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A Synthesis Study to Identify and Make Recommendations on the Appropriate Nondestructive Testing Tools for Bridge Beam Ends, Piers, and Abutments

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16. Abstract

The aim of this research was to identify suitable NDT methods for bridge components by evaluating their advantages, disadvantages, and limitations. The research objectives are: (1) to identify suitable NDT tools and techniques for condition evaluation of bridge beam-ends, abutments, and piers based on their advantages and disadvantages, (2) to identify gaps in NDT tools and techniques for assessing the condition of concrete bridge members (excluding decks), and (3) to recommend NDT methods for further investigation. The scope of this research was limited to reinforced and prestressed concrete bridge piers, pier caps, beam-ends, and abutments, excluding decks. The research produced four guideline tables to assist INDOT in selecting appropriate NDT methods for piers, pier caps, beam-ends, and abutments, along with a consolidated summary table. Applying these resources early in the inspection planning phase allows INDOT to streamline NDT method selection, minimize unnecessary fieldwork, improve inspection quality, and enhance the reliability of collected data. Whether used by INDOT personnel or supervised consultants, this implementation ensures higher-quality evaluations, better maintenance decisions, and ultimately improved bridge safety and longevity.

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EXECUTIVE SUMMARY

Introduction

This research evaluated nondestructive testing (NDT) methods for reinforced and prestressed concrete bridge components, piers, pier caps, beam ends, and abutments through literature review, standards, and surveys of departments of transportation (DOTs), Indiana Department of Transportation (INDOT) personnel, and experts. The study compared advantages, limitations, and gaps of key NDT methods and integrated emerging technologies. The outcome is a set of guideline tables that INDOT can directly apply or recommend to consultants, ensuring systematic, standards-based, and cost-effective bridge inspections. The aim of this research was to identify suitable NDT methods for bridge components by evaluating their advantages, disadvantages, and limitations. The research objectives are: (1) to identify suitable NDT tools and techniques for condition evaluation of bridge beam ends, abutments, and piers based on their advantages and disadvantages, (2) to identify gaps in NDT tools and techniques for assessing the condition of concrete bridge members (excluding decks), and (3) to recommend NDT methods for further investigation. The scope of this research was limited to reinforced and prestressed concrete bridge components piers, pier caps, beam ends, and abutments, excluding decks. The intent of this research was to provide INDOT with practical, standards-based guideline tables that can be directly applied or recommended to consultants, ensuring consistent and efficient bridge inspections through the strategic selection of complementary NDT methods.

Research tasks included: (1) reviewing and synthesizing existing publications such as peer-reviewed articles, NDT manufacturers' websites, and standards from ASTM International (ASTM), the International Organization for Standardization (ISO), the American Concrete Institute (ACI), the American Association of State Highway and Transportation Officials (AASHTO), and the Japan Society of Civil Engineers (JSCE), as well as guidelines from the Federal Highway Administration (FHWA) and various state DOTs; (2) conducting surveys for state DOTs, an internal survey for INDOT, and a survey for industry experts; and (3) developing tables for the selection of suitable NDT methods for piers, pier caps, beam ends, and abutments, along with the underlying rationale for each selection.

Findings

Findings from synthesizing existing articles, guidelines, and standards:

- Integrating multiple NDT methods is the key to enhancing accuracy.
- Accurate and efficient NDT for reinforced and prestressed concrete bridges may require limited integration with core sampling for calibration purposes, along with statistically planned test locations and method-specific grid mapping.
- Selecting NDT methods for reinforced and prestressed concrete bridge components must be tailored to exposure conditions, geometry, accessibility, functionality, expected defect types, and cost.
- Each bridge component, pier, abutment, beam end, and pier cap, has distinct structural functions, load paths, exposure conditions, and accessibility challenges that influence inspection and maintenance strategies; therefore, the selection of suitable NDT methods should be based on these attributes.

Findings from surveys:

- Sixteen INDOT personnel: Ground-penetrating radar (GPR) emerged as the standout method, likely due to its unparalleled capability in corrosion assessment, one of the most commonly targeted defect types. Consistent concerns about the accuracy of NDT tools, arising from both instrument limitations and variability in user expertise, highlight the need for standardized training and clear operational procedures. Standardized training would help reduce operator-dependent variability and improve the reliability of NDT data interpretation across agencies.
- Fourteen DOTs representatives: NDT use among state DOTs is common, with GPR, infrared thermography (IRT), impact-echo (IE), ultrasonic pulse velocity (UPV), ultrasonic pulse echo (UPE), and half-cell potential (HCP) as the most frequently applied methods for detecting defects, mostly delamination and corrosion.
- Eight NDT experts: More than 50% of respondents suggested the practicability of GPR and ultrasonic methods (UPV and UPE). The respondents frequently identified HCP as a primary corrosion assessment.

Findings from synthesis existing literature and expert opinion:

- Four detailed tables (Available in the report as Tables 9.1–9.4 and consolidated in Table 10.2, as shown here) were provided to match beam ends, abutments, piers, and pier caps with optimal NDT methods, outlining each method's advantages and limitations.

No.	Common Defect/ Condition	Suitable NDT Methods with Key Notes on Use
1	Subsurface cracks (from stress, load, or settlement)	**Ultrasonic Pulse Echo (UPE):** One-sided detection of deep internal cracks; good for massive/inaccessible members. **Impact-Echo (IE):** Estimates crack depth/extent in thick sections. **Acoustic Emission (AE):** Monitors live crack propagation during service loads. **Ultrasonic Pulse Velocity (UPV):** Bulk integrity/residual strength when two-sided or semidirect access exists.
2	Delamination (near reinforcement, joints, freeze–thaw zones, bearing seats)	**UPE:** One-sided depth/location of delamination. **IE:** Deeper delamination in thick members. **Ground-Penetrating Radar (GPR):** Rapid mapping near reinforcement, limited in saturated/chloride-contaminated concrete. **Infrared Thermography (IRT):** Near-surface delamination via thermal contrast, weather dependent.

No.	Common Defect/ Condition	Suitable NDT Methods with Key Notes on Use
3	Spalling/surface scaling	**Rebound Hammer (RH):** Quick qualitative check of surface hardness/local strength loss. **IRT:** Highlights shallow spalls or scaled areas by showing temperature contrasts on the surface that indicate underlying defects.
4	Corrosion of reinforcement or prestressing tendons	**Half-Cell Potential (HCP):** Probability of active corrosion (does not give rate). **GPR:** Maps bars/ducts, cover, corrosion-prone anomalies. **UPE:** Voids/debonding around corroded bars/tendons. **AE:** Active cracking in concrete and fracture of prestressing tendons under load.
5	Moisture ingress/joint leakage/poor drainage/saturation	**GPR:** Moisture pathways and subsurface anomalies. Its effectiveness is limited in highly saturated zones. **IRT:** Non-contact mapping of surface moisture or leakage using temperature gradients.
6	Voids/honeycombing (due to poor compaction)	**UPE:** Localized voids/honeycombing with one-sided access. It is good in congested reinforcement. **IE:** Large voids and thickness variation. It is not sensitive to micro-voids (< ~5 mm).
7	Debonding of prestressing tendons/duct defects	**GPR:** Maps ducts and highlights anomalies at anchorage/tendon zones. **UPE/UPV:** Detect loss of bond or voids around tendons. **AE:** Monitors cracking/slip under service loads.
8	Surface deterioration/ in-place concrete strength estimation	**UPV:** Residual strength/degraded zones. It needs two-sided or semi-direct access. **RH:** Fast, low-cost surface hardness check. It correlates with other NDT for strength.
9	Freeze–thaw damage (delamination, scaling, cracking)	**IE:** Depth/extent of delamination from freeze–thaw. **IRT:** Maps shallow thermal anomalies. **RH:** Screens surface hardness reduction due to scaling.
10	Foundation settlement/ tilting/scour-induced stress cracking	**AE:** Live crack activity from differential movement or scour. **UPV:** Internal cracking/strength loss (needs semi-direct access). **UPE:** Useful when only one face is accessible in massive sections.
11	Soil–structure interaction effects (earth pressure, buried faces)	**UPE:** One-sided deep flaw detection on accessible faces. **AE:** Stress-related crack activity from earth pressure. **HCP/GPR:** Corrosion risk mapping and bar layout where accessible.
12	Settlement-related delamination or joint defects (bearing/pier or abutment interfaces)	**AE:** Live crack growth at bearing seats or pier/abutment interfaces. **UPV:** Internal cracking continuity across interfaces (requires access).
13	Scour or waterline deterioration in piers	**AE:** Monitors cracking due to scour-induced instability. **GPR:** Subsurface voids/washout zones. **IRT:** Moisture saturation bands near waterlines.
14	General weathering/aging/ shrinkage cracking	**RH and UPV combo:** Surface vs. in-depth degradation. **UPE and IE:** Internal cracks or shrinkage-related delamination.

Implementation

This research was conducted through a review of literature and standards, analysis of survey data from INDOT personnel, state DOTs, and industry experts, and synthesis of the results into guideline tables recommending appropriate NDT methods for specific bridge components. The findings of this research have resulted in four guideline tables (Tables 9.1–9.4) for INDOT to determine the most suitable NDT methods for reinforced and prestressed concrete bridge components, piers, pier caps, beam ends, and abutments, as well as a consolidated Table 10.2 for a quick reference. These tables integrate best practices from AASHTO, ASTM, ACI, and other relevant standards, combined with insights from INDOT staff, other DOTs, and industry experts. By implementing these findings, INDOT can directly apply the tables in-house or recommend consultants to follow them, ensuring a consistent, systematic, and standards-based approach while reducing reliance on trial-and-error methods.

INDOT can embed Tables 9.1–9.4 into existing inspection manuals, bridge condition rating protocols, and consultant contract requirements. This ensures that NDT method selection is not left to individual judgment but follows a structured, agency-wide standard. INDOT can require consultants to document their selected NDT methods and tools, cross-referencing them with the guideline tables to ensure oversight of inspection reports and provide justification for maintenance planning decisions.

The guideline tables serve as quick-reference tools for developing component-specific, multimethod inspection plans, confirming that no single NDT method is sufficient. Instead, strategic combinations of complementary techniques deliver the most accurate, reliable, and cost-effective results for actionable bridge condition assessments. Applying these resources early in the inspection planning phase allows INDOT to streamline NDT method selection, minimize unnecessary fieldwork, improve inspection quality, and enhance the reliability of collected data. Whether used by INDOT personnel or supervised consultants, this implementation ensures higher-quality evaluations, better maintenance decisions, and ultimately improved bridge safety and longevity.

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1. INTRODUCTION

Nondestructive testing (NDT) is a qualitative method used to identify flaws, defects, or discontinuities in materials and structures without causing damage. Nondestructive evaluation (NDE) encompasses NDT but extends beyond defect detection to include material characterization, stress analysis, and performance assessment. As a quantitative approach, NDE is utilized for life-cycle assessment, predictive maintenance, and engineering evaluations, providing deeper insights into material integrity and structural performance.

NDT encompasses a diverse array of analytical techniques employed to evaluate a material's characteristics, constituents, or systems without compromising its structural integrity. This methodology yields a comprehensive understanding of surface and structural irregularities and hindrances. NDT finds its roots in the early 1900s with the inception of the first technique, radiography, which utilizes x-rays or gamma rays to produce an image of the internal composition of an object. In the 1920s, ultrasonic testing (UT) was introduced to discern internal imperfections in metal components using high-frequency sound waves. Magnetic particle testing, developed in the 1930s, employs a magnetic field to detect surface and near-surface flaws in ferromagnetic materials. Liquid penetrant testing, established in the 1940s, identifies surface-breaking defects in a material using a liquid medium. Further NDT methodologies were developed in the 1950s, including eddy-current testing (ET). In the 1960s, integrating computers with NDTs enhanced the precision and efficacy of these techniques (The American Society for Nondestructive Testing [ASNT], 2024; ASTM International [ASTM], 2024a).

Early NDT methods, such as radiography and UT, primarily focused on identifying defects in homogeneous metal structures. However, advancements made in the mid-20th century allowed for the application of techniques like ultrasonic pulse velocity (UPV) and ground-penetrating radar (GPR) to heterogeneous materials, such as reinforced concrete (RC). The variable composition of concrete and the presence of embedded reinforcements presented challenges for effective defect detection, leading to the need for adaptations in testing methods. Hence, dynamic NDT techniques, including vibration testing, were improved to assess the overall performance of structures under load. Additionally, developments in pulse velocity and Impact-Echo (IE) techniques enhanced the detection of voids and delamination in large RC components, although challenges related to signal distortion caused by the reinforcements remained (ASTM, 2022c; Gucunski et al., 2013; Malhotra & Carino, 2003).

NDTs offer significant advantages in assessing the safety conditions of structural components and entire RC structures. These methods allow for detailed inspection without causing damage, which is crucial for long-term structural health monitoring (Bolborea et al., 2025). NDT provides critical data for evaluating the material properties and strength of RC components, aiding in the prediction and prevention of potential failures. Dynamic NDT methods, such as vibration testing, are useful in assessing whole structural performance by analyzing dynamic responses under various loads. It demonstrated the utility of dynamic NDT in monitoring a footbridge's performance, where dynamic testing was used to calibrate numerical models and ensure compliance with serviceability guidelines. Similarly, dynamic testing in RC structures can help verify design assumptions and improve maintenance strategies by detecting real-time structural anomalies (Nicoletti et al., 2023).

In the last two decades, NDT tools and methods have seen many technological advancements and are still evolving. Diagnosis of historic buildings using different NDTs was researched (Boccaccia et al., 2024). The application of common NDT tools such as GPR, laser, infrared thermal imaging, and ultrasonic in the assessment of road surface was investigated (Yang et al., 2024). A combination of drilling resistance testing UPV and rebound hammer (RH) showed promising results for the compressive strength of concrete (Gunes et al., 2023). Concrete specimens subjected to compressive and flexural preloading were assessed by NDTs (Bensaber et al., 2023).

This study reviews the RH, UPV, IE, Acoustic Emission (AE), GPR, ET, Half-Cell Potential (HCP), and Electrical Resistance (ER) tests. This study primarily examines various NDT tools utilized for RC structures, highlighting their respective advantages and disadvantages. The findings derived from the literature review, along with the results of a conducted survey, specifically focus on the RC bridge pier, pier cap, abutment, and beam end.

1.1 Problem Statement

Numerous NDT tools and techniques are utilized to assess the structural integrity of concrete structural elements. The Indiana Department of Transportation (INDOT) has previously investigated NDT tools for the assessment of concrete bridge decks. The department has identified a need for further research to determine suitable NDT methods for bridge piers, pier caps, beam ends, and abutments. This will require exploring NDT methods, as well as their respective advantages, disadvantages, and limitations.

1.2 Objectives

To address these needs, research objectives are:

1. To identify suitable NDT tools and techniques used for condition evaluation of bridge beam ends, abutments, piers, and pier caps based on their advantages and disadvantages.
2. To identify gaps in NDT tools and techniques for assessing the condition of concrete bridge members (excluding decks).
3. To recommend NDT methods for further investigation.

2. TYPES OF NDT TOOLS AND METHODS USED FOR RC BRIDGE INSPECTION

The eight NDT methods discussed in this article were selected based on their effectiveness in detecting critical defects in RC structures, including cracks, voids, and corrosion. Their applicability to various structural components also significantly influenced the selection process. Key factors influencing the selection of the nine methods are availability, reliability, accuracy, ease of use, and adherence to established standards such as ASTM and American Concrete Institute (ACI) guidelines. Furthermore, advancements in specific methods, such as UPV and GPR, were pivotal to their inclusion due to their broader range of applications and enhanced technological capabilities.

2.1 Rebound Hammer

The Schmidt hammer, or rebound hammer (RH), measures the rebound of a spring-loaded mass impacting against the surface of a sample. The hammer hits the concrete at a defined energy. Its rebound distance depends on the concrete hardness and is measured by the test equipment. By reference to a conversion chart, the rebound number is used to determine the compressive strength of concrete. The rebound number shows how far the spring-loaded hammer bounces back after hitting the concrete. While useful for quality control and comparative assessments, it requires calibration with core samples for accurate strength estimation (ASTM, 2019). The hammer is used in various positions, provided it is perpendicular to the test surface, as shown in Figure 2.1. Research has shown that the Schmidt hammer is not wholly nondestructive. Instead, Chun et al. (2020) performed impact experiments using the CTS-02V4 concrete tester. This tool measures compressive strength by utilizing the relationship between elastic modulus and compressive strength. The RH is cost-effective, easy to use, and efficient for restoring historic structures. It is used to evaluate the uniformity of concrete in place, identify variations in concrete quality throughout a structure, and estimate the in-place concrete strength (ASTM-C805/C805M; ASTM, 2019). Results are affected by surface smoothness, specimen size, shape, rigidity, age, moisture conditions, type of cement and aggregate, and carbonation of the concrete surface. An RH is only suitable for homogeneous materials (Gucunski et al., 2011; International Atomic Energy Agency, 2002). According to ASTM C805, ten readings should be taken from each test area (ASTM, 2019). The distances between impact points shall be at least 25 mm (1 in.), and the distance between impact points and edges of the member shall be at least 50 mm (2 in.). The concrete element being tested should have a minimum thickness of 100 mm (4 in.) to ensure reliable rebound readings (ASTM, 2019).

2.1.1 Advantages

- Quick and Portable: Instant readings with a compact device, suitable for on-site assessments.
- Cost-Effective: No expensive equipment or lab tests required.
- Useful for Quality Control: Helps detect variability in concrete strength across different areas.
- Preliminary Screening Tool: Identifies weak zones before core sampling or further testing (ASTM, 2019).

2.1.2 Limitations

- Measures only surface hardness: Results do not directly represent core strength.
- Affected by surface conditions: Roughness, moisture, and carbonation distort readings (British Standards Institution, 2012).
- Orientation sensitivity: Rebound numbers vary with testing angle, requiring correction factors.

Figure 2.1 RH Test Performing on a Concrete Surface.

- Limited for high-strength concrete: Reduced effectiveness for strengths above 60 MPa (8.70 ksi; Malhotra & Carino, 2003).
- Cannot detect internal defects: Ineffective for cracks, voids, and delamination (ACI Committee 228, 2013).
- Requires calibration: Needs correlation with core tests for reliability.

2.2 Ultrasonic Pulse Velocity

UPV and ultrasonic pulse echo (UPE) are methods under the broader category of UT, which is sometimes referred to as ultrasonic velocity testing (UVT) in concrete applications. While UPV measures the speed of sound waves traveling between two points to assess material quality, UPE uses reflected echoes from internal features to detect flaws from a single accessible surface.

UPV uses a transducer that sends a vibration pulse into the concrete using a liquid, such as grease or paste, to help the signal pass through. The ultrasonic pulse travels through the concrete and is received by a second transducer. The travel time is then measured electronically. The UPV is calculated by dividing the distance by the travel time. This velocity is utilized to identify internal deterioration and flaws within the concrete based on how fast the pulse travels through the material. Higher velocity usually means the concrete is dense and intact, while lower velocity indicates possible internal issues like cracks, voids, delamination, or poor-quality zones. In short, UPV employs longitudinal ultrasonic (sound) waves, and an electric pulse (high-frequency AC voltage) is applied via a transducer. UPV measures the wave travel time variations to infer the defects. Moisture content, concrete temperature, path length, proximity of reinforcing bars, and concrete uniformity are among the factors that can influence pulse velocity measurement (ASTM, 2023).

UPV test has good penetrating power, sensitivity, accuracy, and portability; however, it is affected by material dependency, surface preparation, skill requirement, limited resolution, and environmental factors such as humidity, temperature, and ambient noise (Gucunski et al., 2011; International Atomic Energy Agency, 2002).

