentiate crack vs friction signals
Counts	Number of threshold crossings	Higher counts suggest greater event activity
Energy	Area under the envelope of the signal	Proportional to severity of damage

4. Hybrid and Advanced NDT Techniques

4.1. Concept and Benefits

Concept

"Hybrid Non-Destructive Testing (NDT) involves combining two or more NDT techniques, either independently or in tandem, to leverage the complementary strengths of each method while minimizing their individual limitations. In underwater concrete structures, hybrid systems offer significantly more reliable and clearer signals with higher resolution compared to localized measurements [48].

Some commonly used hybrid approaches include:

- IE + UT for detecting voids and delamination's
- Acoustic Emission (AE) + Electrochemical Impedance Spectroscopy (EIS) for monitoring corrosion due to CO_2
- AE + Infrared Thermography (IRT) for assessing crack progression and moisture levels
- Ultrasonic Testing (UT) + Ground Penetrating Radar (GPR) for internal structural imaging"

Benefits

Benefit	Description
Enhanced Defect Detection	Combines shallow and deep scanning techniques (e.g., surface AE + deep UT)
Reduced False Positives/Negatives	Cross-validation across methods ensures higher diagnostic accuracy
Comprehensive Structural Evaluation	Simultaneous detection of mechanical, chemical, and thermal indicators
Adaptability to Complex Conditions	Useful in high-noise, submerged, or heterogeneous environments
Improved Localization of Anomalies	Fusion of spatial and temporal data allows precise mapping of damage
Real-Time and Continuous Monitoring	Some hybrid setups enable ongoing health tracking with minimal manual input

Illustrative Example

Component	Method 1	Method 2	Hybrid Outcome
Corrosion Detection	AE	EIS	Detect initiation (AE) and quantify extent (EIS)
Crack Growth	AE	IRT	Monitor propagation (AE) + thermal signature (IRT)
Delamination Mapping	IE	UT (Pulse-Echo)	Cross-check reflection signals for accurate depth

Mathematical Representation: Data Fusion

Hybrid systems often rely on **data fusion** techniques to combine outputs. A basic data fusion model:

$$D_{\text{hybrid}} = f\left(D_1, D_2 \cdots D_n\right)$$

where:

- D_{hybrid} : fused diagnostic decision
- D_i : diagnostic data from method iii
- f fusion function (e.g., weighted average, machine learning model)

4.2. Examples of Hybrid NDT Techniques

Hybrid Approaches in Non-Destructive Testing (NDT)

Hybrid approaches are increasingly prevalent in both field and laboratory applications, addressing the limitations of individual NDT techniques. Below, we present two illustrative examples that highlight the utility and convenience of these methods for underwater assessments [49].

4.2.1. Acoustic Emission (AE) and Voltammetry Monitoring

Philosophy:

Acoustic Emission (AE) techniques are capable of detecting mechanical energy resulting from both active cracking and corrosion. When combined with electrochemical methods—such as half-cell potential measurements and electrochemical impedance spectroscopy (EIS)—these techniques provide valuable insights into corrosion kinetics and the electrochemical behavior of reinforcing materials [50].

Applications:

- Inspection of underwater bridge piles and subaqueous tunnel linings
- Monitoring the initiation and progression of corrosion in reinforced concrete over the service life [51].

Benefits:

- Localization and timing of damage mechanisms (e.g., crack initiation) through AE
- Comprehensive corrosion assessments, including corrosion rates and states (passive/active) via electrochemical methods
- Integrated early warning and tracking capabilities [52]

Example Workflow:

1) AE transducers are employed to continuously monitor microcrack emissions.

2) These emissions are spectrally correlated with anodic corrosion activity using electrochemical probes.

3) The resulting data on the location and severity of damage, as determined by AE and EIS, informs maintenance priorities.

Parameter	AE System	Electrochemical System
Data type	Mechanical (waveform)	Electrochemical (voltage, current)

Continued

Sensitivity	High to active events	High to passive/active states
Output	Location, frequency, energy	Corrosion rate, potential
Combined benefit	Correlates cracking with corrosion onset	Predictive maintenance

4.2.2. Drones Equipped with GPR and Infrared Sensors

Drone vehicles are equipped with Ground Penetrating Radar (GPR) for subsurface scanning and Infrared Thermography (IRT) for surface temperature mapping. This technology effectively identifies moisture ingress, delaminations, and thermal anomalies in concrete structures, particularly those near or extending to bodies of water.

Applications:

- Bridge decks, dam faces, and harbor structures above the waterline
- Access-restricted or hazardous areas

Benefits:

- GPR detects subsurface flaws, including voids and corrosion zones in steel
- IRT captures temperature gradients indicative of moisture entrapment or delamination
- UAVs enable rapid, wide-area, and repeatable scanning [53]

Case Example:

During the inspection of a sea-facing retaining wall, drones equipped with 1 GHz GPR antennas and FLIR IRT cameras were deployed. The GPR identified areas of steel corrosion, while the IRT revealed heat concentrations corresponding to water ingress. This combined analysis produced a detailed 3D damage map [54].

Feature	GPR	Infrared Thermography	Drone-Based Hybrid Outcome
Defect type	Subsurface (voids, rebar)	Surface/subsurface (moisture)	Integrated surface-depth analysis
Best conditions	Dry or mildly damp surfaces	Clear weather, thermal gradient	Coastal & marine inspections
Limitation	Attenuation in saltwater zones	Low contrast in uniform temps	Offset by combining both sensors

4.3. Limitations and Challenges of Hybrid Techniques

Hybrid Non-Destructive Testing (NDT) techniques offer higher accuracy and improved diagnostic capabilities. However, their application, particularly in underwater concrete structures, is limited due to various technical, practical, and economic challenges. Understanding these limitations is essential for optimizing their use and guiding future advancements [55].

4.3.1. Technical Complexity

- **Data Synchronization**: Acquiring and synchronizing data from multiple

NDT techniques, such as Acoustic Emission (AE) and Electrical Impedance Spectroscopy (EIS), requires precise timing, calibration, and sophisticated synchronization algorithms.

- **Sensor Integration**: Hybrid systems necessitate that sensors be compatible not only physically (in terms of environmental and mechanical factors like waterproofing and pressure resistance) but also functionally, ensuring they can operate effectively under similar conditions [56].
- **Interference**: Signal integrity can be compromised due to overlapping frequency bands or electromagnetic interference among devices, leading to distorted or corrupted data [57].

4.3.2. Fusion and Interpretation of Data

- **Complex Algorithms**: Effective integration of data across different modalities (mechanical, thermal, electrical) often relies on machine learning (ML), artificial intelligence (AI), or statistical modeling, which can introduce significant computational demands [58].
- **Required Expertise**: Interpreting the combined outputs necessitates expertise across various domains, including signal processing, electrochemistry, and structural engineering.
- **Uncertainty Quantification**: The results from integrated methods must quantify confidence intervals and uncertainties, a process that can be more complex than that associated with single-method approaches.

Equation (Basic Data Fusion Model):

$$D_{\text{hybrid}} = \sum_{i=1}^{n} w_i D_i$$

where:

D_{hybrid} : combined diagnostic decision;

D_i : diagnostic data from method iii;

w_i : weighting factor based on reliability or signal quality.

4.3.3. Operational Constraints

Increased Equipment Size and Weight: The integration of multiple tools (such as Ground Penetrating Radar (GPR) and Infrared Thermography (IRT) with drones or Autonomous Underwater Vehicles (AUVs)) typically leads to an increase in payload, which can compromise mobility and maneuverability, particularly in robotics designed for underwater environments [59].

Power Consumption: Operating several devices simultaneously demands greater power, necessitating larger power supplies. As a result, our devices may have reduced operational time.

Environmental Compatibility: Each technique has optimal environmental conditions. For example, Infrared Thermography requires thermal gradients, while GPR works best with dry materials. Achieving these conditions can be particularly challenging in underwater or marine settings [60].

4.3.4. Cost and Practicality Factors

Increased Capital Costs: Hybrid systems often require:

- Advanced hardware and software development
- Specialized drones or platforms
- More highly educated and trained personnel

Maintenance and Calibration: The need for maintenance scales with the number of devices; more equipment means more frequent upkeep. Additionally, calibration is necessary for each sensor type that a device accommodates, which poses significant challenges for long-term underwater deployments.