2.2.1 Advantages

- Correlates with strength: When appropriately calibrated, UPV values can help estimate concrete compressive strength.
- Detects internal defects: Identifies voids, cracks, and honeycombing that may not be visible externally.
- Assesses homogeneity: Determines variability in concrete properties within a structure.
- Multiple testing modes: Can be used in direct, semidirect, and indirect transmission to adapt to different site conditions with high, medium, and low accuracy, respectively (British Standards Institution, 2012), as seen in Table 2.1.
- Applicable to various structures: Used in bridges, tunnels, pavements, and historical buildings without damaging integrity.

For optimal accuracy, UPV should be used in the direct (two-sided) mode, as shown in Figure 2.2. Table 2.1 summarizes different UPV transmission modes, their transducer placements, typical accuracy levels, and suitable applications.

2.2.2 Limitations

- Influenced by material properties: Concrete moisture content, aggregate type, and reinforcement presence affect wave velocity (Malhotra & Carino, 2003).

TABLE 2.1
UPV Transmission Modes and Their Applications.

Transmission Mode	Transducer Placement	Accuracy	Best for Detecting
Direct (Two-Sided)	Opposite sides	High	Internal defects, homogeneity
Semidirect (Angle Placement)	Adjacent sides	Moderate	Corner cracks, near-edge voids
Indirect (One-Sided)	Same surface	Low	Surface cracks, shallow defects

Figure 2.2 Two-Sided UPV Test on Concrete for Internal Quality Assessment.

- Limited direct strength estimation: Does not directly measure compressive strength but requires correlation with lab tests.
- Surface preparation required: Requires smooth surfaces and good coupling with transducers for accurate readings.
- Cannot differentiate defect type: Detects anomalies but does not identify the exact nature (e.g., crack vs. void), and therefore additional tests, such as IE or GPR, may be needed to classify the defect type (ACI Committee 228, 2013). This is because:
  - It only measures wave travel time and does not provide detailed imaging.
  - The same reduction in wave velocity could be caused by different issues (e.g., a void, a microcrack, or a weakened zone due to poor compaction).

2.3 Ultrasonic Pulse Echo

UPE is to detect internal flaws in concrete when access is available from only one side. Unlike UPV, which requires two transducers on opposite sides, UPE uses a single transducer to both transmit and receive ultrasonic waves. A short ultrasonic pulse is emitted into the concrete, and the transducer records the reflected echoes that bounce back from internal features such as cracks, voids, or interfaces.

The time it takes for the echo to return is used to determine the depth and location of internal anomalies. UPE is particularly effective in identifying delaminations, honeycombing, voids, and thickness variations, making it highly suitable for assessing concrete bridge decks, tunnel linings, and precast elements where only one side is accessible.

This method typically uses low-frequency longitudinal waves for deeper penetration and can function without coupling liquids in some cases, although gel or paste is often used to enhance wave transmission. The reflected signal patterns are displayed as waveforms or image profiles that help interpret the internal condition of the concrete (ACI Committee 228, 2013).

2.3.1 Advantages

- Single-side access: Ideal for components where the backside is inaccessible, such as slabs, pavements, and tunnel linings.
- Detects internal flaws: Identifies internal defects like delaminations, voids, and honeycombing with good depth resolution.
- Estimates element thickness: Measures total thickness of concrete members and identifies changes in layer boundaries.
- Visual output: Echoes are visualized as waveforms or B-scans, aiding in interpreting depth and defect shape.

2.3.2 Limitations

- Limited penetration depth: Typically effective for elements up to about 500–1000 mm thick, depending on concrete quality.
- Affected by reinforcement: Steel bars and mesh can reflect or scatter waves, complicating signal interpretation.
- Requires smooth surfaces: Uneven or rough surfaces can distort echo signals, reducing test reliability.
- Skill-dependent interpretation: Accurate reading of waveforms and echo patterns requires trained operators.
- Cannot estimate compressive strength: UPE is not intended for strength estimation and must be combined with other methods like UPV or RH for comprehensive evaluation.

TABLE 2.2
Application-Based Comparison of UPV and UPE Techniques.

Aspect	UPV	UPE
Best For	Estimating material quality, uniformity, and general defects	Locating depth and position of internal defects (e.g., cracks, voids, delamination)
Thickness Measurement	Not ideal (requires access to both sides)	Yes, can estimate thickness based on echo return time
Strength Estimation	Yes, with calibration to core tests	No, not suitable for compressive strength estimation

Table 2.2 compares the UPV and UPE in terms of their application.

2.4 Impact-Echo

IE detects structural defects by measuring how fast elastic waves travel and how they reflect, bend, or spread inside the material. This approach is valuable for pinpointing sizable voids or delamination in plate-like structures, such as pavements or bridge decks, especially when the flaw runs parallel to the test surface (Sansalone & Carino, 1986).

IE uses low-frequency P-waves (primary or compressional waves), generated by tapping the surface with a small steel ball. First, the P-wave speed is measured in sound, defect-free concrete as a reference (Procedure A). Then, the travel time is recorded in the concrete under inspection (Procedure B). A difference in travel time between the two suggests the presence of internal flaws or anomalies in the tested concrete (ASTM, 2024b).

Research conducted on NDT on various bridge decks has revealed that the IE results were promising, particularly for project-level scanning of bridge decks with the selective concrete cores extracted from these decks (Jia et al., 2022). IE's application is restricted by surface access requirements, depth limitation, and complex data interpretation. Collecting IE data for delamination detection is a time-consuming process that necessitates lane closure. The required dense test grid for data collection is often impractical. However, analysis of the collected data for delamination characterization is relatively quick, with interpretation typically yielding unambiguous results (Gucunski et al., 2011). The measured thickness of concrete slabs may have some error due to the way digital data is recorded. This error depends on the slab's thickness, how often data is recorded (sampling interval), and the total time recorded (sampling period) (ASTM, 2024b). The IE application is limited to slow data collection, dense test grid, complex evaluation of bridge deck condition, and consideration of structural elements like girders, piers, and pier caps (FHWA, 2022).

2.4.1 Advantages

- Detects internal defects: Identifies voids, cracks, honeycombing, delamination, grout quality in ducts, debonding under overlays, and measures slab or wall thickness (ACI Committee 228, 2013).
- Determines structural thickness: Can measure concrete element thickness and detect hidden defects (ASTM, 2024b). Figure 2.3 shows this method in use for determining a concrete element's thickness.

Figure 2.3 IE Testing on a Concrete Bridge Soffit for Thickness and Defect Evaluation.

- Works on various materials: Applicable to concrete, masonry, and stone structures (Sansalone & Carino, 1986).
- High penetration depth: Can assess deep-seated defects that other NDT methods may not detect.

2.4.2 Limitations

- Requires skilled interpretation: Signal analysis is complex and requires trained personnel (ACI Committee 228, 2013).
- Surface condition affects results: Rough or uneven surfaces reduce accuracy.
- Cannot differentiate defect type: It identifies anomalies but cannot distinguish between cracks, voids, or delaminations without complementary testing (Sansalone & Carino, 1986). This is because:
  - Cracks, voids, and delaminations act as reflectors, disrupting wave propagation similarly.
  - The frequency and travel time of the reflected wave may not be unique to a specific defect.
- Affected by material heterogeneity: Variations in aggregate type, moisture, and layering influence wave reflections, requiring careful calibration.

2.5 Acoustic Emission

AE refers to the generation of elastic waves within solids due to irreversible changes in their internal structure, such as the formation of cracks or plastic deformation. These changes may stem from various factors, including aging, temperature differentials, or external forces. These activities are detected by piezoelectric transducers, converted into electric signals, and captured by a digital oscilloscope.

Analyzing the time of arrival at each transducer allows for determining the source, frequency, and amplitude of the AE events, which can provide quantitative insights into the nature of microfractures in materials. An AE event is a localized, sudden release of energy from within the material's structure, which is then detected by sensors on the surface. The velocity of the waves in the specimen is ascertained by applying the UPV method (ASTM-E750-15; ASTM, 2020b) can detect defects in the early stages. By using multiple sensors, as shown in Figure 2.4, it can locate damage sources. However, AE can only provide a qualitative assessment of the damage and does not give quantitative measurements. AE is used to monitor extensive areas of a structure and identify cracks and damage in hard-to-reach places. However, it requires intricate data analysis and can only identify progressive damage, such as an expanding crack (FHWA, 2022). In short, AE is a real-time monitoring technique. Its sensors detect stress waves generated by emerging defects, converting them into electrical signals, which are then compared to reference values.

2.5.1 Advantages

- Real-time monitoring: Detects damage as it occurs, allowing for early intervention
- Highly sensitive to microcracks: Can capture subtle crack formation before they become visible (ACI Committee 228, 2013).
- Minimal intrusion: Unlike other methods, AE does not require active wave generation; it listens to naturally occurring emissions.
- Locates active defects: Can identify growing cracks and defects which are more critical than dormant defects.
- Useful for large structures: It is suitable for bridges, pipelines, pressure vessels, and concrete dams where continuous monitoring is needed.

2.5.2 Limitations

- Requires active damage: only detects ongoing damage; does not assess existing, dormant defects (ASTM, 2022a).
- Difficult signal interpretation: requires advanced expertise to differentiate between background noise and true emissions (ACI Committee 228, 2013).
- Environmental sensitivity: results can be affected by ambient noise, temperature changes, and external vibrations.
- Limited to surface monitoring: cannot provide detailed imaging of internal defects like GPR or IE (ASTM, 2022a).
- Expensive for long-term monitoring: continuous AE monitoring requires specialized sensors and data acquisition systems, increasing cost.

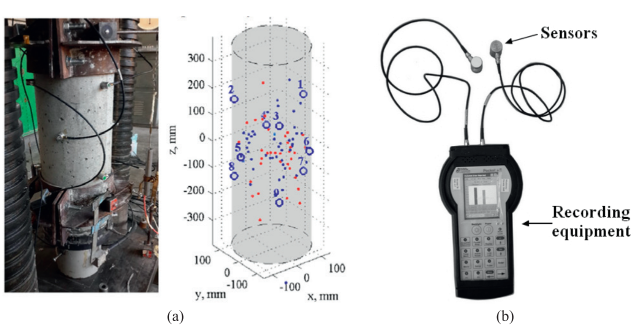

Figure 2.4 AE Monitoring Setup: (a) AE Sensors Mounted on a Concrete Column During Compression Testing With 3D Event Localization; (b) AE Recording Equipment With Sensors.

2.6 Ground-Penetrating Radar

GPR is often called impulse radar or just radar, particularly when applied to inspect concrete structures. It utilizes electromagnetic waves to conduct a survey of wave reflections. GPR, shown in Figure 2.5, transmits high-frequency electromagnetic waves into a structural member using an antenna. These waves reflect back to the surface when they encounter interfaces between materials with different dielectric properties, such as between concrete and embedded steel reinforcement. Some energy continues to penetrate deeper, producing additional reflections until it is fully attenuated. The wave propagation speed depends on the dielectric properties of the materials. By analyzing the arrival time and amplitude of the reflected signals, GPR can estimate subsurface depths and wave velocities and assess the condition of concrete as well as locate and inspect the position, spacing, and potential corrosion zones of reinforcing bars.

The outcomes and interpretations of GPR investigations can vary widely depending on the specific application, equipment used, and investigative techniques employed. Factors such as the scope of the study, evaluation criteria, chosen methodology, and the expertise of the personnel conducting the survey all play a critical role in the accuracy and reliability of the results (ASTM, 2020a; Gucunski et al., 2011).

A study focusing on the NDT of concrete box beams in bridges has demonstrated that GPR effectively locates embedded

Figure 2.5 GPR Testing on a Vertical Concrete Member.

strands within concrete. GPR can identify regions of delaminated concrete, indicating potential corrosion sites. While GPR commonly utilizes high-frequency radio waves, this study determined that the 8 dB threshold exhibited a weak correlation with delaminated concrete areas, whereas the 6 dB threshold showed a strong correlation. Consequently, it is recommended to use the 6 dB threshold for delamination detection. GPR is particularly valuable for determining the actual number of strands present in a section, particularly in cases where construction drawings are unavailable (Frosch et al., 2020). GPR can be classified as air-launched GPR and ground-coupled GPR. Air-launched GPR uses radar systems deployed from airborne platforms, such as unmanned aerial vehicles, for subsurface detection and imaging. Ground-coupled GPR antennas are typically installed on pushcarts. The ground-coupled design places the transmitter (T) and receiver (R) close to the surface to maximize the energy transferred to the subsurface (Diamanti & Annan, 2017).

GPR application suffers from postprocessing, and the interpretation of data becomes complicated, which requires NDT expertise. Moreover, differentiating between the different subsurface features can be difficult, and detecting small defects such as fine cracks is challenging (FHWA, 2022).

According to ASTM D6432-19 (ASTM, 2020a), effective GPR testing requires the understanding of the target and site conditions, including material types and moisture levels. Selecting the appropriate antenna frequency is crucial. Higher frequencies offer better resolution but less depth, while lower frequencies penetrate deeper with less detail. Calibration using areas of known thickness helps ensure accuracy, and maintaining good antenna contact with a clean, dry surface improves signal quality. Scanning in a grid pattern, ideally in both directions, enhances interpretation especially in areas with dense reinforcement. Positioning tools like encoders can improve spatial accuracy. Interpreting both signal travel time and amplitude enables better depth estimation and feature detection; however, it is essential to verify the dielectric constant for reliable results. Post-processing software can enhance data clarity, and recording environmental conditions such as temperature and moisture ensures consistent and accurate reporting (ASTM, 2020a).

2.6.1 Advantages

- Rapid data collection: Provides real-time imaging without damaging structures.
- Detects subsurface features: Identifies voids, delaminations, rebar placement, and thickness variations in concrete (ACI Committee 228, 2013).
- Penetrates various materials: Works on concrete, asphalt, soil, and masonry, making it versatile.
- High-resolution imaging: Produces detailed subsurface maps for reinforcement layout and defect detection.
- Applicable to vertical and horizontal structures: Can be used for piers, abutments, walls, and bridge decks.

2.6.2 Limitations

- Limited penetration depth: High-frequency antennas provide high resolution but only penetrate a few centimeters (ASTM, 2020a).
- Signal attenuation in moist materials: Water-saturated concrete, clay, and certain aggregates can weaken GPR signals.
- Difficult interpretation: Requires expertise to analyze radargrams and differentiate between anomalies and actual defects (ACI Committee 228, 2013).
- Interference from reinforcement: Dense rebar configurations scatter and distort radar waves, reducing accuracy.
- Expensive equipment and training: Advanced GPR systems require high initial costs and skilled operators.

2.7 Half-Cell Potential

The HCP method provides an indication of the probability of corrosion within the rebar in steel-reinforced and prestressed concrete structures. The method is user-friendly, featuring durable electrodes that are easy to maintain. A cell with two half-cells contains the working electrode (rebar), and the other has a reference electrode. The working electrode is the embedded rebar inside the concrete, which is the part being tested for corrosion. The reference electrode is a portable, stable electrode (such as copper/copper sulfate or silver/silver chloride) placed on the concrete surface, as shown in Figure 2.6. A wire connects the embedded steel reinforcement to a reference electrode, forming a closed electrical circuit. While the current flows through the concrete from one electrode to the other, a voltmeter measures the potential difference between the embedded rebar (working electrode) and the reference electrode, with the concrete acting as the electrolyte. This measured potential helps assess the likelihood of corrosion in the steel reinforcement. According to ASTM C876-22b standard (ASTM, 2022b; Appendix X1.1.3), if the measured potential is more negative than -0.35 V (versus a copper-copper sulfate reference electrode), there is a greater

Figure 2.6 HCP Measurement on a Concrete Using a Copper-Copper Sulfate Reference Electrode to Assess Corrosion Activity in Embedded Steel Reinforcement.

than 90% probability that active corrosion of the reinforcing steel is occurring at the time of measurement. To establish electrical contact with the reinforcement in the structure being inspected, a small hole may be necessary, and surface preparation may also be required. Furthermore, the impact of concrete cover depth on the accuracy of the method has not been extensively researched.

It is advisable to utilize this method in conjunction with other nondestructive evaluation methods (Gucunski et al., 2011). HCP has been effectively employed to identify regions with heightened susceptibility to reinforcement corrosion in structures situated in marine environments, as well as in bridge decks and abutments (International Atomic Energy Agency, 2002). HCP can be applied at any stage of a concrete structure's lifespan and in diverse climatic conditions, provided the temperature exceeds 20 °C. It is vital to perform HCP measurements on a clean concrete surface, as the presence of insulating layers like asphalt, coating, or paint can result in inaccurate or unattainable measurements (Elsener et al., 2003).

In a study by Frosch et al. (2020) focusing on NDT of concrete box beams in bridges, it was discovered that there exists a significant correlation between HCPs and the actual corrosion of strands near visible signs of degradation. The study found that severely corroded steel strands influenced the HCP readings, producing a distinct ring-shaped pattern known as the "halo effect." This effect appears as a circular zone of more negative potentials on the HCP map, surrounding the corroded area. This effect was particularly evident in specimens exhibiting deterioration associated with leaking longitudinal joints or water runoff along the exterior beam. While the assessment of HCP necessitates access to specific points of the reinforcement and is not entirely nondestructive, it proved to be the most effective method for identifying corrosion in strands adjacent to visible indicators of deterioration.

2.7.1 Advantages

- Simple to perform: It requires no concrete removal and provides an on-site corrosion assessment (ASTM, 2022b).
- Effective for corrosion detection: Identifies areas with high corrosion risk before visible deterioration occurs (ACI Committee 222, 2019).
- Cost-effective: Lower cost than other corrosion evaluation methods, making it widely used in infrastructure maintenance.
- Applicable to large areas: It can be used for bridges, piers, decks, and other RC structures (Broomfield, 2007).
- Can be combined with other NDT methods: It works well with ER tests, UPV, and GPR radar for comprehensive structural evaluation (Polder et al., 2000).

2.7.2 Limitations

- Does not measure corrosion rate: Only indicates the probability of corrosion, not the extent or rate of deterioration (ASTM, 2022b).
- Surface preparation required: Requires concrete surface moisture and electrical continuity for accurate readings.
- Affected by environmental conditions: Temperature, humidity, and surface contamination influence potential readings.
- Limited to RC: Cannot assess corrosion in unreinforced structures or other materials (ACI Committee 222, 2019).
- Depth limitation: Effective for detecting corrosion near the surface but less reliable for deep reinforcement (Polder et al., 2000).

2.8 Infrared Thermography

Infrared thermography (IRT) is used to detect voids, delamination, and other flaws in concrete structures, as well as corrosion of steel beneath paint, by capturing temperature differences on the surface. This approach relies on the differential heat conductance between air and solid concrete. Infrared cameras are utilized to measure temperature variances within the structure, producing thermal maps. The testing results may be influenced by various factors, including material density, thermal conductivity, ambient air temperature, and humidity (Jia et al., 2022).

Infrared radiation emitted by an object is captured by an infrared camera (thermal imager) and converted into an electronic signal by a built-in sensor. This signal is then processed to generate a thermal image (thermogram), where color variations correspond to different temperature levels, enabling the identification of heat distribution and thermal anomalies.

In IRT, defects like delamination are detected by using the fact that air and solid concrete conduct heat differently. Solid concrete transfers heat efficiently, while air trapped in voids or cracks acts as an insulator. During the day, sunlight heats the surface, and delaminated areas with air gaps trap more heat, appearing as hot spots in thermal images, as shown in Figure 2.7. At night, the surface cools, and solid concrete loses heat faster than delaminated zones, which retain heat longer. This temperature difference helps identify hidden defects (ASTM, 2022c).

IRT's application is limited to expensive cameras, accuracy issues due to surface conditions, and difficulty detecting flaws deeper than 4–5 in. Moreover, heating large areas may be impractical, limiting its use to surveys of small areas (FHWA, 2022). ASTM D4788-03 (ASTM, 2022c) states that it is not possible to specify the precision of the procedure in this test method for measuring delamination of bridge decks because comparative data is not available. Repeatability studies are available. Since a precision statement for this standard has not

Figure 2.7 IRT Being Used to Detect Thermal Anomalies in a Concrete Structure.

been established, this test method is intended for research or informational purposes only. Therefore, this standard should not be used for acceptance or rejection of a material for purchasing purposes (ASTM, 2022c). Therefore, it should be used for assessment, not procurement. IRT is qualitative, best for screening and mapping rather than exact measurement. It may miss deeply buried defects because the thermal contrast is strongest near the surface.

2.8.1 Advantages

- Contactless: No physical contact is needed, making it ideal for large-area inspections (ACI Committee 228, 2013).
- Detects subsurface defects: Can identify delaminations, voids, cracks, and moisture intrusion by analyzing thermal gradients (Maldague, 2001).
- Rapid and efficient: Provides real-time data for quick assessments, reducing downtime for structures (ASTM, 2022c).
- Applicable for large-scale surveys: Useful for inspecting bridges, highways, and buildings without disrupting traffic or operations.
- Effective for moisture detection: Identifies water infiltration and moisture accumulation in concrete and insulation layers (Clark et al., 2003).

2.8.2 Limitations

- Dependent on environmental conditions: Temperature fluctuations, wind, and humidity affect accuracy, requiring ideal conditions for reliable results (Maldague, 2001).
- Limited depth penetration: Can only detect shallow defects (typically up to a few centimeters) and struggles with deep structural issues (ACI Committee 228, 2013).
- Requires skilled interpretation: Image analysis is complex, and incorrect interpretation can lead to false positives or negatives (ASTM, 2022c).
- Material and surface sensitivity: Works best on uniform surfaces; rough or reflective materials may distort results.
- High equipment cost: Advanced thermal cameras and software can be expensive, increasing initial investment (Clark et al., 2003).

2.9 Electrical Resistivity

This technique evaluates the concrete's resistance to chloride ion penetration (used to estimate the corrosion rate) and electrical current flow, making it valuable for quality control and durability assessment. When a surface defect such as a crack or void forms, it can disrupt the path of electrical current, increasing resistivity and leading to a more complex distribution of electrical potential within the concrete. Overall, ER and conductivity reflect how easily ions can move through the concrete under an applied electric field

In the Wenner four-probe method, as shown in Figure 2.8, four equally spaced electrodes are placed in a straight line on the concrete surface. The outer two electrodes inject electrical current, while the inner two measure the resulting voltage difference. This setup allows calculation of the concrete's surface ER. This measurement helps determine the material's ER, which indicates its properties such as moisture content, permeability, or corrosion potential.

Figure 2.8 Surface ER Test Being Performed on a Concrete Cylinder Using a Wenner Four-Probe Device.

There are no universally acknowledged standards that link resistivity to corrosion rate. However, some tool providers offer guidance for interpreting measurements to assess the likelihood of significant corrosion in nonsaturated concrete with active steel. The ER test assesses the concrete's resistance to ionic movement, which correlates with its susceptibility to reinforcement corrosion in moist or chloride-exposed environments, but it does not directly measure corrosion rates (ASTM, 2024a).

Data collection can be labor intensive and results can be influenced by environmental factors, making interpretation challenging. Measurements on elements with electrically isolating coatings or overlays may yield unreliable results (FHWA, 2022).

2.9.1 Advantages

- Continuous monitoring: Allows real-time tracking of corrosion progression (ASTM, 2022b).
- Sensitive to corrosion rate changes: Detects early signs of reinforcement corrosion, aiding in preventive maintenance (Broomfield, 2007).
- Works in various environments: Applicable in marine structures, bridges, and high-moisture conditions (ACI Committee 222, 2019).
- Cost-effective for long-term monitoring: Can be installed permanently for continuous data collection, reducing maintenance costs.

2.9.2 Limitations

- Limited to surface and near-surface corrosion: Less effective for deeply embedded reinforcement (ASTM, 2022b).
- Requires proper calibration: Results vary with moisture content, concrete resistivity, and temperature fluctuations (ACI Committee 222, 2019).
- Affected by external conditions: Chloride content, carbonation, and humidity can influence accuracy (Broomfield, 2007).

- Interpretation requires expertise: Data analysis can be complex and requires skilled professionals to perform accurate assessments.
- Limited application in dry concrete: ER increases significantly in dry conditions, reducing test sensitivity.

2.10 Tabulated Summary of NDT Methods' Methodology, Advantages, and Limitations

Table 2.3 summarizes the NDT methods' advantages and limitations that were discussed in this section.

3. INTEGRATION OF EMERGING TECHNOLOGIES WITH NDT TOOLS

As the demand for safer, more efficient, and data-driven infrastructure management grows, NDT is undergoing a major transformation through the integration of advanced digital technologies. This section explores how emerging innovations are revolutionizing traditional NDT practices. These technologies enhance defect detection, improve data accuracy, and enable continuous monitoring of RC bridge components. By embracing these tools, transportation agencies can transition from reactive

TABLE 2.3
NDT Methods and Summary of Their Methodology.

NDT Method	Methodology	Citations
UPV	Employs longitudinal ultrasonic (sound) waves, measures travel time variations to infer material density, uniformity, and presence of anomalies	ACI Committee 228, 2013; ASTM, 2023
GPR	Transmits high-frequency electromagnetic waves, evaluates signal attenuation and reflection to identify embedded features and defects	ASTM, 2020a; FHWA, 2022
RH	Uses a spring-loaded hammer impact, records rebound height to estimate surface hardness, indirectly linked to compressive strength	ACI Committee 228, 2019; ASTM, 2019
IRT	Captures infrared emissions, assesses temperature differentials to identify variations in material properties and hidden defects, a non-contact method	ASTM, 2022c; FHWA, 2022
HCP	Measures E potential differences between embedded steel and a reference electrode to predict corrosion probability. Drilling may be needed to access a point on rebar (0.6 to 1 inch)	ACI Committee 222, 2019; ASTM, 2022b
ER	Applies an electrical current, analyzes resistivity to determine moisture content, permeability, and ion penetration characteristics	ASTM, 2024a; FHWA, 2022
IE	Uses stress waves to assess material integrity, detect hidden cracks, and evaluate structural condition	ASTM, 2024b; FHWA, 2022
AE	Detects transient AE, categorizes crack growth and stress behavior through frequency-based analysis	ASTM, 2022a; FHWA, 2022

TABLE 2.4
NDT Methods' Advantages and Limitations.

NDT Method	Key Advantages	Limitations
UPV	• Non-destructive and precise: Provides insight into material integrity • Effectively detects internal voids, cracks, and inhomogeneities • Quantitative assessment: Correlates wave velocity with material strength for predictive analysis.	• Typically requires access to opposite sides for best results • Influenced by material properties such as moisture content, aggregate size, and steel reinforcement • Does not provide a detailed defect size or location, requiring complementary tests
GPR	• One-sided, fast, and effective for scanning subsurface structures • Can locate rebar, detect voids, and measure slab thickness • Works in real-time, allowing immediate data analysis	• Performance is limited in wet or highly conductive environments due to signal attenuation • Data analysis is complex, requiring expert interpretation to distinguish between signal noise and actual defects • Cannot directly measure material properties such as strength or modulus.
RH	• Simple, non-destructive, and cost-efficient for rapid surface hardness evaluation • Provides an indirect estimation of concrete compressive strength • Requires minimal training and allows on-site assessment	• Only measures surface hardness, which does not always correlate with internal strength • Results are affected by surface conditions such as moisture, carbonation, and roughness • Cannot detect internal defects or material degradation beyond the surface layer
IRT	• Non-contact, fast, and covers large areas in real-time • Detects thermal anomalies indicating voids, moisture intrusion, and delaminations • Useful for monitoring material degradation over time	• Limited penetration depth: Cannot detect deep internal defects. • Environmental sensitivity: Affected by sunlight, wind, and ambient temperature changes • Requires high emissivity materials for accurate readings

(*Continued*)

TABLE 2.4
NDT Methods' Advantages and Limitations. (*Continued*)

NDT Method	Key Advantages	Limitations
HCP	• Non-destructive and simple to perform • Provides corrosion risk assessment before visible damage occurs • Enables large-scale corrosion mapping with minimal equipment	• Does not measure actual corrosion rate: Only predicts probability • Requires electrical continuity in the reinforcement system for accurate results. • Moisture-dependent: Dry concrete can produce unreliable readings
ER	• Non-invasive test that evaluates concrete permeability, helps predict the likelihood of chloride-induced corrosion • Applicable over large surfaces for preventive maintenance.	• Only provides indirect corrosion assessment: Does not detect actual corrosion activity • Sensitive to environmental conditions, especially moisture content • Cannot differentiate between different corrosion mechanisms
IE	• One-sided test capable of detecting internal voids and delaminations • Effective for evaluating thick concrete structures, provides depth estimation of flaws using wave propagation analysis	• Interpretation requires experience: Signals can be complex • Limited accuracy in thin structures: Best suited for medium to thick elements • Not effective for detecting fine or hairline cracks
AE	• Real-time monitoring detects active cracking and structural deterioration • Can be used for long-term condition assessment • Non-intrusive method with continuous data collection	• Requires long observation periods for meaningful results • Sensitive to external noise: Distinguishing structural emissions from background noise can be challenging • Cannot detect inactive cracks or dormant defects

to predictive maintenance strategies, ultimately extending the service life of bridges and improving public safety.

3.1 NDT 4.0

NDT has undergone significant advancements, transitioning from traditional manual inspection methods to sophisticated digital systems. NDT 4.0 integrates digital technologies, including artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), cloud computing, robotics, and augmented reality (AR), enhancing inspection accuracy (Singh & Vrana, 2021).

Traditional NDT methods, such as radiographic testing (RT), UT, magnetic particle testing (MT), and ET, primarily rely on human expertise and subjective interpretations (Vrana et al., 2020). NDT 4.0 adopts digital transformation driven by Industry 4.0 principles, which was first conceptualized in Germany to modernize manufacturing, providing improved consistency, efficiency, and accuracy. NDT 4.0 reduces reliance on subjective human interpretation by using digital technologies that objectively analyze inspection data, minimizing human error, biases, and inconsistencies.

3.2 Internet of Things and Wireless Sensor Networks

IoT refers to a network of interconnected physical devices. IoT and wireless sensor networks (WSN) facilitate real-time monitoring of RC structural health, enabling early detection and assessment of deterioration such as cracking, corrosion, and spalling. It is critical for the early detection of deterioration in bridge components (Abdelgawad, 2017).

3.2.1 Example

A study by Huang et al. (2021) implemented a WSN-based system to monitor bridge pile foundations for detecting scouring depth. The system utilized wireless sensors to measure frequency and amplitude of vibrations of bridge piers, converting and linking these measurements into meaningful data for assessing structural integrity such as strain and stress measurements, corrosion level, crack width and growth rate, and scour depth data.

3.3 Robotics and Autonomous Inspection Systems

Marine robots are increasingly used for inspecting hard-to-access bridge components, such as piers and underwater sections, enhancing safety and reducing inspection time. Marine robots, also known as underwater robots, are autonomous or remotely operated robotic systems designed for performing inspections, surveys, or monitoring in marine or underwater environments (Ahmed et al., 2020; Mineo & Javadi, 2023).

3.3.1 Examples

For the John Coffee Memorial Bridge, opened to traffic in 1964, climbing robots were used to inspect 36 concrete piers, as shown in Figure 3.1, carrying ultrasonic sensors and GPR to evaluate internal damage, analyze cracks, and assess spalling deep within the concrete. This helped engineers assess structural health without risking human inspectors or damaging the bridge (The University of Alabama at Birmingham, n.d.).

In a research project sponsored by the CANDU Owners Group (2022–2023), Olson Engineering and Gecko Robotics conducted robotic NDE on a 6 × 6 × 1 ft concrete wall embedded behind a ½-inch steel plate, representative of nuclear spent fuel storage containers. A Gecko Monarch climbing robot was equipped with integrated IE and Spectral Analysis of Surface Waves (SASW) sensors, enabling "inch-by-inch" high-resolution scanning of concrete flaws behind the steel. The robot detected honeycombs, voids, and delaminations through the bonded steel surface, with IE proving more sensitive under partial bonding conditions. The robotic platform overcame accessibility challenges and significantly accelerated the inspection process. Robotic NDE enhances speed and mapping quality for complex enclosures. Figure 3.2 shows Gecko Monarch climbing robot conducting IE and SASW Scanning on steel-plated concrete wall (Olson, 2025).

Figure 3.1 RC Pier in John Coffee Memorial Bridge.

Figure 3.2 Gecko Monarch Climbing Robot Conducting NDT on a Vertical Concrete Wall (Olson, 2025).

3.4 Applications of Emerging Technologies in RC Bridge Inspection

It is essential to know how emerging technologies enhance inspection of key RC bridge components by enabling early defect detection and real-time monitoring. Tools like fiber optic sensors and AR improve safety, reduce maintenance costs, and support proactive decision making. Table 3.1 summarizes the possible applications of emerging technologies in inspection of bridge components, based on their attributes.

3.5 Challenges and Future Research Directions

Despite significant benefits, the combination of NDT with emerging technologies in bridge inspections encounters several challenges:

- Data Security and Privacy: Managing cybersecurity risks is critical, particularly with cloud-based NDT systems (Dawood et al., 2023).
- High Implementation Costs: High initial investment for infrastructure required to support AI-driven systems, robotics, and IoT technologies, particularly challenging for small-scale infrastructure owners (Pallardy, 2025).
- Standardization and Regulatory Compliance: There is a critical need to update existing NDT codes (American Association of State Highway and Transportation Officials [AASHTO], 2018; ACI Committee 228, 2013, 2019, 2023;) to reflect digital advancements and assure consistent implementation across regions and industries.
- Workforce Training: Transitioning from traditional to digitalized methods demands specialized skills in digital technologies, automation, and cybersecurity (Adegbite, 2024).

NDT combined with emerging technologies such as robotics and fiber optic sensing is significantly improving the inspection and monitoring of RC bridges. These technologies enable better structural assessments and proactive maintenance strategies, improving reliability and safety. Addressing challenges like implementation costs, standardization, cybersecurity, and training gaps remains essential to facilitate a widespread combination of emerging technologies with NDT.

4. NEW NDT TOOLS

The rapid evolution of NDT technology has led to the development of cutting-edge tools that significantly enhance accuracy, efficiency, and ease of use compared to traditional methods. These advancements improve defect identification, corrosion monitoring, and reinforcement assessments, offering valuable insights for bridge maintenance and rehabilitation. This section explores the latest NDT tools introduced, detailing their capabilities, applications, and applicability to key RC bridge components, including piers, abutments, beam ends, and pier caps. The latest NDT tools offer improvements in imaging, corrosion detection, and defect identification. The following section outlines these tools and their enhanced capabilities compared to traditional inspection methods.

TABLE 3.1
Applications of Emerging Technologies in RC Bridge Inspection.

Component	Exposure to Environmental Factors	Geometry and Shape	Functionality	Benefit from Emerging Technologies in Bridge Inspection
Pier and Abutment	Exposure to moisture, scour (soil erosion around foundations), corrosion from water flow	Vertical cylindrical or rectangular shapes; often partially submerged below water	Supports vertical and lateral loads, transferring bridge loads to foundations	Distributed fiber optic sensors provide real-time monitoring for early detection of scour and corrosion, improving safety, minimizing unexpected failures, and reducing maintenance costs.
Pier Cap	Subject to moisture penetration, freeze-thaw cycles, and chemical attack	Horizontal rectangular or square-shaped elements	Distributes loads from the deck and beams to piers	Advanced UT and AR provide precise defect detection and visualization, enabling accurate identification of internal defects, such as delaminations and corrosion, ensuring structural reliability.
Beam-End	Highly vulnerable to moisture, corrosion, and cracking due to stress concentration	Typically rectangular or T-shaped cross-sections	Critical for load transfer between beams and pier caps	Advanced ultrasonic scanning, distributed fiber optic sensors, and AR-based inspections enable precise, rapid detection of internal defects such as cracks, delamination, and corrosion, reducing risks of localized failures.
RC Solid Slab Bridge	Prone to moisture, freeze-thaw damage, chloride-induced corrosion (due to standing water), and temperature fluctuations	Typically horizontal, continuous flat slab sections	Carries vehicle loads directly, distributes traffic loads	Technologies such as fiber optic sensors, ultrasonic scanning, and augmented reality provide real-time, accurate monitoring of internal defects, enabling proactive maintenance planning, extending service life, and preventing failures.

4.1 Flex NX

Figure 4.1 NDT Tool: Flex NX.

- **Manufacturer:** Geophysical Survey Systems, Inc.
- **Year Introduced:** 2023
- **Advancement Over Traditional Methods:** Compared to traditional GPR, this technology features dual antenna polarization, allowing for clearer differentiation between embedded objects, regardless of their orientation. It provides real-time imaging, which enables immediate and intuitive visualization without the need for complex post-processing. Additionally, it supports rapid preliminary scanning, significantly reducing inspection time compared to conventional GPR. This system can measure depths of up to 60 in., creates a three-dimensional (3D) model of the scan, and works on both horizontal and vertical surfaces.
- **Application:** The Flex NX is essential for detailed structural assessments. It allows engineers to quickly and accurately locate and identify targets within concrete structures, such as rebar, conduits, post-tension cables, and voids. Its advanced imaging capabilities facilitate the evaluation of concrete cover depth and assessment of potential corrosion risks before deterioration progresses. Figure 4.1 shows how the Flex NX can be applied in the field.
- **Applicability to RC Bridge Components:**
  - **Pier:** Provides precise reinforcement mapping, ensuring compliance with design specifications and detecting insufficient cover depth.
  - **Abutment:** Evaluates reinforcement distribution in abutments to prevent localized corrosion and structural weakness.
  - **Beam End:** Identifies improperly embedded reinforcement, a common cause of stress concentration and cracking.
  - **Pier Cap:** Ensures adequate concrete cover over reinforcement, reducing the risk of corrosion-induced failures.
- **Source:** GSSI (2023)

4.2 Elop Insight

- **Manufacturer:** Elop Technology
- **Year Introduced:** 2020
- **Advancement Over Traditional Methods:** It is a 3D ultrasound scanner that generates intuitive 3D images without complex post-processing. This technology allows for real-time 3D scanning of large concrete surfaces, significantly reducing inspection time. It can scan both horizontal and vertical concrete

structures, enhancing its versatility for inspections. It accurately identifies features such as rebars, air pockets, voids, delamination, and tendon ducts, surpassing traditional ultrasound methods. Additionally, it provides an advanced evaluation of concrete cover and corrosion risk, facilitating early intervention and preventative maintenance.

- **Application:** Elop Insight is essential for detailed structural assessments. It allows engineers to quickly and accurately locate and identify targets within concrete structures, such as rebars, air pockets, voids, delamination, and tendon ducts. Its advanced imaging capabilities facilitate the evaluation of concrete cover depth and assessment of potential corrosion risks before deterioration progresses. Figure 4.2 shows a practical use of the Elop Insight for collecting field measurements.
- **Applicability to RC Bridge Components:**
  - **Pier:** Provides precise reinforcement mapping, ensuring compliance with design specifications and detecting insufficient cover depth.
  - **Abutment:** Evaluates reinforcement distribution in abutments to prevent localized corrosion and structural weakness.
  - **Beam End:** Identifies improperly embedded reinforcement, a common cause of stress concentration and cracking.
  - **Pier Cap:** Ensures adequate concrete cover over reinforcement, reducing the risk of corrosion-induced failures.
- **Source:** Elop Insight (2020)

4.3 A1040 MIRA 3D

- **Manufacturer:** Acoustic Control Systems (ACS) in Germany
- **Year Introduced:** 2018
- **Advancement Over Traditional Methods:** Traditional UT methods rely on single-path wave transmission, which limits defect detection capabilities and depth penetration. The A1040 MIRA 3D introduces pulse-echo tomography, a cutting-edge imaging technique that provides multi-angle scanning and full 3D visualization of internal concrete structures. This allows engineers to precisely locate voids, honeycombs, and delaminations that are typically hard to detect with conventional ultrasonic systems. Additionally, it offers superior depth penetration, making it highly effective for assessing thick concrete elements. Figure 4.3 shows the A1040 MIRA 3D in use to collect field measurements.