Lack of Commercial Solutions: Despite several years of development in hybrid systems, most available options remain prototypes or laboratory-level solutions. Currently, there are no integrated, off-the-shelf solutions specifically designed for underwater concrete applications [61] (**Table 4**).

Table 4. Summary of challenges in Hybrid NDT systems.

Challenge Category	Description
Technical	Sensor integration, synchronization, signal interference
Data Interpretation	Complex fusion models, need for multi-domain expertise
Operational	Heavier equipment, energy demands, conflicting environmental requirements
Economic & Logistical	High cost, limited availability, increased maintenance and deployment effort

5. Comparative Analysis of NDT Methods

A comparative analysis helps highlight the strengths, weaknesses, and suitability of each Non-Destructive Testing (NDT) method for underwater concrete structures, assisting practitioners in selecting the most appropriate technique or combination thereof.

5.1. Performance Comparison

NDT Method	Strengths	Limitations	Suitability for Underwater Use	Recent Advances
Impact-Echo (IE)	- Good for detecting voids, delaminations, and thickness	- Sensitive to surface conditions and coupling	- Challenging underwater due to coupling and noise	- Adaptive signal processing; multitransducer arrays
Ultrasonic Testing (UT)	- Deep penetration and thickness measurement	- Requires coupling medium; signal attenuation	- Difficult to maintain coupling underwater; signal loss in water	- Phased Array Ultrasonic Testing (PAUT); advanced signal filtering
Acoustic Emission (AE)	- Real-time monitoring of active cracks and corrosion	- High susceptibility to ambient noise; complex source localization	- Challenging to isolate signals underwater but useful for continuous monitoring	- Integration with fiber-optic sensors; AI-based signal classification
Hybrid Techniques	- Combines strengths of multiple methods, reduces false positives	- Complex data fusion and higher costs	- Most promising for comprehensive underwater inspection despite complexity	- AI-driven data fusion; drone-based hybrid sensors

5.2. Key Parameters for Evaluation

Parameter	Impact-Echo	Ultrasonic	Acoustic Emission	Hybrid Methods
Detection Depth	Medium	High	Surface to medium	High
Sensitivity	Moderate	High	High	Very High
Data Complexity	Moderate	High	High	Very High
Portability	High	Medium	High	Medium
Cost	Low to Medium	Medium to High	Medium	High
Environmental Impact	Sensitive to water coupling	Affected by water properties	Noise sensitive	Depends on components

5.3. Summary

- **Impact-Echo** is ideal for detecting delaminations and thickness changes but struggles with underwater coupling.
- **Ultrasonic Testing** excels at penetration and resolution but requires sophisticated coupling methods underwater [62].
- **Acoustic Emission** provides valuable real-time data on active defects but faces challenges with noise and signal localization underwater [63].
- **Hybrid Techniques** offer the most comprehensive approach by combining complementary strengths but come with increased complexity and costs.

6. Challenges and Future Directions

Despite significant advancements in Non-Destructive Testing (NDT) techniques for underwater concrete structures, several challenges remain that hinder their full potential. Addressing these obstacles is crucial for enhancing the efficiency, reliability, and practicality of inspection systems [64].

6.1. Persistent Challenges

6.1.1. Environmental Limits

- **Water Attenuation:** The quality of signals in acoustic and ultrasonic methods is adversely affected by water attenuation, scattering, and absorption [65].
- **Severe Environments:** Conditions such as saltwater corrosion, biofouling, and turbulent underwater currents pose challenges to sensor durability and data collection accuracy.
- **Temperature and Pressure Effects:** Variations in temperature and pressure can impact sensor calibration and accuracy, especially in deep-water applications [66].

6.1.2. Sensor Distribution and Coupling

- **Coupling:** Reliable methods for coupling underwater ultrasonic or impact-echo transducers are currently lacking, necessitating innovations to create stable interfaces between sensors and structures.