Figure 4.2 NDT Tool: Elop Insight.

Figure 4.3 NDT Tool: A1040 MIRA 3D.

- **Application:** The A1040 MIRA 3D is particularly effective in bridge condition assessments, where comprehensive structural integrity evaluations are required to identify hidden defects in RC elements.
- **Applicability to RC Bridge Components:**
  - **Pier:** Provides high-resolution 3D imaging to detect internal voids and cracks that may compromise load-bearing capacity.
  - **Abutment:** Offers deep penetration scanning, ensuring early detection of structural weaknesses.
  - **Beam End:** Identifies delaminations and hidden defects, preventing localized failures.
  - **Pier Cap:** Ensures critical load-bearing areas remain defect-free, reducing failure risks.
- **Source:** Acoustic Control Systems (2018)

4.4 Giatec iCOR

- **Manufacturer:** Giatec Scientific Inc.
- **Year Introduced:** 2015
- **Advancement Over Traditional Methods:** Traditional HCP measurements require direct electrical contact with reinforcement, making assessments time-consuming and invasive. The Giatec iCOR is the first wireless corrosion rate measurement device, eliminating the need for rebar connection. It integrates multi-sensor technology, combining corrosion rate, HCP, and concrete resistivity assessments in a single test, providing real-time data collection and enhanced accuracy compared to conventional techniques. The Giatec iCOR is shown collecting measurements in Figure 4.4.
- **Application:** This device is particularly effective for early-stage corrosion detection in RC structures, preventing costly maintenance and extending bridge service life.
- **Applicability to RC Bridge Components:**
  - **Pier:** Identifies early signs of corrosion, ensuring reinforcement durability.

Figure 4.4 NDT Tool: Giatec iCOR.

– **Abutment:** Assesses corrosion potential in abutments to prevent deterioration.
– **Beam End:** Detects high-risk corrosion zones in beam ends, critical for structural stability.
– **Pier Cap:** Provides continuous monitoring, ensuring long-term corrosion prevention.

- **Source:** Giatec Scientific Inc. (2015)

4.5 Pundit PD8050

- **Manufacturer:** Screening Eagle Technologies
- **Year Introduced:** 2021
- **Advancement Over Traditional Methods:** Traditional UPV testing requires dual-sided access for accurate defect detection. The Pundit PD8050 revolutionizes this approach by enabling single-sided testing, making it more practical for field applications. It incorporates advanced phased-array ultrasonic technology, allowing for high-resolution imaging and real-time data analysis. Additionally, it features enhanced signal processing that minimizes noise interference, providing more precise assessments of voids, honeycombing, and delaminations in concrete structures. Figure 4.5 shows the use of this NDT technology.
- **Application:** This tool is particularly effective in evaluating internal defects in piers, abutments, beam ends, and decks, where access may be limited. It enables rapid, non-invasive testing, reducing inspection time while improving accuracy in detecting material inconsistencies and deterioration.
- **Applicability to RC Bridge Components:**
  – **Pier:** Detects internal defects such as voids and honeycombing, ensuring long-term structural integrity.
  – **Abutment:** Identifies delaminations and voids, helping in early damage assessment to prevent further deterioration.
  – **Beam End:** Assesses material homogeneity, ensuring load transfer efficiency and preventing premature failure.

Figure 4.5 NDT Tool: Pundit PD8050.

  – **Pier Cap:** Provides detailed internal imaging to detect cracks and hidden defects, crucial for load distribution stability.
- **Source:** Screening Eagle Technologies (2021)

4.6 Profometer PM-650 AI

- **Manufacturer:** Screening Eagle Technologies
- **Year Introduced:** 2017
- **Advancement Over Traditional Methods:** Conventional rebar locators and cover meters provide limited detection accuracy and require manual interpretation. The Profometer PM-650 AI integrates AI to automate rebar detection, diameter estimation, and concrete cover measurement with unmatched precision. Unlike older models, which rely on basic electromagnetic sensors, this tool employs advanced machine learning algorithms to generate real-time reinforcement maps with high-density scanning capabilities. Figure 4.6 shows the use of the Profometer PM650 AI on a vertical concrete member.
- **Application:** The Profometer PM650 AI is essential for detailed structural assessments, allowing engineers to quickly and accurately identify reinforcement layouts, evaluate concrete cover depth, and assess corrosion risks before deterioration progresses.
- **Applicability to RC Bridge Components:**
  – **Pier:** Provides precise reinforcement mapping, ensuring compliance with design specifications and detecting insufficient cover depth.

Figure 4.6 NDT Tool: Profometer PM-650 AI.

– **Abutment:** Evaluates reinforcement distribution in abutments to prevent localized corrosion and structural weakness**.**
– **Beam End:** Identifies improperly embedded reinforcement, a common cause of stress concentration and cracking.
– **Pier Cap:** Ensures adequate concrete cover over reinforcement, reducing the risk of corrosion-induced failures.

- Source: Screening Eagle Technologies (2017)

4.7 Advanced NDT Tools vs. Conventional NDT Tools

It is important to compare advanced NDT tools with their conventional counterparts, highlighting key improvements such as real-time imaging, AI integration, wireless sensing, and greater accuracy. These innovations enable faster, more precise, and less invasive inspections of concrete structures. Table 4.1 compares the advanced NDT tools to the conventional methods.

4.8 Applicability to RC Bridge Components

The newly developed NDT tools significantly enhance the evaluation of RC bridge components, ensuring structural integrity and proactive maintenance. These technologies provide improved imaging, corrosion detection, and defect identification, enabling engineers to assess the condition of piers, pier caps, abutments, and beam ends more accurately.

- Piers benefit from high-resolution imaging and deep penetration scanning, allowing early detection of voids, cracks, and reinforcement corrosion that could compromise load-bearing capacity.
- Abutments are better assessed with advanced tools that detect material degradation, voids, and early-stage cracking, preventing long-term structural weaknesses.
- Beam Ends are crucial for load transfer and structural stability; the latest NDT devices enable precise detection of improperly embedded reinforcement, cracks, and delaminations.
- Pier Caps require detailed internal assessments to ensure proper load distribution and durability; modern tools detect hidden defects and insufficient concrete cover that could lead to failure.

The introduction of advanced NDT tools in 2024 marks a significant milestone in the evaluation and maintenance of RC structures. By integrating AI-driven analytics, wireless technology, and high-resolution imaging, these tools enhance the detection of internal defects, corrosion, and structural weaknesses with unprecedented precision. Their application in bridge inspections enables early intervention, reducing maintenance costs and ensuring long-term infrastructure reliability. As the demand for durable and resilient infrastructure grows, the adoption of these state-of-the-art NDT techniques will play a crucial role in preserving the safety and longevity of RC bridges.

5. REVIEW OF GLOBAL CODES AND STANDARDS FOR NDT IN RC STRUCTURES

Various NDT methods are governed by standards and codes developed by different international organizations. However, discrepancies among these standards create challenges in data interpretation and implementation across regions (Bertovic, 2015; Gandhi et al., 2022). These inconsistencies can lead to variations in test methodologies, result interpretation, and calibration protocols, thereby limiting the universal applicability of NDT techniques.

A research study highlights that the reliability of NDT is affected by human factors, which have received minimal attention in reliability assessments. The study emphasizes that human inspectors play a crucial role even with increased automation in mechanized testing, and the associated risks are poorly understood (Bertovic, 2015). This underscores the need for harmonized standards that consider technological and human elements to ensure consistent data interpretation and implementation across regions.

Moreover, FHWA (2023) discusses the challenges in integrating data from various NDT systems into asset management frameworks. The report points out that the lack of standardized data formats and interpretation guidelines complicates the effective use of NDT data in decision-making processes, leading to

TABLE 4.1
Advanced NDT Tools vs. Conventional NDT Tools.

Name of NDT Tool	Similar Conventional NDT Tool	Year Introduced	Advancement Compared to Conventional NDT
Flex NX	GPR	2023	Dual antenna polarization, real-time imaging without post-processing, rapid inspection capabilities, accurate object identification, improved depth measurement.
Pundit PD8050	UPV	2021	Single-sided UT capability, rapid non-invasive assessment, enhanced accuracy in defect detection, provides detailed internal imaging even with limited access.
Elop Insight	UT	2022	Real-time 3D visualization, rolling scanner for rapid inspections, improved accuracy in feature identification (rebar, voids, delamination, ducts), advanced corrosion risk evaluation.
Profometer PM-650 AI	Rebar Locator and Cover Meter	2017	AI-driven, automated rebar detection and concrete cover measurements, real-time high-density scanning, superior precision due to machine learning integration.
A1040 MIRA 3D	UT (Single-path)	2018	Pulse-echo tomography providing multi-angle scanning, 3D visualization, enhanced detection and deeper penetration, accurate identification of hidden voids, cracks, and defects.
Giatec iCOR	HCP Method	2015	Wireless, non-invasive corrosion assessment, combined multi-sensor data collection (corrosion rate, resistivity, HCP), faster, more accurate, and less intrusive than conventional methods.

inconsistencies in infrastructure assessment and maintenance strategies. These examples illustrate that without harmonized standards, discrepancies in NDT practices can lead to challenges in data interpretation and implementation, affecting the reliability and safety assessments of structures across different regions.

In the FHWA NDE Roadmap (FHWA, 2023), particularly in the section titled “Data Analysis and Interpretation,” the agency emphasizes the need for standardized NDE data formats. The roadmap highlights that NDEs are conducted using a variety of modalities, each often presenting data in different formats requiring specialized proprietary software. This diversity in data presentation poses long-term issues for asset owners responsible for maintaining records. The roadmap suggests that standardizing data formats is essential to facilitate the integration of NDE data into asset management systems, thereby enhancing infrastructure assessment and maintenance strategies (FHWA, 2023). The primary objective of this section is to analyze and compare international key NDT standards and identify inconsistencies and gaps.

5.1 Overview of NDT Standards and Regulatory Frameworks

Internationally recognized organizations have established comprehensive NDT guidelines to facilitate uniformity in testing methodologies. The most widely used codes and standards discussed in this review are ACI and AASHTO, as well as Standard Specifications for Concrete Structures from Japan Society of Civil Engineers (JSCE), ASTM, and the International Organization for Standardization (ISO). AASHTO and JSCE focus on infrastructure applications, while ACI provides a broad framework for NDT in structural engineering. ASTM and ISO create strictly standardized test methods and certification requirements to ensure uniform testing procedures worldwide.

5.2 ASTM International

ASTM is a globally recognized leader in developing and delivering voluntary consensus standards, including those for NDT. NDT encompasses a range of techniques used to evaluate the properties of materials, components, or systems without causing damage. ASTM’s Committee E07 on NDT is responsible for developing and maintaining standards that guide the application of various NDT methods. These standards ensure consistency, reliability, and safety across industries that utilize NDT techniques. They provide guidelines for detecting and evaluating flaws in materials and objects without compromising their integrity. ASTM has published more than 180 NDT standards, compiled in the Annual Book of ASTM Standards, Volumes 03.03 and 03.04 on NDT.

5.3 International Organization for Standardization

ISO plays a pivotal role in the development of global standards for NDT, which are essential for evaluating the integrity of materials and structures without causing damage. These standards ensure uniformity and reliability in NDT practices across various industries worldwide (ISO, 1997, n.d.).

ISO/TC 135 is the Technical Committee of the ISO responsible for developing and maintaining international standards for NDT. This committee focuses on creating and maintaining standards covering a wide range of NDT techniques, including radiographic, ultrasonic, MT, and penetrant testing. The objective is to facilitate consistent application of NDT methods, thereby enhancing safety and quality in manufacturing and service sectors (ISO, n.d.).

5.4 AASHTO: *Manual for Bridge Evaluation*

AASHTO (2018) is a nonprofit, nonpartisan association representing highway and transportation departments across the United States, including all 50 states, the District of Columbia, and Puerto Rico. AASHTO serves as a liaison between state departments of transportation (DOTs) and the federal government, playing a critical role in establishing guidelines and standards for the design, construction, and maintenance of transportation infrastructure. The NDT-related standards are spread across multiple AASHTO publications, mainly: *Materials Book* (Concrete, soil, and asphalt test methods), *Manual for Bridge Evaluation* (MBE), *Guide for Pavement Evaluation*, and other manuals covering safety testing and structural evaluation.

AASHTO develops and publishes standards that are essential for evaluating the integrity and quality of materials and structures without causing damage. It establishes test methods for evaluating concrete, asphalt, steel, a44nd other construction materials using NDT. These methods allow engineers to detect cracks, voids, corrosion, and material deterioration without physically altering or damaging the infrastructure. These standards are compiled in the *AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, commonly referred to as the *Materials Book*. This publication is a critical resource for ensuring consistency and reliability in testing methodologies across various transportation projects (AASHTO, 2024). AASHTO’s (2018) *MBE* provides guidelines for bridge inspections and evaluation, including NDT methods for detecting deterioration. These NDT methods are GPR, UT, IE, AE, and IRT. They are available in separate publications of AASHTO, often updated every few years (AASHTO, 2018).

5.4.1 NDT for the RC Bridge Pier, Abutment, and Beam End, in Bridge (MBE Section 4: Inspection)

Section 4 of the MBE focuses on inspection procedures, including the application of NDT methods. The inspection procedures are classified based on the purpose of the inspection and the type of information obtained. They include categories such as visual, routine, in-depth, and special inspections (e.g., underwater, fracture-critical). NDT techniques like UT, GPR, and IRT are highlighted for their ability to detect internal defects and deterioration without causing damage to the structure.

5.4.2 NDT for the RC Bridge Pier, Abutment, and Beam End in Bridge (MBE Section 5: Material Testing)

Section 5 addresses material testing, emphasizing both destructive and nondestructive methods to evaluate the properties and condition of bridge materials. For RC components, NDT methods such as UPV, RH testing, and corrosion potential mapping are discussed. This section classifies the NDT test based on the type of materials to be evaluated: concrete, steel, and timber.

5.4.3 Similarities and Differences Between Sections 4 and 5

Both Sections 4 and 5 emphasize the importance of NDT methods in evaluating bridge components. Section 4 focuses on the inspection types and procedure, while Section 5 delves into material testing, providing detailed methodologies for assessing material properties and conditions. The primary difference lies in their focus: Section 4 centers on inspection procedures, whereas Section 5 concentrates on material evaluation techniques.

5.4.4 NDT Methods

The MBE discusses various NDT methods across its sections. In Section 4, methods like UT, GPR, and IRT are highlighted for inspection purposes. Section 5 expands on these by including techniques such as UPV, RH testing, and corrosion potential mapping for material evaluation.

5.4.5 NDT Tools

The MBE references several NDT tools pertinent to bridge evaluation. In Section 4, tools like ultrasonic flaw detectors, GPR systems, and infrared cameras are mentioned for inspection purposes. Section 5 discusses tools such as UPV meters, RH, and corrosion potential measurement devices for material testing.

5.4.6 Strength

The *MBE*'s strength lies in its comprehensive coverage of bridge evaluation procedures, including detailed guidance on inspection and material testing.

5.4.7 Classification of NDT Tools and Methods

In the *MBE*, NDT tools and methods are classified based on their application context. Section 4 categorizes NDT methods used during inspections to detect defects and deterioration, while Section 5 classifies NDT methods based on the type of materials to be evaluated: concrete, steel, and timber.

5.5 ACI Code

ACI's NDT-related standards include ACI 228 and ACI 222. In short, ACI 228 is divided into three subdivisions: ACI 228.1 covers methods for estimating in-place concrete strength, ACI 228.2 focuses on NDT methods for structural evaluation, and ACI 228.3 provides guidance for owners (such as INDOT) on NDT applications.

ACI 228.2 provides a detailed overview of NDT techniques for assessing concrete structures, focusing on stress-wave, electromagnetic, and radiographic (ACI Committee 228, 2013, 2019, 2023) methods.

ACI 222 discusses NDT methods specific to corrosion testing, ensuring the early detection and mitigation of reinforcement deterioration in concrete (ACI Committee 222, 2019). ACI 228.2R focuses on various NDT methods for evaluating structural integrity in concrete, while ACI 222R emphasizes NDT techniques for corrosion detection, ensuring early diagnosis and protection of reinforcement. Both standards are essential for infrastructure maintenance, durability, and safety, helping engineers prolong the lifespan of concrete (ACI Committee 222, 2019; ACI Committee 228, 2013) structures.

5.5.1 ACI-228.1R-19: Report on Methods for Estimating In-Place Concrete Strength

5.5.1.1 NDT for the RC Bridge Pier, Abutment, Beam End, and Solid Slab in RC Solid Slab Bridge. This code emphasizes the critical importance of establishing reliable correlations between the NDT measurements and the actual in-place concrete compressive strength (ACI-Committee 228, 2019). Achieving this involves conducting a correlation testing program that combines in-place test results with direct strength measurements from core samples. The correlation should include concrete specimens reflecting similar mix proportions, curing conditions, and maturity levels as the in-place concrete. To improve reliability, statistical regression analysis must evaluate variability and uncertainty in the correlation data, thus ensuring accurate strength estimation (ACI-Committee 228, 2019; Sections 1.1, 3.1, 5.1, 5.2, and 5.3). Moreover, UPV can effectively evaluate concrete through greater depths (up to 20 ft or 6 m) as mentioned in section 4.2.5 of ACI-228.1R-19, whereas the RH is restricted to near-surface assessments (a few centimeters at most).

5.5.1.2 NDT Methods. The NDT methods discussed in ACI 228.1R-19 include the rebound number method, penetration resistance (probe and pin penetration), pullout test, pull-off test, UPV, maturity method, and cast-in-place cylinders. Each method is comprehensively discussed in terms of operating principles, applications, inherent limitations, and recommended procedures. These methods total seven standardized approaches and include both fully nondestructive methods (e.g., UPV) and methods causing minor superficial damage (e.g., pullout and penetration tests; ACI-Committee 228, 2019; Chapter 3, Sections 3.2–3.8).

5.5.1.3 NDT Tools. ACI 228.1R-19 discusses specific NDT tools including the rebound (Schmidt) hammer (ASTM C805/C805M), penetration devices like the Windsor probe and pin tester (ASTM C803/C803M), pullout test inserts and apparatus (ASTM C900), pull-off test equipment (ASTM C1583/C1583M), UPV instruments (ASTM C597), maturity sensors with data loggers (ASTM C1074), and cast-in-place cylinder molds (ASTM C873/C873M). Each tool varies in its operational characteristics and the type of concrete property it measures. Both purely nondestructive tools (e.g., UPV) and methods involving minor invasive action (pullout, pull-off, penetration) are covered (ACI-Committee 228, 2019; Chapter 3, Sections 3.2–3.8).

5.5.1.4 Strengths. The strengths of ACI 228.1R-19 include comprehensive instructions for correlating NDT measurements with concrete compressive strength through rigorous statistical methods. This standard clearly addresses various factors influencing measurement accuracy, such as test repeatability, single-operator variability, concrete mixture consistency, specimen geometry, and curing conditions. Additionally, it provides practical statistical techniques for regression analysis (ordinary least-squares and Mandel's procedure) to quantify uncertainty and ensure accuracy in strength prediction, thus enhancing the reliability of strength estimation for structural safety assessments (ACI-Committee 228, 2019; Sections 1.6, 3.11, Chapters 4 and 5).

5.5.1.5 Classification of New and Existing Constructions. In ACI 228.1R-19, new and existing constructions are distinguished primarily based on the timing of correlation establishment between NDT results and actual concrete strength measurements. For new construction, correlations should be developed prior to field testing through laboratory-prepared specimens representing the intended concrete mix and placement conditions. For existing constructions, the standard recommends establishing the correlation through in-place tests carried out concurrently with drilled cores taken directly from the structure itself. Thus, the classification criterion relies specifically on whether concrete has been freshly placed (new construction) or previously placed and already hardened (existing construction) when correlation testing occurs (ACI-Committee 228, 2019; Sections 1.1, 5.2, and 5.3).

5.5.2 ACI 228.2R-13: Report on Nondestructive Test Methods for Evaluation of Concrete in Structures

5.5.2.1 NDT for the RC Bridge Pier, Abutment, Beam End, and Solid Slab in RC Solid Slab Bridge. Using NDT methods for RC bridge piers, attachments, beam ends, and solid slabs of RC bridges involves selecting methods appropriate for identifying internal defects, reinforcement condition, concrete uniformity, and detecting potential deterioration. Effective evaluation requires establishing correlations and selecting appropriate methods considering structure geometry, accessibility, and the condition of concrete. Methods such as UPV, radar, IE, and impulse response are suitable for these structural elements because they provide internal quality assessment, detect hidden anomalies, and evaluate structural integrity without significant disruption (ACI Committee 228, 2013; Sections 1.1, 1.2, and 4.1).

5.5.2.2 NDT methods. ACI 228.2R-13 discusses approximately 13 NDT methods: visual inspection, UPV (through-transmission and echo), IE, SASW, impulse-response, sonic-echo, impedance logging, crosshole sonic logging (CSL), parallel seismic, nuclear methods (radiometry and radiography), magnetic and electrical methods (covermeter), HCP, concrete resistivity, linear polarization, magnetic flux leakage), methods for transport property measurement, IRT, and GPR. Not all these tests are purely nondestructive; for example, nuclear radiography involves radiation, and some methods like penetration tests cause minor surface damage (ACI Committee 228, 2013; Chapter 3 of the code).

5.5.2.3 NDT Tools. The standard describes more than 15 distinct NDT tools, including UPV instruments, RHs, IE devices, SASW setups, impulse-response geophones and hammers, sonic-echo equipment, CSL transducers, parallel-seismic hydrophones, radiometric gauges, radiography (X-ray/gamma-ray equipment), covermeters, HCP equipment, resistivity meters (Wenner Array), linear polarization resistance setups, magnetic-flux leakage tools, IRT cameras, and GPR equipment. All these are genuine NDT tools; however, some tools, such as penetration probes and pullout tests discussed in the broader context of NDT, cause minor, repairable surface damage and are thus considered partially destructive methods (ACI Committee 228, 2013; Chapter 3 of the code).

5.5.2.4 Strengths. The primary strength of ACI 228.2R-13 is its comprehensive and detailed presentation of various NDT methods, clearly describing their underlying principles, typical applications, detailed instrumentation, data acquisition, analysis techniques, advantages, and limitations. An important additional strength is its thorough elaboration on method selection (Section 4.1), guiding users explicitly on how to choose appropriate test methods based on clearly defined evaluation objectives, structural geometry, accessibility, depth of the area to be tested, sensitivity to various concrete conditions, and the type and extent of anomalies being investigated. The standard emphasizes selecting suitable NDT methods based on the intended goals of investigation (quality control, troubleshooting, or condition assessment) and practical considerations (accessibility, required depth of penetration, and the expected defect type and size). By providing systematic criteria for method selection, the standard enhances structural evaluations' effectiveness, accuracy, and efficiency (ACI Committee 228, 2013; Sections 1.1, 1.3, 4.1, 4.2, and Table 3).

5.5.2.5 Classification of NDT Methods. In ACI 228.2R-13, NDT tools and methods are classified based primarily on the underlying physical phenomena they exploit. The categories include visual inspection, stress-wave methods, nuclear methods, magnetic and electrical methods, methods measuring transport properties, IRT, and radar. While stress-wave-based methods are classified according to the wave type (ultrasonic, seismic, surface waves), other methods are categorized by their underlying physical principle (nuclear, magnetic/electrical, thermographic, electromagnetic).

5.5.3 ACI-228.3R-23: What an Owner Should Know about Nondestructive Testing-TechNote

5.5.3.1 INDOT, as an Owner. INDOT can benefit from ACI 228.3R-23 (ACI Committee 228, 2023) by gaining essential knowledge to make informed decisions when procuring NDT services. Specifically, this standard assists INDOT in understanding the appropriateness of proposed NDT methods, evaluating qualifications of testing personnel, ensuring proper calibration and functionality checks of equipment, and comprehending how the results will be validated and presented clearly. By leveraging these insights (ACI Committee 228, 2023; Section: Discussion), INDOT can ensure reliability and usefulness from NDT results, leading to improved decision-making regarding the safety, integrity, and maintenance of concrete structures under their jurisdiction.

5.5.3.2 INDOT and Certified NDT Providers. This document guides INDOT in evaluating the qualifications of NDT inspectors by recommending key questions regarding the inspector's training, experience, certification, licensing, and insurance coverage (ACI Committee 228, 2023; Section: Qualifications of Testing Personnel). Specifically, it highlights the ACI certification program, "NDT Specialist-Concrete Strength," as a recommended qualification for inspectors who conduct concrete strength determination tests. This program covers NDT methods given in ACI 228.1R. INDOT can thus use these guidelines to select inspectors who possess adequate experience and credentials and have proven training and certification, ensuring reliable results and enhancing overall project outcomes.

5.5.4 ACI 222R-19: Guide to Protection of Metals in Concrete Against Corrosion

5.5.4.1 NDT for the RC Bridge Pier, Abutment, Beam End, and Solid Slab in RC Solid Slab Bridge. The ACI 222R-19 emphasizes the importance of visual inspections, delamination surveys (to detect subsurface separations within concrete structures caused by corrosion-induced expansion of reinforcing steel), and corrosion potential mapping to assess corrosion-induced deterioration in concrete structures, such as bridge piers, abutment, beam ends, and solid slabs (ACI Committee 222, 2019). These NDT methods help identify corrosion activity and concrete deterioration without causing damage to the structure, thereby guiding informed decisions regarding repairs and maintenance (ACI Committee 222, 2019; Section 5.3.1).

5.5.4.2 NDT Methods. The standard discusses ten specific NDT methods for evaluating corrosion, including visual inspection, delamination surveys, concrete cover measurement, chloride analyses, depth-of-carbonation testing, electrical continuity testing, moisture and resistivity measurements, corrosion potential mapping, corrosion rate measurements, and cross-section loss determination by exposing reinforcement (ACI Committee 222, 2019; Section 5.3.1).

5.5.4.3 NDT Tools. The ACI 222R-19 discusses several NDT tools, including GPR, IRT, IE instruments, and devices for corrosion potential and corrosion rate measurements, making a total of at least five explicitly mentioned tools for NDT assessment (ACI Committee 222, 2019; Section 5.3.1.2).

5.5.4.4 Strengths. One of the primary strengths of ACI 222R-19 is its thorough coverage of both indirect and direct methods for evaluating corrosion activity and the condition of RC. Direct methods measure actual corrosion phenomena or physical changes directly associated with corrosion, such as corrosion potential mapping, corrosion rate measurements, and determining the cross-section loss of reinforcement by physically exposing and inspecting the reinforcement bars. In contrast, indirect methods assess conditions or factors indicative of corrosion potential or risk, without directly measuring corrosion itself, such as visual inspections and concrete resistivity measurements.

5.5.4.5 Classification of NDT Methods. Methods are primarily classified based on their purpose and measurement principles. The standard organizes methods into those assessing corrosion activity (e.g., corrosion potential mapping, corrosion rate measurements) and those evaluating concrete condition (e.g., visual inspection, core extraction, chemical analysis), clearly distinguishing them by their functionality and measurement objectives (ACI Committee 222, 2019; Section 5.3.1 and 5.4)

5.6 ICRI: Guide for NDE Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures

5.6.1 NDT for the RC Bridge Pier, Abutment, Beam End, and Solid Slab in RC Solid Slab Bridge

The guideline from International Concrete Repair Institute (ICRI) emphasizes that NDE, combined with invasive testing for correlation, is crucial in identifying hidden internal distress, providing quality control during repairs, and long-term performance monitoring. Recommended methods include visual inspection, GPR, IE, UPV/tomography, AE, impulse response, HCP, corrosion rate measurements, and IRT particularly effective for internal anomaly detection in bridge elements (ICRI, 2021; Sections 1.0, 3.1, 4.0, and Tables 7.2-7.4).

5.6.2 NDT Methods

The ICRI 210.4R-2021 guideline discusses approximately 27 NDT methods (ICRI, 2021). These include visual methods, GPR, radiography, covermeter, acoustic impact, IE, AE, UPV, ultrasonic tomography, ultrasonic pulse-echo, impulse response, modal analysis, SASW, nuclear density radiation measurements, petrographic examination, moisture meter and probes, IRT, penetrability methods, HCP, corrosion rate testing methods (linear polarization, galvanostatic pulse, electrochemical impedance), ER, low strain impact integrity testing (sonic-echo, impulse response),CSL, crosshole tomography, parallel seismic, and gamma-gamma nuclear density logging (ICRI, 2021; Tables 7.1–7.4 and Appendix A).

5.6.3 NDT Tools

ICRI 210.4R-2021 discusses more than 20 distinct NDT tools, including RHs, maturity meters, tensile pull-off testing equipment, probe and pin penetration testers, pullout testing setups, UPV transducers, GPR antennas, radiography (X-ray sources and film/detectors), covermeters (ET and magnetic reluctance), acoustic impact hammers and chains, IE devices, AE sensors, ultrasonic tomography transducers, UPE setups, impulse response instrumentation (instrumented hammers and geophones), modal analysis instrumentation, surface wave testing equipment (SASW), nuclear density gauges, petrographic microscopy, moisture meters and probes, IRT cameras, permeability testing apparatus, HCP measurement equipment, corrosion rate measurement systems (linear polarization, galvanostatic pulse, electrochemical impedance devices), ER meters (Wenner Array), CSL transducers, tomography equipment, parallel seismic hydrophones, gamma-gamma nuclear density logging instruments, and other embedded instrumentation for structural monitoring (ICRI, 2021, Appendix A).

5.6.4 Strength

It is structured and provides practical guidance for selecting NDE methods based on concrete properties, types of distress, project objectives (condition assessment, repair quality assurance/control, performance monitoring), and structure accessibility. The guideline offers comprehensive tables linking various NDT methods to specific applications, such as strength prediction, reinforcement assessment, general concrete condition assessment, and foundation evaluation. Including practical details on correlating NDE with invasive sampling and laboratory tests further enhances accuracy and applicability. The guideline also supports using NDE to perform quality control and monitoring repairs, highlighting the benefits of NDE for identifying internal distress without causing damage, aiding effective repairs, and ensuring their long-term performance (ICRI, 2021; Sections 3.1–3.4, Tables 7.1-7.4, and Appendix A).

5.6.5 Classification of NDT Methods

In ICRI 210.4R-2021, NDE methods are primarily classified according to their practical application areas and specific concrete conditions they evaluate. The classification includes methods for concrete strength prediction, reinforcement and metal condition assessment (location, sizing, corrosion), structural and general concrete condition assessment, and methods specifically applied for foundation condition, integrity, and length assessment. Within these categories, methods are also indirectly grouped based on the physical phenomena exploited, such as acoustic/stress-wave methods, electromagnetic techniques (GPR, radiography), electrical and electrochemical techniques (corrosion assessment), nuclear radiation measurements (density testing), thermal techniques (IRT), and methods measuring physical penetrability (permeability, moisture content; ICRI, 2021; Tables 7.1–7.4, and Appendix A).

5.7 JSCE-Standard Specifications for Concrete Structures

The JSCE (2024) released the 2022 edition of the *Standard Specifications for Concrete Structures*, which includes comprehensive guidelines on NDT methods for evaluating and maintaining concrete structures. These specifications emphasize performance-based approaches and integrate advanced NDT techniques to ensure structural integrity and longevity. The key aspects of NDT in the 2022 edition are as follows (JSCE, 2024; Niwa et al., 2023):

- **Performance Evaluation:** The specifications provide detailed methodologies for assessing the performance of concrete structures using NDT methods, facilitating early detection of potential issues without causing damage.
- **Updated Inspection Techniques:** Incorporation of the latest NDT technologies, such as UT, GPR, and IRT, to accurately detect and analyze internal defects and deterioration.
- **Maintenance:** Guidelines on the application of NDT in inspections and maintenance planning, enabling data-driven decisions to enhance the durability and safety of structures.

5.7.1 NDT for the RC Bridge Pier, Abutment, Beam End, and Solid Slab in RC Solid Slab Bridge

NDT is emphasized for assessing deterioration, such as cracking, delamination, and internal defects, in concrete structures, including RC bridge piers, abutments, beam ends, and solid slabs. Regular inspections should combine visual and tapping-based NDT methods to quantitatively measure crack dimensions and identify internal issues early (JSCE, 2024; Maintenance Standards, Chapter 3, Section 3.7).

5.7.2 NDT Methods

The standard discusses visual-based methods, tapping-based methods, electromagnetic methods (including electromagnetic induction), elastic wave methods (ultrasonic methods, AE, elastic wave tomography), methods utilizing electromagnetic waves (X-ray, IRT, radar), optical methods (FBG and OTDR), digital imaging methods (photogrammetry, DIC, fluorescent impregnation, Moiré method), surface water absorption tests, and air permeability tests. Approximately at least 14 distinct methods are explicitly mentioned (JSCE, 2024; Maintenance Standards, Chapter 3, Section 3.7.4).

5.7.3 NDT Tools

The standard specifically mentions tools for electromagnetic induction, UT devices, GPR, IRT equipment, AE devices, and elastic wave tomography instruments. While at least six different categories of tools are explicitly described, the exact number of individual tools might vary based on the classification adopted (JSCE, 2024; Maintenance Standards, Chapter 3, Section 3.7.4).

5.7.4 Strength

The key strength of the JSCE standard is its guidance on combining basic visual and tapping inspections with advanced nondestructive methods. In other words, it suggests simple, routine methods (such as visual checks and sounding or tapping to detect surface defects and delamination) followed with sophisticated techniques like UT, radar scanning, and IRT. The standard emphasizes beginning inspections with quick, cost-effective techniques to identify general areas of concern, and subsequently using advanced nondestructive methods for detailed evaluation and precise measurement of internal conditions and deterioration severity (JSCE, 2024; Maintenance Standards, Chapter 3, Section 3.7).

5.7.5 Classification of NDT Methods

The standard classifies NDT tools and methods based primarily on the underlying physical principle or phenomenon they utilize, such as visual-based, tapping-based, electromagnetic induction, elastic wave, electromagnetic wave (radar, infrared, X-ray), optical methods, and digital imaging methods. Each classification is related directly to the information the method or tool provides regarding concrete conditions, defects, or internal deterioration, supporting clear and purposeful method selection (JSCE, 2024; Maintenance Standards, Chapter 3, Section 3.7.4).

5.8 Comparison of ASTM and ISO Standards Regarding NDT Methods

ASTM and ISO are instrumental in the development of standards for NDT methods. Both entities aim to enhance the quality and reliability of materials and structures through standardized testing procedures. However, their approaches and scopes exhibit significant differences, which can influence their applicability in various contexts. Table 5.1 summarizes these differences.

5.9 Comparison of ACI, AASHTO, and JSCE Regarding NDT Methods

- **Methodological Overlap:** ACI, AASHTO, and JSCE standards all emphasize the importance of NDT techniques, commonly recognizing UT, IRT, and RH methods as effective tools for assessing concrete condition.

TABLE 5.1
Comparison of ASTM and ISO Standards Regarding NDT Methods.

Name of NDT Method	ASTM and ISO	Evaluation of Standards	Gaps to be Filled	Details of Strengths and Weaknesses
AE Testing	ASTM E3100-22, ISO 16837:2019	ASTM provides a well-defined framework for AE in concrete structures, while ISO focuses more on damage detection in RC beams.	A unified framework integrating ASTM's general methodology with ISO's damage-specific evaluation would improve consistency across international practices.	**Strengths:** ISO has better guidelines for beams; ASTM is versatile. **Weaknesses:** Lack of harmonization.
UPV	ASTM C597-16, ISO 1920-7:2004	ASTM offers a detailed and modernized procedure for UPV, while ISO's guidelines are outdated and lack procedural depth. ASTM is more suitable for current industry applications.	Updating ISO 1920-7 with modern UPV techniques to match ASTM's standards would enhance its relevance and accuracy.	**Strengths:** ASTM is well-established. **Weakness:** ISO may be outdated and less detailed.
RH Testing	ASTM C805/C805M-18, ISO 1920-7:2004	ASTM focuses exclusively on rebound number, whereas ISO includes multiple non-destructive tests, including RH.	Harmonization between ASTM and ISO standards to ensure global consistency in RH testing.	**Strengths:** ASTM is precise for surface hardness testing. ISO provides a general approach to multiple NDT methods.
HCP Measurement	ASTM C876-15, ISO 12696:2016	ASTM provides a detailed methodology for measuring corrosion, ISO focuses on broader cathodic protection	Harmonization of corrosion assessment methodologies between ASTM and ISO.	**Strengths:** Accurate corrosion detection. **Weaknesses:** ASTM is specific but lacks cathodic protection guidelines; ISO is broader but less detailed on corrosion potential.
IRT	ASTM E1934-99a (2020), ISO 10878:2013	ASTM provides procedural guidelines, while ISO focuses on terminology and diagnostics.	An updated ISO standard should include practical methodologies similar to ASTM's, ensuring consistency in defect detection procedures.	**Strengths:** ASTM offers structured guidelines for testing. **Weaknesses:** ISO lacks detailed procedural guidelines.
GPR	ASTM D6432-19 (No ISO Standard)	ASTM standard exists, but no dedicated ISO standard for GPR.	Establishment of uniform procedures for GPR data acquisition, interpretation, and validation specifically for assessing reinforcement depth, voids, and deterioration in RC structures.	**Strengths:** ASTM provides comprehensive guidelines for GPR use in detection of reinforcement, voids, and deterioration. **Weaknesses:** No ISO standard exists for GPR
IE Testing	ASTM-C1383-15 (No ISO Standard)	ASTM standard exists, but no ISO equivalent for RC structures.	Development of an ISO standard to harmonize testing methods.	**Strengths:** Effective for determining thickness and detecting flaws. **Weaknesses:** No ISO counterpart.

- **Regional Adaptations:** While ACI and AASHTO provide detailed standards and test methods tailored to practices in the United States, JSCE's guidelines are adapted to address Japan's unique environmental challenges and construction practices.
- **Scope of Application:** ACI's documents offer a broad overview of various concrete structures, AASHTO focuses specifically on transportation infrastructure like bridges and pavements, and JSCE emphasizes maintenance procedures suited to Japan's infrastructure needs.

Table 5.2 provides a comparison of these three codes on NDT.

This section highlights inconsistencies in the current global standards. ACI stands out for its comprehensive guidelines. AASHTO's focus on transportation infrastructure limits its broader applicability, while JSCE's lack of direct NDT standards calls for greater integration with existing regulatory frameworks. Furthermore, the discrepancies between ASTM and ISO standards must be addressed to ensure procedural harmonization.