- **Remote Deployment:** Accessing submerged structures typically requires Remotely Operated Vehicles (ROVs) or Autonomous Underwater Vehicles (AUVs) equipped with NDT sensors [67].

6.1.3. Processing and Interpretation of Data

- **Complex Data Fusion:** Effective data fusion involves not only integrating multi-modal data but also utilizing advanced algorithms and AI models to address noise, redundancy, and uncertainties inherent in such data.
- **Expertise Required for Hybrid NDT:** The interpretation of hybrid NDT data necessitates a diverse skill set, which poses scalability and widespread adoption challenges.

6.1.4. Normalization and Validation

- **Insufficient Standard Procedures:** The absence of standardized procedures for underwater NDT complicates the comparison of test results and the certification of methods.
- **Insufficient Field Validation:** Many innovations are developed and tested in laboratory settings at small scales, lacking adequate field validation [68].

6.2. Future Directions

6.2.1. Advanced Sensing Technologies

- **Fiber Optic Sensors:** These sensors offer high sensitivity, electromagnetic immunity, and enhanced robustness for underwater applications [69].
- **Miniature and Wireless Nodes:** These can be easily installed on ROVs/AUVs and at challenging access points [70].
- **Self-Powered Sensors:** Energy harvesting from underwater currents or vibrations can power these sensors, significantly extending their operational lifespan.

6.2.2. Artificial Intelligence and Machine Learning

- **Automation of Fault Detection:** AI models can provide more accurate results and reduce the risk of human interpretation errors.
- **Predictive Maintenance:** Real-time data sharing with NDT and IoT platforms facilitates in-service structural integrity monitoring and predicts defects and failures.
- **Data Fusion Algorithms:** Employing robust multi-sensor integration and real-time analytics can enhance the effectiveness of hybrid NDT.

6.2.3. Improvements in Coupling and Deployment Tools

- **Non-Contact NDT Methods:** Techniques such as laser ultrasonics or air-coupled ultrasound can eliminate the need for underwater coupling.
- **Integrated ROV/AUV Platforms:** Custom NDT payloads can be developed for underwater robots to enable autonomous inspections.

6.2.4. Standardization Efforts

- Establishing international standards and procedures for underwater NDT techniques, along with constructing benchmark datasets and validation methods, will facilitate method comparison and certification (Table 5).

Table 5. Summary of challenges and future research areas.

Challenge Area	Description	Future Research Focus
Environmental Constraints	Signal loss, corrosion, biofouling	Durable sensors, adaptive signal processing
Sensor Deployment	Coupling issues, difficult access	Wireless, miniaturized, non-contact methods
Data Interpretation	Complex fusion, expertise shortage	AI-driven analysis, predictive maintenance
Standardization	Lack of protocols and validation	International standards, benchmark datasets

7. Conclusions

The Non-Destructive Testing (NDT) procedures for assessing the condition of underwater concrete structures—critical components of infrastructure such as bridges, dams, and offshore platforms, are essential for ensuring their safety and durability. This paper reviews the major NDT methods, including Impact-Echo, Ultrasonic Testing, Acoustic Emission, and Hybrid Techniques, highlighting their principles, applications, limitations, and recent advancements.

Impact-Echo and Ultrasonic Testing are effective for detecting voids and measuring thickness; however, they face challenges related to aquatic coupling and signal strength attenuation. Acoustic Emission offers excellent *in-situ* monitoring capabilities but is susceptible to environmental noise and complex signal interpretation. Hybrid approaches, which integrate multiple methods, demonstrate improved diagnostic performance and greater inter-operator agreement, albeit at the cost of increased complexity and expense.

The widespread adoption of these methods is hindered by several persistent challenges, including adverse underwater environmental conditions, difficulties in sensor deployment, complex data processing, and the absence of standardized protocols. However, ongoing advancements in sensor technology, intelligent algorithms, unmanned inspection platforms, and international standardization efforts can help overcome these obstacles.

Future research should focus on developing robust, miniature sensors, advanced AI-driven data fusion techniques, and innovative deployment concepts. Such advancements will facilitate more effective, reliable, and automated testing and maintenance of submerged concrete structures, ultimately enhancing their safety, durability, and lifespan.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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