6. CASE STUDIES ON THE APPLICATION OF NDT METHODS IN BRIDGE ASSESSMENT

This chapter presents a series of real-world case studies that demonstrate the application of various NDT methods in evaluating the condition of concrete bridge components. These investigations, conducted across different states and countries, highlight both the capabilities and limitations of NDT methods. Each case study offers insights into the structural assessment process, showcasing how NDT supports informed decision-making for maintenance, rehabilitation, and safety assurance of bridge infrastructure.

TABLE 5.2
Comparison of ACI, AASHTO, and JSCE regarding NDT methods.

Attribute	ACI (228 & 222R)	ICRI 210.4R–2021	AASHTO (Bridge & Pavement Evaluation)	JSCE
Focus	Provides guidelines for NDT methods in concrete evaluation (ACI 228) and corrosion assessment & prevention (ACI 222R)	Emphasizes the selection of NDE methods for condition assessment, quality assurance /quality control during repairs, and long-term performance monitoring of concrete structures.	Primarily targets transportation structures (bridges, highways) with an emphasis on inspection and asset management	Focuses on long-term durability and maintenance of concrete structures, adapting to seismic effects and environmental factors
Key Documents	ACI 228.1R (Strength estimation), ACI 228.2R (NDT methods), ACI 228.3R (Owner guidance on NDT), ACI 222R (Corrosion protection & mitigation)	NDE Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures	AASHTO Manual for Bridge Evaluation (MBE), AASHTO T 338 (Surface Resistivity), AASHTO T 356 (UT for Pavements)	JSCE Standard Specifications for Concrete Structures with specific guidance for NDT-based structural health monitoring
NDT Methods Used	ACI 228: UPV, IE, GPR, RH, HCP ACI 222R: Surface Resistivity, HCP, ER, Polarization	Visual inspection, GPR, Radiography (X-ray), Covermeters, IE, AE, UPV/Tomography, IRT, HCP, ER, Crosshole Sonic Logging, Nuclear Density.	GPR, UT, AE, IRT, HCP	UT, RH, IRT, Visual Inspection, HCP, Resistivity Measurements
Application	ACI 228: Research, material strength estimation, structural integrity assessment ACI 222R: Corrosion prediction, chloride penetration, durability assessment	Condition assessment prior to repairs, quality assurance and quality control of repairs, performance monitoring to identify internal defects, evaluate structural integrity, monitor corrosion activity, and assess concrete durability.	Used for asset management, performance-based evaluation, and bridge condition rating	Used for maintenance-based assessment, predictive durability modeling, and post-earthquake evaluations
Limitations	ACI 228: Not specifically tailored for transportation infrastructure like bridges ACI 222R: Limited outside of corrosion monitoring	Dependent on invasive tests for correlation; NDT tools calibration; inherent limitations based on concrete conditions, moisture content, reinforcement density, and structure complexity.	Limited applicability outside of transportation structures	Primarily focused on Japan's unique construction challenges
Regional Adaptation	Global relevance, widely used in engineering and research	Applicable globally, designed for broader use with clear guidelines for method selection, correlation with invasive/lab testing, and flexibility for diverse structural concrete assessment contexts.	Aligns with FHWA and state DOT practices	Adapted to Japan's seismic risks and environmental exposure

Sources: AASHTO, 2018; ACI Committee 222, 2019; ACI Committee 228, 2013, 2019, 2023; JSCE, 2024

6.1 Case Study: GPR Investigation of Bridge Pedestals (NDT Corporation, 2018)

The study investigates the concrete pedestals in a bridge located in Portage, Indiana. The bridge is a steel-girder bridge, as evident by the green-painted steel girders connected to the concrete pedestal through a bearing system. The pedestals are located at south abutment and north abutment.

GPR data was collected and archived along three horizontal and two vertical lines for all 36 pedestals. A typical data collection archive is shown in Figure 6.1.

The primary goal of this research was to utilize GPR to establish the actual reinforcing layout (both vertical and horizontal bars), spacing, and concrete cover depth within the concrete pedestals.

A 2000 MHz GPR antenna coupled with a SIR-4000 processing unit was employed for data collection, providing penetration depths of approximately 7–8 in. Data acquisition involved measuring along three horizontal and two vertical reference lines for each pedestal. Visual marking of detected reinforcement was conducted on-site for immediate verification and clearer interpretation.

Due to the limited depth penetration of GPR, the data for the inner part of the pedestal was not collected. Figure 6.2 shows the top view of the pedestal, where the locations of horizontal and vertical reinforcement (in green) and anchor bolts (in blue) are detected by GPR. The gray area is not assessed due to insufficient depth penetration of GPR.

The accuracy of GPR in this study was identified as ±0.5 in. for locating reinforcing bars.

The accuracy was significantly influenced by factors such as moisture content, concrete density, the presence of closely spaced bars, and signal scattering. Thus, while GPR was effectively able to locate reinforcing bars, the results required professional interpretation and confirmation through supplementary physical investigation methods, such as test pits or coring. The results of GPR indicate the following.

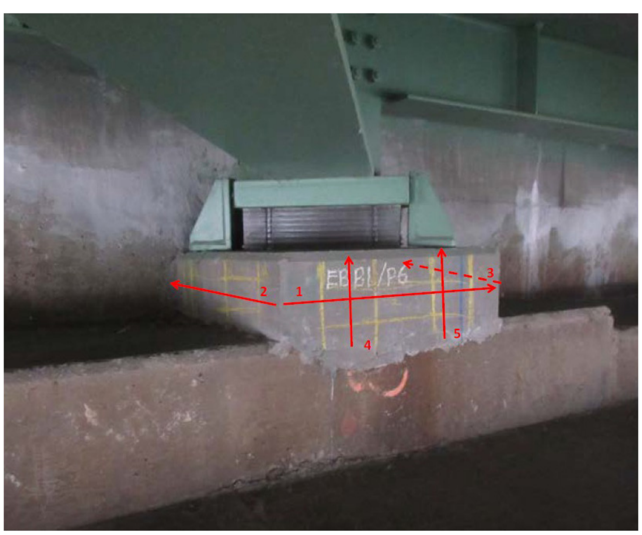

Figure 6.1 Horizontal and Vertical Lines Where GPR Was Used to Collect Data on Pedestals.

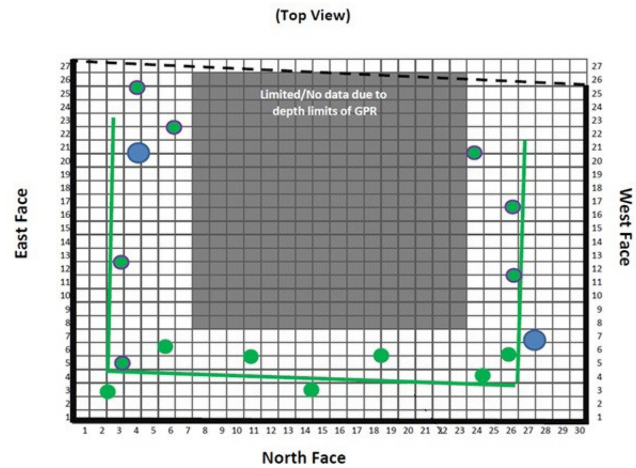

Figure 6.2 Top View of Pedestal With Detected Layout of Reinforcement.

6.1.1 Results and Observations

- GPR revealed significant inconsistencies in reinforcement placement, with notable variations in the number and spacing of vertical reinforcing bars, ranging between 5 to 12 per pedestal.
- Horizontal reinforcement bars exhibited skewed and nonuniform placements with varying concrete covers. There was noticeable variation in the depth of the concrete cover over reinforcement bars, even on the same surface (face) of a single concrete pedestal. Specifically, the concrete cover (the distance from the surface of the concrete to the embedded reinforcement bars) was not uniform, showing variations of approximately 2 in. (50.8 mm) to 3 in. (76.2 mm).
- The positions of the anchor bolts were also documented, highlighting that some may not be properly surrounded or enclosed by the steel reinforcing cage within the pedestal.

GPR results presented reflective patterns that required careful interpretation. Reinforcing bars appeared as parabolic reflections within GPR records, demanding professional judgment to distinguish between bars, anomalies, or signal artifacts. Due to GPR's depth limitation, certain pedestal areas had limited or no data, requiring additional investigative measures for comprehensive understanding.

The results included detailed top-view grid layouts (1-in. increments) illustrating the reinforcement and anchor bolt positions. The visuals clearly marked vertical bars along front and side faces, horizontal reinforcement bars, and anchor bolt positions, as well as regions with depth limitations.

GPR proved an effective NDT method for preliminarily assessing reinforcing layouts and identifying construction discrepancies within bridge pedestals. The findings underscored the necessity for professional judgment in interpreting NDT results and recommended complementary invasive verification methods to confirm GPR findings conclusively. The study provided critical insights into construction quality, highlighting inconsistencies that could lead to structural vulnerabilities and advocating for stricter quality control during the construction phase.

6.1.2 *Lessons Learned from the GPR*

- GPR is Effective but has Accuracy Limitations:
  - GPR provided valuable insights into reinforcement placement but showed inherent accuracy limitations of ±0.5 in. (±12.7 mm). Hence, while beneficial, it should be complemented with physical verification (Page 2 of the reference).
- Influence of Material and Environmental Conditions:
  - Concrete moisture content, density, and closely spaced rebars significantly influenced the accuracy and reliability of GPR results, causing variability and sometimes unclear signals (Page 2 of the reference).
- Interpretation of GPR Data Requires Expertise:
  - GPR data presented in the report required careful, professional interpretation. Reinforcement appeared as parabolic patterns, and distinguishing these clearly from signal noise or other anomalies demanded experienced judgment (Appendix 1 of the reference).
- Limited Depth of GPR Signal Penetration:
  - The GPR antenna used had a maximum penetration depth of approximately 7–8 in. (177.8–203.2 mm). Beyond this, information was not reliable, emphasizing the need to recognize depth limitations (Page 2 of the reference).
- On-Site Visual Marking Aids Interpretation:
  - Visually marking reinforcement locations immediately on-site using keel improved clarity, minimized interpretation errors, and enhanced the practical usability of GPR results (Page 2–3 of the reference).

6.2 Case Study: Load Rating Summary Report for Rehabilitation and Design Review (CiorbaGroup, 2022)

INDOT did a deck overlay project on this structure. The joints in the bridge were replaced as part of the work. When they removed portions of the deck to replace the joints, they exposed the ends of the concrete beams. MIRA (Multi-channel Instrument for Reflective Analysis) was used to inspect the concrete beam ends. Eventually, the decision was made to replace the concrete beams through a change order in the construction process. The construction project initially was slated to be completed during the 2022 season, but because of these beams, it ended up extending into the 2023 season. Figure 6.3 shows the bridge under inspection. Figure 6.4 through Figure 6.6 show MIRA instrument, a section of beam end, and condition mapping of beam end, respectively.

6.2.1 *Bridge Specifications*

- Bridge Information
  - **Bridge number:** 23-71-04992 B
  - **NBI number:** 005820
  - **Location:** SR 23 over SR 933 NB/Lincoln Way, St. Joseph County, Indiana.
  - **Structure type:** Prestressed Concrete I-Beams (Type I) and Composite Steel Beam Bridge
  - Built in 1962, rehabilitated multiple times (1983, 1994, 2020, and 2022).
- Condition and Issues
  - Beam Ends were identified as critical areas with severe deterioration, more extensive than visible during regular inspections.
  - Deterioration included:

Figure 6.3 Bridge Under Inspection.

Figure 6.4 Use of MIRA on Concrete Beam End.

1. Cracks: Identified primarily through visual inspection.
2. Unsound concrete detected via:
   - Hammer sounding (manual method) which produces a dull or hollow sound indicating internal delamination or deterioration not visually apparent.
   - The NDT instrument MIRA was used in this case study, but the details of its application were found in the available report.
3. Spalls which were detected visually.

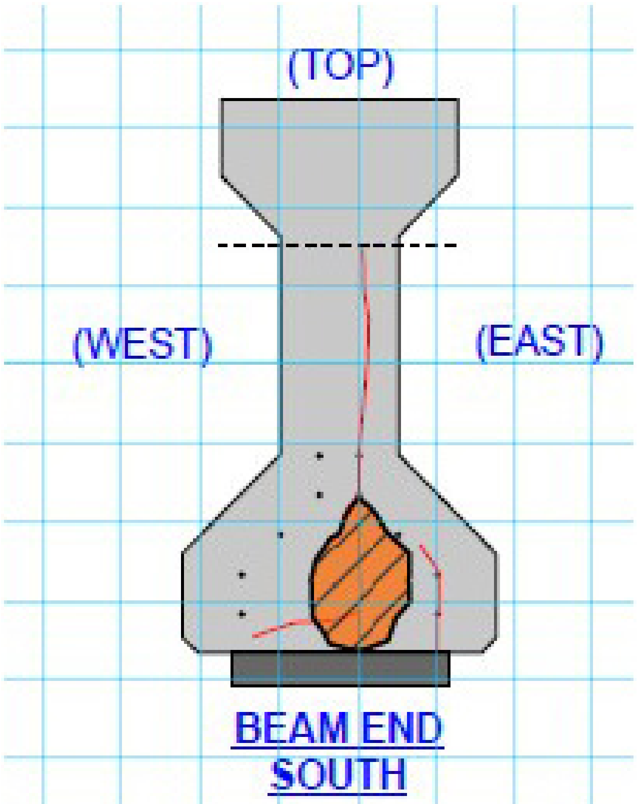

Figure 6.5 Section of RC Beam End.

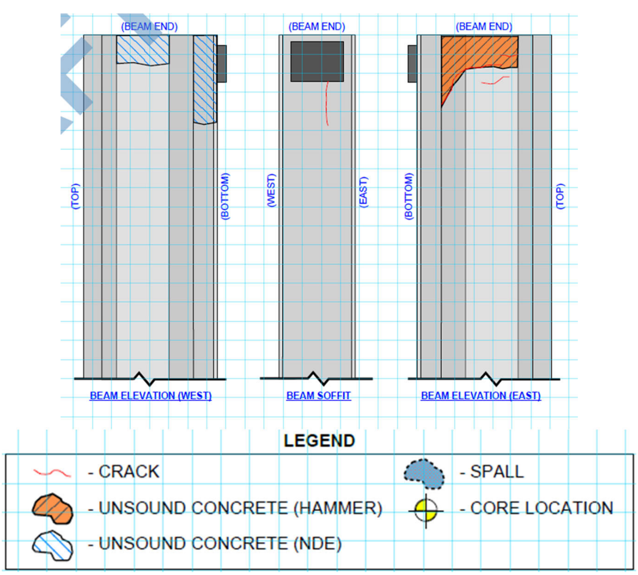

Figure 6.6 Beam end Inspected: Bottom, Top, and Web.

6.2.2 Core Sampling

Core sampling was conducted for validation of NDE findings and to determine concrete strength and internal conditions. This is recommended by ICRI-210.4R–202. The unsound hammer testing and NDT using the MIRA instrument were performed for inspection.

6.2.3 Recommended Actions and Decisions

- Due to severe beam end deterioration, beams were scheduled for replacement via a change order in the 2022 rehabilitation project, extending into 2023.
- The report explicitly states traffic restrictions due to poor beam conditions, indicating the need for prompt repair measures.

6.3 Case Study: Abisko Bridge (Hedlund, 2020)

The primary objective of the case study was to examine various NDT techniques and gain a deeper understanding of their challenges and advantages of the bridge. The bridge and its cross-section are shown in Figure 6.7 and Figure 6.8, respectively.

6.3.1 Bridge Specifications

- **Location:** Abisko, Sweden (near the Norwegian border)
- **Function:** Railway bridge on the Iron Ore Line
- **Type:** Continuous prestressed concrete box girder
- **Spans:** 3
- **Cross-Section:** Hollow rectangular box girder (provides high torsional stiffness)

6.3.2 Structural Element Clarifications

- **Side Wall (Beams 1 & 2):** These are the vertical webs of the box girder.
- **Beam 1:** South side
- **Beam 2:** North side
- **Roof Slab:** The top surface of the box girder that supports rail tracks—also tested during the project.

6.3.3 Lessons Learned from the Abisko Bridge Case Study

Table 6.1 shows the summary of findings about the use of NDT in this bridge.

The key findings of this case study were as follows.

- NDT is valuable but challenging in the field.
  - NDT techniques like RH and covermeter provided useful data on reinforcement layout and concrete strength.

Figure 6.7 The Railway Bridge in Abisko Used for Experiments During the Case Study.

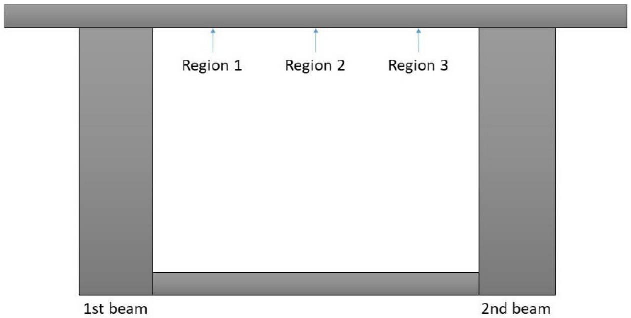

Figure 6.8 Cross-Section of the Bridge: Hollow Rectangular Box Girder.

TABLE 6.1
NDT Instruments Used in Abisko Case Study.

Instrument	Commercial Name	Purpose	Part of Bridge Used
Covermeter	Proceq Profometer 650 AI	• Locate reinforcement • Measure spacing and orientation • Measure concrete cover	• Side walls (vertical webs) • Areas with observed cracks
RH	Proceq SilverSchmidt Hammer	• Estimate concrete compressive strength • Data used for SONREB method	• Side walls • Roof slab
GPR	Not specified	• Tried to detect tendons or reinforcement	• Unspecified (likely areas with expected tendons): reported inconclusive due to signal ambiguity

  - However, field conditions (e.g., surface roughness, accessibility) impacted the accuracy and ease of use compared to lab settings.
- Covermeter was a reliable tool.
  - The Proceq Profometer 650 AI performed well in locating reinforcement, determining spacing, and measuring cover depth even in crack-prone areas.
  - It was easy to use and produced repeatable results, making it suitable for both lab and field applications.
- RH was useful but sensitive to surface conditions.
  - The SilverSchmidt Hammer gave reasonable compressive strength estimates but required good surface prep.
- GPR was attempted but inconclusive.
  - GPR was trialed but failed to reliably distinguish between tendons and other reinforcement, highlighting interpretation challenges with this method.
- User experience is critical.
  - The success and accuracy of NDT heavily depend on operator experience and knowledge of both the tools and the structure.

6.4 Case Study: NDT of Segmental Concrete Bridge-Florida DOT (Rehmat et al., 2017)

This project was prepared by Florida International University and sponsored by the Florida Department of Transportation in 2017. It presents the results of an in-depth study that evaluated various NDT methods on a segmental post-tensioned concrete bridge. The bridge, scheduled for demolition, offered a rare opportunity to test NDT techniques both in the field before demolition and in the lab using extracted bridge segments. An analytical study was carried out for demolition sequence, and segments of the bridge were transported to Florida International University.

The study focused on detecting corrosion, voids, and strand breakage in internal post-tensioning tendons. NDT technologies of Impulse Response (IR), IRT, Magnetic Flux Leakage (MFL), AE, Inductance Testing, and Interferometric Radar were used. The bridge and its cross-section are shown in Figures 6.9 and 6.10, respectively.

6.4.1 Bridge Specifications

Bridges general information:

- **Location:** Fort Lauderdale, Florida (exit ramp to Southbound US Route 1)
- **Bridge ID:** 860434
- **Type:** Segmental prestressed concrete bridge
- **System:** Internal post-tensioned (PT) tendons
- **Status:** Decommissioned and scheduled for demolition; used for experimental testing
- **Segments:** Four 10-ft-long segments were extracted and tested in both field and laboratory

Segmental Box Girder Cross Section in this study:

- **Type:** Post-tensioned segmental box girder
- **Shape:** Hollow box girder, typically rectangular
- **Tendons:** Internal post-tensioning ducts embedded in the concrete
- **Ducts:** Located close to the bottom flange and web surfaces, which posed challenges for NDT access and inspection
- **Diaphragms:** Present over piers (as is typical in balanced cantilever construction)

Figure 6.9 Overall View of the Bridge.

Figure 6.10 Box Girder Cross-Section of the Bridge.

6.5 Case Study: NCHRP IDEA Research: Test Girder with Simulated Voids (Olson, 2025)

Figure 6.11 through Figure 6.13 show a bridge segment cross-section, a grout defect simulation with embedded Styrofoam voids, and vertical IE scans along 6-in.-spaced lines on the bridge girder.

- **Project Title:** NCHRP IDEA Contract No. 102
- **Year:** 2022
- **Component Assessed:** Bridge girder webs with embedded post-tension ducts
- **Techniques Used:** Impact-echo scanning (IES), SASW, 3D GPR
- **Challenges:**
  - Detecting voids in ducts that are internally embedded and inaccessible
  - Differentiating between fully grouted and partially voided PT ducts
- **Limitations:**
  - Requires proper calibration and baseline measurements
  - Echo signal interpretation can vary with geometry and material conditions
- **Advantages:**
  - IES clearly detected 22% increase in echo thickness at voided locations
  - Data fusion of IES, SASW, and GPR enhanced defect resolution
- **Lessons Learned:**
  - Void detection is effective when combining multiple NDE methods
  - Data fusion enhances confidence in interpreting structural defects

Figure 6.11 Bridge Segment Cross-Section (Olson, 2025).

Figure 6.12 Grout Defect Simulation With Styrofoam Voids (Olson, 2025).

Figure 6.13 Vertical IES on 6-in. Spaced Lines on Bridge Girder (Olson, 2025).

Table 6.2 summarizes the NDT methods, corresponding commercial instruments, their purposes, and the specific parts of the bridge where each method is typically applied.

6.5.1 Lessons Learned from the NCHRP IDEA Research Case Study

- Each NDT method has specific strengths and limitations
  - No single NDT method was sufficient for complete assessment.
  - IR was useful for global stiffness changes**,** but not detailed damage.
  - MFL and Inductance Testing showed the most promise for detecting internal tendon damage and section loss**.**
  - IRT worked well with active heating in lab but was less reliable in field due to limitations in passive heating and concrete thermal properties.
- Field conditions can significantly limit NDT effectiveness
  - Real-world noise, access constraints, and material interference (e.g., transverse rebar, thick concrete covers) reduced accuracy of some NDT results.
- Combining multiple NDT methods improves reliability
  - Using a hybrid approach (e.g., MFL + IRT or AE + IR) provided cross-validation and more comprehensive insights.
  - Data correlation between methods improved confidence in damage detection.
- Need for standardized protocols and NDT training
  - Proper use and interpretation of NDT requires skilled operators and clear guidelines**.**
  - The study emphasized the need to develop standardized procedures for PT bridge inspection using NDT.

6.6 Case Study: Flyover Footbridge in Cairo, Egypt (Shubbar et al., 2020)

This case study was conducted to evaluate the structural integrity of a RC footbridge flyover, featuring post-tensioned concrete girders, located in Cairo, Egypt, as shown in Figure 6.14. The bridge had been exposed to long-term environmental factors, including corrosion and visible signs of distress. The goal

TABLE 6.2
NDT Instruments Used, Purpose, and Application Areas.

NDT Method	Commercial Instrument	Purpose	Part of Bridge
IR	*Olson Instruments – IR System*	Evaluate global stiffness and detect structural degradation	Bridge deck and spans
IRT	*FLIR Thermal Cameras* (exact model not specified); Butane torch & inductive heating used for active IRT	Detect deficient grout and possible voids in tendons	Bridge surface (deck, underside, tendons)
AE	*Freedom Data PC (Olson Instruments)* with accelerometer arrays	Detect tendon breakages	Tendon regions and deck
MFL	*Custom-built MFL system* with Hall Effect sensors and permanent magnets	Detect physical discontinuities and corrosion in internal steel tendons	Bridge segments (tendons inside ducts)
Inductance Measurement	*Custom inductor coils* with inductance meters	Detect section loss in strands and assess grout quality	On surface over tendon ducts

Figure 6.14 Conducting Half-Cell Corrosion Potential Testing.

of the study was to assess the in-situ condition of the bridge structure without causing any damage, using a suite of NDT techniques.

6.6.1 Bridge Specifications

Table 6.3 outlines the key structural and material characteristics of the post-tensioned concrete pedestrian bridge's cross-section, including its girder configuration, deck composition, tendon arrangement, duct type, and construction materials.

TABLE 6.3
Bridge Cross-Section Details.

Aspect	Description
Structural Type	Post-tensioned concrete pedestrian bridge (flyover footbridge)
Main Girders	Two post-tensioned concrete girders, forming the primary longitudinal supports
Deck	RC slab cast over the girders
Cross-Section Shape	Likely an I-shaped or box girder profile (inferred from use of ducts and post-tensioning)
Post-Tensioning	Internal post-tensioned tendons used within the girders
Ducts	Corrugated plastic ducts embedded within the girders to house steel tendons
Materials	Cast-in-place RC for deck and girders
Wing Walls	RC wing walls at abutments
Substructure	RC piers and abutments

6.6.2 Application of NDT Tools

- Bridge Piers:
  - NDT Techniques Used:
    - **UPV:** To assess the internal quality and detect possible voids or cracking within the concrete.
    - **RH:** To estimate surface hardness and infer compressive strength.
    - **Carbonation Test:** To measure carbonation depth and assess potential corrosion risk near reinforcement.
    - **HCP Test:** To evaluate the likelihood of corrosion activity in the embedded steel.
- Girders and Beams
  - NDT Techniques Used:
    - **UPV:** Applied to the web and bottom flange of the beams to detect internal flaws.
    - **RH:** Used on side faces to estimate surface hardness and identify weakened zones.
    - **Carbonation Test:** Core samples taken near the reinforcement zone to check carbonation depth.
    - **HCP Test:** Used to identify areas of active corrosion, especially in the rebar near the beam bottom or sides.
- Deck Slab and Wing Walls
  - NDT Techniques Used:
    - **UPV:** To evaluate internal concrete integrity and detect delaminations or poor quality zones.
    - **RH:** Conducted on a grid across the slab surface for assessing strength variability.
    - **Carbonation Test:** Drilled core samples from the slab to measure carbonation, typically above reinforcement depth.
    - **HCP Test:** Used across a grid pattern to map corrosion potential in the deck reinforcement.
    - **UPV (Wing Walls):** Applied to vertical faces of the wing walls to detect internal cracking or low-density areas.

6.6.3 Lessons Learned from the Flyover Footbridge Case Study

- Multitechnique NDT provides more reliable assessments
  - The study demonstrated that employing a combination of NDT techniques such as UPV, RH, HCP, and Carbonation Testing yields a more holistic and reliable evaluation of the structural health of RC elements. Cross-verification between methods enhanced confidence in the results.
- UPV and RH work well together
  - These two methods complement each other by providing both internal and surface-level assessments of concrete integrity. While UPV assesses internal flaws, the RH identifies surface deterioration and strength variability.

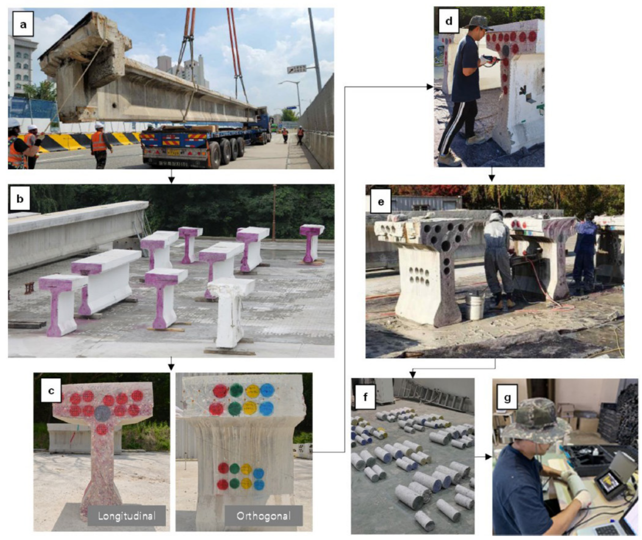

Figure 6.15 Core Sampling Process From the Target Structures: (a) Collection of Structural Members From the Target Structures, (b) Section Zoning and Cutting the Members Into Sections, (c) Marking the Coring Positions, (d) Testing the Rebound Hardness for Coring Position, (e) Coring From Various Directions, (f) Precuring of Cores Before Testing (48 h in air), and (g) Measuring UPV (Kwon et al., 2025).

- Carbonation and half-cell tests are critical for corrosion prediction
  – The carbonation test helped assess the depth of carbon dioxide penetration, while the HCP test enabled mapping areas with a high risk of corrosion. Together, they provided valuable insights into the durability of the reinforcement system, especially in areas affected by aging and environmental exposure.
- Effective on Multiple Bridge Elements
  – NDTs were successfully applied to piers, girders, deck slabs, and wing walls. This proved the versatility of NDT in evaluating various structural components without the need for invasive procedures.

6.7 Case Study: Concrete Strength Estimation of Aged Concrete Bridges in South Korea (Kwon et al., 2025)

The purpose of this study was to evaluate how NDT methods, RH can be used to estimate in-situ compressive strength of aged concrete in a bridge structure, as shown in Figure 6.15, and to propose a reliable protocol that minimizes the need for coring.

6.7.1 Methodology of Testing

- **Structures Studied:** 7 aged concrete bridges in South Korea (most >40 years old)
- **Components Tested:** Slabs and girders
- **NDT Methods:**
  – Rebound Hardness (RH): ASTM C805
  – UPV: ASTM C597
- **Reference Testing:** Over 500 concrete cores were extracted and tested for compressive strength.
- **Comparative Analysis:** NDT-estimated strengths were compared with actual core strengths.

TABLE 6.4
Technical Findings.

Observation	Details
RH and UPV typically underestimate strength	Estimated values using standard equations were generally lower than actual core strength.
NDT variance is lower than core strength variance	Suggests NDT is more consistent but tends to bias toward lower strength.
Low correlation (R^2) in aged concrete	In many cases, the R^2 between NDT signals and core strength was <0.5, especially in deteriorated concrete.
NDT-Estimated Minimum not equal to True Minimum Strength	In 5 out of 7 bridges, the weakest zone identified by NDT did not match the actual lowest core strength location.
Surface degradation affects NDT	RH and UPV are sensitive to surface conditions like carbonation or fatigue, which may not reflect deeper concrete strength.
NDT can identify minimum strength range	While it may not detect the exact lowest strength spot, it can estimate a range representative of minimum values.

TABLE 6.5
Application Scenarios Ranked by Confidence Level.

Level	Application	Method
1	Estimate strength without coring	Use standard NDT equations directly
2	Estimate strength with a few cores	Develop regression between NDT and cores
3	Locate weak zones for coring	Use NDT minimums as target locations
4	Estimate lower bound of strength	Use NDT to define minimum range
5	Assess soundness/uniformity	Evaluate signal consistency, not strength

Table 6.4 summarizes key NDT findings, noting that RH and UPV often underestimate strength, show lower variance than core tests, have low correlation in aged concrete, may misidentify the weakest location, are affected by surface degradation, but can estimate a representative minimum strength range.

6.7.2 Proposed Protocol for Strength Estimation Without Coring

A probabilistic simulation was used to validate this approach:

1. Collect RH or UPV readings from ≥5 locations per structure.
2. Use multiple standard equations to estimate compressive strength.
3. Select the minimum estimated value as the characteristic in-situ strength.
4. This method yielded characteristic strengths within 60–80% of actual core strength (with Coefficient of Variation < 30%).

Table 6.5 shows different application scenarios for NDT, ranked by confidence level, along with the corresponding methods used for each application.

TABLE 6.6
Summary of Types of Defects and NDT Methods Used in Case Studies.

Case No	Defect Type	Bridge Component	NDT Method Used
Case (1)	Reinforcement detailing and anchorage defects (irregular bar spacing, skewed placement, variable concrete cover, and improperly caged anchor bolts)	Concrete pedestals (abutments of steel-girder bridge)	GPR
Case (2)	Severe beam end deterioration: cracks, spalling, and unsound and delaminated concrete	Prestressed concrete I-beam ends	IE Tomography
Case (3)	Reinforcement layout errors, cover variability, concrete strength estimation, tendon detection attempts	Prestressed concrete box girder (side walls and roof slab of Abisko Bridge)	Covermeter, RH, GPR
Case (4)	Corrosion, voids, and strand breakage in internal post-tensioning tendons	Segmental post-tensioned concrete box girder bridge (Florida DOT)	Impulse Response (IR), IRT, Magnetic Flux Leakage (MFL), AE, Inductance Testing, Interferometric Radar
Case (5)	Grout voids, tendon discontinuities, and section loss in post-tension ducts	Bridge girder webs with embedded post-tensioning ducts	IES, SASW, 3D GPR, IR, IRT, AE, MFL, Inductance Testing (IT)
Case (6)	Concrete deterioration, internal flaws, surface hardness variability, carbonation depth, and active corrosion risk	Multiple elements: RC piers, post-tensioned girders, deck slab, and wing walls (Cairo flyover footbridge)	UPV, RH, Carbonation Test, HCP
Case (7)	Compressive strength degradation and weak zone identification in aged concrete	RC slabs and girders of aged concrete bridges (>40 years old, South Korea)	RH, UPV

6.7.3 Lessons Learned from the Aged Concrete Bridges in South Korea Case Study

- NDT (RH & UPV) is best suited for identifying general strength levels or weak zones, not for precise strength estimation in aged concrete.
- For practical maintenance of bridges, the proposed NDT-only protocol can reliably estimate in-situ strength range without extensive coring.
- NDT is more qualitative or semiquantitative rather than precisely quantitative for compressive strength prediction, especially in existing structures.

7. CONCRETE STRENGTH ESTIMATION USING NDT

Accurate estimation of in-place concrete strength is essential for both newly constructed and existing structures, particularly when direct destructive testing is impractical or undesirable. This chapter explores established practices and standards for evaluating concrete compressive strength using non-destructive and semi-destructive methods, primarily guided by ACI guides such as ACI 228.1R-19 and ACI 228.2R-13, along with ICRI guidelines such as ICRI 210.4R-2021. The discussion covers fundamental principles, applicable ASTM standards, regression-based modeling approaches, and statistical tools used to interpret NDT results.

7.1 ACI 228.1R-19 (ACI Committee 228, 2019)

The code categorizes concrete construction into new and existing constructions. Table 7.1 summarizes these categories.

7.1.1 Indirect Measurement

NDT methods measure properties like surface hardness, penetration resistance, wave velocity, or temperature history.

TABLE 7.1
Concrete Classification in NDT Applications According to ACI 228.1R-19.

Type	Definition in ACI 228.1R-19	Typical Use	Age of Concrete
New Construction	Concrete recently placed and still under construction. Testing is used to estimate strength early, e.g., for form-work removal, post-tensioning, or curing termination.	Real-time quality control, curing monitoring	1 to 28 days
Existing Construction	Concrete in completed, in-service structures. Testing is for structural evaluation, condition assessment, or retrofit design.	Strength validation, damage assessment, rehabilitation planning	28 days to decades

7.1.2 Strength Correlation

These properties are correlated to compressive strength using empirical regression models, developed either in the lab (new construction) or using core samples (existing construction).

7.1.3 Standardization

Only ASTM-standardized tests are included in the ACI 228.1R-19 document.

Table 7.2 has been designed by the authors of this report from the contents of ACI 228.1R-19.

Wave velocity, in the UPV test, measures how fast a stress wave (P-wave) travels through concrete. Wave speed increases with stiffness (elastic modulus), which correlates with strength. In UPV testing (ASTM C597), stress waves travel faster in stiffer concrete. Wave velocity is proportional to the square root of (Elastic Modulus/Density). Since strength and stiffness generally increase together, wave velocity correlates

TABLE 7.2
In-Place Concrete Strength Estimation Methods (ACI Committee 228, 2019).

Method	ASTM Standard	Measured Property	Strength Estimation Basis	Application Context	New/Existing	Key Technical Notes	NDT or Not?	Accuracy/ Reliability
RH	C805	Surface hardness (rebound number)	Empirical correlation to compressive strength	Concrete surface testing	Primarily Existing (some New)	Influenced by moisture, carbonation, surface roughness; requires calibration	NDT	Low
UPV	C597	Travel time of ultrasonic wave	Velocity correlates to elastic modulus, which correlates to strength	Internal quality and uniformity check	Both	Indirect; sensitive to steel, cracks, moisture; suitable for in-depth scanning	NDT	Moderate
Maturity Method	C1074	Temperature-time history (maturity index)	Correlated maturity index → strength gain	Strength monitoring during curing	New Only	Highly accurate if calibrated for mix; ideal for form removal and post-tensioning timing	NDT	High
Penetration Resistance	C803	Depth of probe or pin penetration	Inversely related to strength via absorbed energy	Surface penetration via probe/pin	Both	Strongly influenced by aggregate; orientation and surface texture critical	Semi-NDT	Moderate
Pullout Test	C900	Force to extract embedded insert	Direct relation to local compressive strength	Insert cast-in or drilled in	New	Localized failure; well-correlated; some surface damage	Semi-NDT	High
Pull-Off Test	C1583	Force to detach disc from surface	Tensile/bond strength (indirect compressive inference)	Bond strength of repairs/overlays	Primarily Existing	Sensitive to coring, alignment, bond failure mode; records failure location	Semi-NDT	Moderate
Cast-in-Place Cylinders	C873	Actual compressive strength	Direct compressive strength measurement	Cylinders cured in-place	New Only	Most reliable; simulates structure conditions but not strictly NDT	Not NDT	Very High

with compressive strength. However, this is not a linear relationship; correlation depends on mix design, age, and moisture. Temperature history, in the maturity method, monitors concrete temperature over time. Since concrete gains strength via hydration (a temperature-driven reaction), the maturity index reflects strength gain over time. New construction refers to structures under construction with fresh or young concrete, where strength needs to be estimated before the structure is in service. NDT for new construction is often used for early-age strength estimation, such as formwork removal, post-tensioning, load application, and curing termination. In penetration resistance, according to ASTM C803/C803M, a steel probe or pin is driven into the concrete surface using a gun (e.g., Windsor Probe) for higher-energy impact. Penetration depth is measured, and the less depth means higher strength.

7.2 Regression Analysis for Concrete Strength Estimation

An approach using a regression analysis involves developing a mathematical model (usually linear or exponential) to relate the measured NDT parameter to actual compressive strength. It is done by testing known-strength concrete samples (lab samples for new constructions or core extracted samples for existing constructions). ACI 228.1R-19 includes log-transformed linear regression models to improve linearity and address variance, particularly when both variables (NDT value and strength) have associated errors. Additionally, in its Appendix A, Mandel's approach and error minimization are presented.

Example: If a rebound number is used, the model could look like:

$$f_c' = a + b \cdot x \text{ (linear)} \quad \text{or} \quad \ln(f_c') = a + b \cdot \ln(x) \text{ (log-linear)}$$

A regression line or curve is fitted to relate:
f_c' = concrete compressive strength
x = NDT test value (e.g., rebound number, maturity index)

7.2.1 Statistical Tools Used for NDT and Concrete Strength Estimation

Statistical tools are used to handle the variability in test results and ensure valid interpretation. Key tools are summarized in Table 7.3.

TABLE 7.3
Statistical Methods for NDT-Based Concrete Strength Estimation.

Tool	Purpose
Regression analysis	Fit a model between NDT value and strength
Standard deviation	Measure variability
Coefficient of variation	Normalize variability across tests
Confidence intervals	Provide statistical certainty (e.g., 90% confident strength ≥ x psi)
Residual analysis	Evaluate fit of regression
Tolerance factors	Establish acceptance limits (e.g., lower 10th percentile strength)

TABLE 7.4
ACI 228.2R-13 and Concrete Strength Estimation (ACI Committee 228, 2013).

Aspect	Details from ACI 228.2R-13
Scope	This report focuses on using NDT to evaluate non-strength properties (e.g., defects, voids, moisture, stiffness, corrosion activity), but it acknowledges that strength estimation is important and refers to ACI 228.1R for detailed procedures.
Strength Estimation	Sections 1.1 and 1.2 state that some NDT methods can indirectly provide information on concrete strength, particularly stress-wave methods like UPV, IE, and Spectral Analysis of Surface Waves (SASW).
UPV and Strength	Section 3.2.1 explains the UPV method. It notes that wave speed is influenced by elastic modulus and density, which can be correlated to compressive strength (indirectly). This supports the use of UPV for estimating relative strength uniformity across a structure.
Elastic Modulus and Wave Velocity	Detailed equations (e.g., Eq. 3.2a) show the relationship between P-wave speed and Young's modulus, density, and Poisson's ratio relevant to estimating stiffness and indirectly strength.
IE & SASW	These methods are described as useful for evaluating stiffness profiles, flaw depth, and indirectly concrete quality, which in calibrated contexts, may relate to strength, especially in combination with other tests.

7.2.2 ACI 228.2R-13 (ACI Committee 228, 2013)

The contents of ACI 228.2R-13 comply with ACI 228.1R-19 in terms of concrete strength estimation and provide limited information about it, as summarized in Table 7.4, designed by the author of this report.

7.3 ICRI 210.4R-2021 (ICRI, 2021)

This guide supports concrete strength estimation using NDT. Table 7.1 and Appendix A.1, in ICRI 210.4R-2021 are dedicated to NDE methods for concrete strength prediction. The guide aligns closely with ACI 228.1R and emphasizes the importance of correlation with destructive tests. Table 7.5 reproduces the content of Table 7.1 from ICRI 210.4R-2021.

A case study combines seven aged bridges in South Korea and discusses the concrete strength estimation using NDT in these bridges. It is presented in the section of case studies in this report (Kwon et al., 2025).

8. SURVEYS' RESULTS AND DISCUSSION

To better understand the current state of NDT practices for reinforced and prestressed concrete bridge components, three separate surveys were conducted and analyzed. These surveys targeted (1) personnel from INDOT with 16 responses, (2) representatives from various DOTs across the United States with 14 responses, and (3) subject matter experts with extensive experience in NDT with eight responses. The questionnaires of the three surveys are provided in Appendix A. The responses to the surveys were received based on the familiarity, knowledge, and experience of the respondents. The findings in this chapter are based solely on the collected survey responses and reflect the views of the specific participants. They should not be generalized to all NDT applications or field conditions.

8.1 INDOT Survey

A survey was administered to personnel from the INDOT to gather insights into current practices and perceptions regarding NDT. The focus was on RC and prestressed concrete bridge components, excluding bridge decks. The questionnaire aimed to assess participants' familiarity, general knowledge, and experience with various NDT tools, as well as their perspectives on technical considerations, practical applications, performance, training, education, applicable standards, and future developments. The survey consisted of 15 questions designed to elicit detailed feedback on these topics. It should be noted that the responses represent the individual views of the participants and may not fully capture the complete range of practices or experiences within INDOT. The survey questionnaire was officially distributed to INDOT personnel via email through a Google Form on March 31, 2025. The survey was distributed to 20 INDOT personnel, of whom 16 submitted responses, yielding an 80% response rate. These respondents represented a range of departments within

TABLE 7.5
NDE Methods for Concrete Strength Prediction (ICRI, 2021).

NDE Methods	Cast-in-Place Cylinders	Maturity	Rebound Hammer	Tensile Pull-off	Pin/Probe Penetration Resistance	Pullout (Fresh and Hardened Concrete)	Pulse Velocity
Reference Standards/ Guidelines	ASTM C873	ASTM C1074	ASTM C805	ASTM C1583 ICRI 210.3R	ASTM 803	ASTM C900	ASTM C597
Appendix Section	A1.1	A1.2	A1.3	A1.4	A1.5	A1.6	A1.7
Property/Condition							
Compressive Strength	x	x	x	-	x	x	x
Tensile Strength	x	x	-	x	-	x	x
Bond Strength/Quality	-	-	-	x	-	-	-

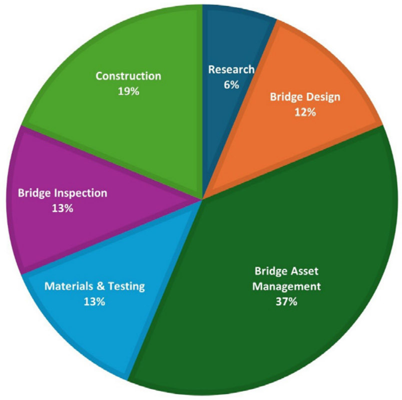

Figure 8.1 Departmental Breakdown of the 16 INDOT Survey Respondents.

INDOT, as illustrated in the pie chart in Figure 8.1. The survey period closed on May 22, 2025. A copy of the questionnaire is provided in Appendix A.

8.1.1 Known NDT Tools and Their Applications

Survey participants were asked to identify NDT tools applicable to beams, piers, and abutments that they were familiar with, had used, or had overseen in practice, including those learned about through seminars, conferences, or similar events. Responses indicated strong interest in NDT techniques for RC structures, with 94% expressing support for their use. As shown in Figure 8.2, GPR was the most frequently cited tool (24.3%), followed by IE (18.9%), IRT (13.5%), and RH (10.8%).

The high usage of GPR among respondents indicates its broad applicability, supported by the fact that participants represented diverse departments within INDOT. Based on the result of INDOT survey, GPR has been applied for rebar location and depth, concrete cover measurement, void and delamination detection, and corrosion-related deterioration. In terms of corrosion evaluation, GPR has significant usage in the field of NDT according to a review of NDT methods in the past three decades (Abdelkader et al., 2023). Additionally, the method is applied in bridge inspection practices for a variety of projects and bridge components (Boldrin et al., 2024). GPR is also used in laboratory conditions and in the field for corrosion, delamination, rebar detection, voids, and more (Boldrin et al., 2024; Rathod et al., 2019; Yehia et al., 2008).

Figure 8.3 provides a heat map of personal knowledge of NDT tools separated by department from the pool of INDOT personnel. While GPR may be the most known, it is not the most popular in every department. According to members of bridge asset management, IRT is actually more known. On the other hand, the bridge asset management department reports the highest awareness of the top three methods. Not all tools were categorized, so all miscellaneous NDT and even semi-destructive testing methods, such as hammer sounding, were listed under "All Else." The Research department had only one respondent, and they replied that all NDT tools available were known to them. Because the total summation of NDT tools known by the

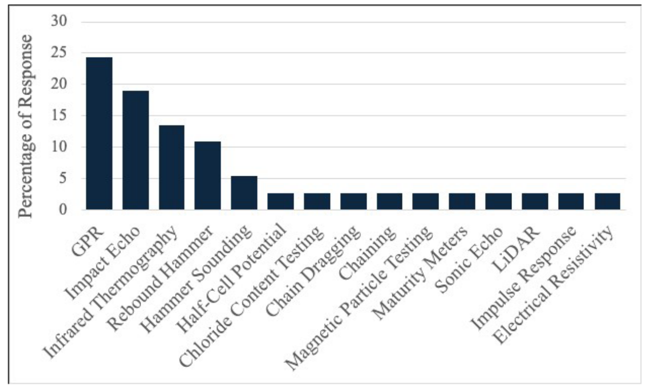

Figure 8.2 NDT Methods Applicable to Reinforced and Prestressed Concrete Elements in Bridges.

Department	GPR	Impact Echo	Infared Thermography	Rebound Hammer	All Else
Bridge Design	2	1	1	0	1
Material & Testing	2	1	0	1	2
Construction	2	2	1	2	5
Bridge Asset Management	3	3	4	1	4
Bridge Inspection	0	0	0	0	2
Total	9	7	6	4	14

Low frequency	Moderate frequency	High Frequency

Figure 8.3 NDT Tools Applicable to Reinforced or Prestressed Concrete Bridges by Departments.

researcher is not explicitly quantifiable, the research department was omitted to avoid inflating numbers of known NDT tools. Higher prominence of miscellaneous tools in bridge asset management and construction may reflect a broader appeal in the use of diverse NDT methods.

Among the various departments, bridge inspection personnel reported comparatively less familiarity with NDT tools and methods. According to the written responses, the perspective of NDT tools by INDOT bridge inspection personnel considered them potentially useful at best, despite their interest in using NDT. A similar mindset is reflected by a survey for a team of Minnesota Department of Transportation bridge inspectors who had low ratings based on previous experiences with technologies for bridge inspection, despite interest in adopting NDT (Moreu et al., 2019).

8.1.2 NDT Use for Defect Detection, Strength Estimation, and Rehab Planning

When requested justification for the perceived value in using NDT tools, respondents answered with multiple circumstances where NDT provided valuable data, as seen in Figure 8.4. The responses of personnel were categorized into the following: determination of internal damage (not visible to the naked eye), rehabilitation strategies, and estimation of compressive strength. The most frequently cited use of NDT methods was to detect defects not visible to the naked eye (46.5%), including delamination, voids, and embedded corrosion. Others noted applications included estimation of concrete strength (26.7%) and rehabilitation planning (26.7%).

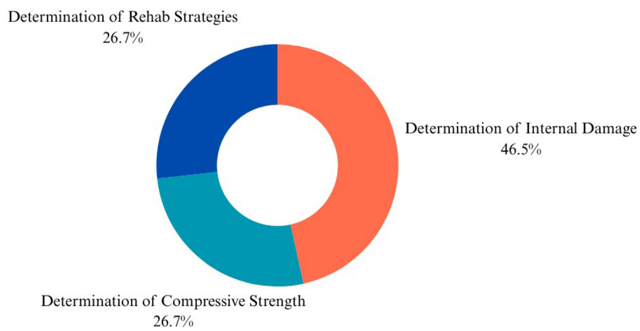

Figure 8.4 Percentage of Responses Citing NDT Use for Defect Detection, Strength, and Rehab Planning.

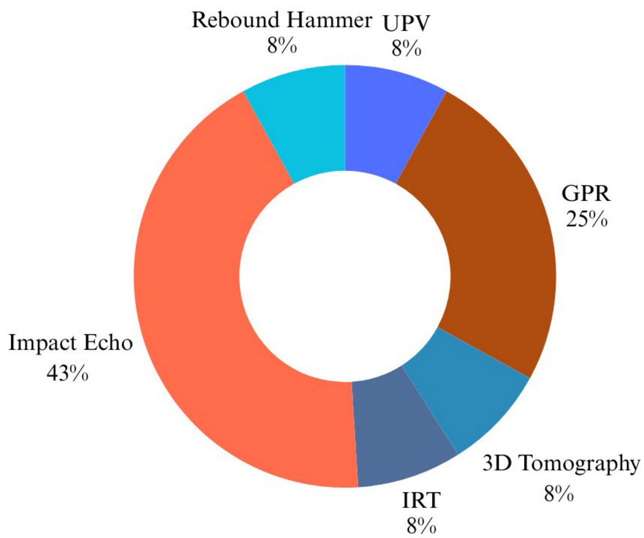

Figure 8.5 NDT Methods That Performed Well and the Corresponding Percentage of Responses.

With a clear positive consensus on the effectiveness of NDT, the focus was on determining internal damages rather than estimating strength and developing rehabilitation strategies. However, it does not undermine the importance of estimating concrete strength using NDT methods, such as UPV and the RH, as many bridges across the United States are aged.

Internal flaws such as corrosion and voids can compromise the integrity of RC structures, often without any visible surface damage. Across the United States, visual inspection was the most applied method according to a FHWA survey of various DOTs (Moore et al., 2001). Given the situation, NDTs that provide information on internal defects may receive higher attention and interest in the field of bridge inspection as they fill a gap that visual inspection cannot perform. Accordingly, methods which can characterize internal features have shown more applications, while methods which compete with visual inspection, like digital photogrammetry, are overlooked (Abdelkader et al., 2023). The mention of NDT tools for estimation of concrete strength is notable, given that only a few NDT methods

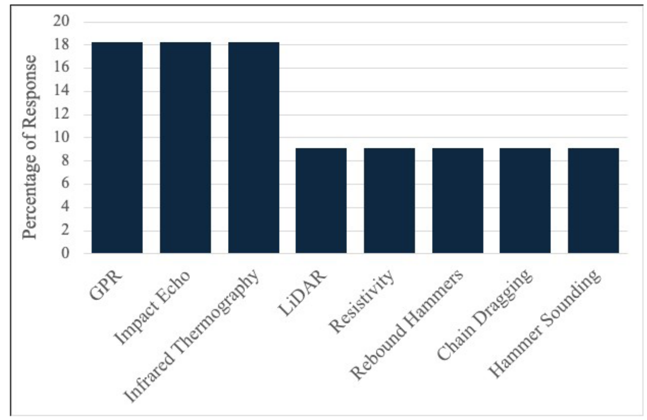

Figure 8.6 Underutilized NDT Tools Mentioned, Corresponding to Percentage of Responses.

can perform this task, and many still require destructive validation. This may indicate either a firm reliance on a few standout techniques.

8.1.3 NDT Methods Known to Have Performed Well

Respondents also described specific projects, scenarios, or conditions in which certain NDT methods performed well or poorly. As illustrated in Figure 8.5, IE was most frequently cited for its strong performance with 43% of the responses, followed by GPR with 25% of responses. IRT, RH, UPV, and 3D tomography trailed behind with 8% each. INDOT personnel, despite recognizing GPR more, default to IE for performance. Both IE and GPR serve comparable diagnostic functions, with IE detecting stress waves and GPR detecting electromagnetic waves. While the underlying principles differ, the distinction in equipment complexity is notable: IE kits are centered around a simple impact device, whereas GPR systems require more sophisticated electronic instrumentation. This disparity underscores a broader trend in field practice, where tools that are practical, portable, and easy to operate are often preferred. Such preferences may also shape the attitudes of bridge inspectors, who have historically relied primarily on visual inspection as their principal assessment method.

8.1.4 Underutilized NDT Methods and Their Potential Benefit

Among the list of NDT tools, it is important to determine which tools are especially effective based on personal experience. As shown in Figure 8.6, GPR, IE, and IRT were most noted as overlooked methods, with each tool being mentioned 18% out of all the tools mentioned. The three methods appear to be considered the best NDT tools available based on the respondents. This consensus aligns with prior findings from Zheng where the same three methods are the most used methods in the field of NDT (Abdelkader et al., 2023). However, according to Zhang et al. (2016), digital photogrammetry was the most underutilized among all others. This suggests an opportunity to raise awareness about digital photogrammetry as a valuable NDT method, especially since it was not mentioned in the INDOT survey responses.

8.1.5 Challenges and Barriers to Using NDT in Bridge Inspections

A focus on the specific obstacles to widespread NDT adoption can provide a basis to understand why, even with high appeal, instruments are not commonplace. Respondents identified key challenges to using NDT in bridge projects, as shown in Figure 8.7. Common challenges included a lack of knowledge of NDT technologies (24%), concerns about their accuracy (24%), and issues related to technology availability (24%). Other challenges included cost (12%), time investment (12%), and ease of use (6%). Even with interests in NDT, practical barriers such as accurate performance affected by environmental conditions can discourage regular use.

While accuracy may be a concern, there is no consensus on which tools are actually accurate. Based on the results of the survey, some personnel praised GPR and IE methods for good accuracy, while others were concerned about their accuracy. The disparity may arise from the sensitivity of the instruments such that tools which are used in favorable environments will perform better than tools applied in unfavorable conditions. With that in mind, it may explain why one respondent can note IE as a gold standard while another was concerned about its accuracy.

Because no universal NDT tool can perform all tasks, the selection is inherently limited by the capabilities of available instruments. Moreover, individual tools can be unreliable under unfavorable conditions. For example, GPR performance is often constrained by environmental and surface conditions, with common difficulties in obtaining accurate data arising from factors such as moisture, rough surfaces, variations in material thickness, high rebar density, and calibration issues (Boldrin et al., 2024; Rathod et al., 2019; Yehia et al., 2008). These issues were reflected in INDOT respondents' personal experiences. While it cannot be said that GPR is inaccurate, the sensitivity to environmental factors and ease of use can significantly affect its performance in terms of accuracy. Similar and unique limitations can be found for IE, such as inability to perform a full condition assessment, interference from background noises, and heterogeneity of concrete (Shokouhi et al., 2006; Zhang et al., 2016). IRT provides a noncontact method of scanning thermal gradients to detect surface or near-surface defects. However, it is sensitive to environmental conditions such as ambient temperature, wind, and moisture, as well as variations in surface emissivity, all of which can affect the accuracy and reliability of the results.

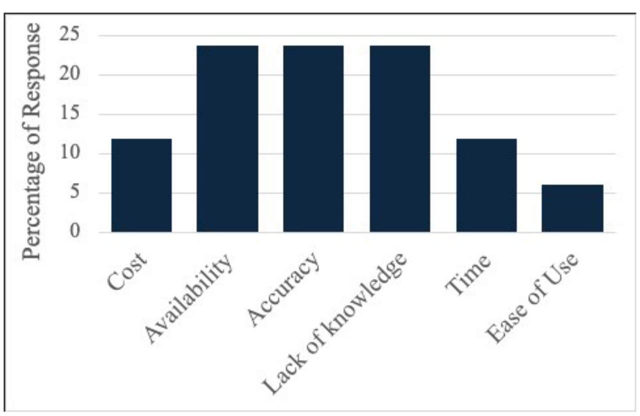

Figure 8.7 Limitations to Implementing NDT Tools and Corresponding Percentage of Responses.

Concerns about accuracy can be addressed by combining the sensing capabilities of multiple NDT tools to compensate for the limitations of any single method. Previous studies have recommended such combined approaches, including IE with GPR (Abramo, 2011), GPR with ultrasonic echo array (UAE; Mehdinia et al., 2023), IR with IE (Andrzej & Marta, 2014), and digital photogrammetry with IRT (Rasib et al., 2022), among other combinations that have yielded positive results (Büyüköztürk, 1998; Kilic & Caner, 2020).

This study suggests that a lack of knowledge is a prevailing trend; however, limited availability of NDT tools adds another dimension that may be creating a reinforcing loop. Although many manufacturers produce NDT equipment, survey responses indicate that supply in the field remains insufficient. While cost, availability, and time constraints are key barriers, increased familiarity with NDT tools and clearer demonstrations of their practicality could significantly enhance their adoption.

8.1.6 Departmental Rankings of Key Attributes for NDT Tools

The metrics of accuracy, ease of use, safety, cost, and portability were ranked by respondents from most important to least, as shown in Figure 8.8. Each attribute was scored from 1 (least important) to 5 (most important). It shows the average score for each attribute by department, based on respondents' rankings. For example, the Research department respondent ranked accuracy the most important and safety the least important. Portability was noted as a lesser consideration across respondents in the Research Department.

Departments which prioritize cost and safety may be more cautious in which NDT methods to adopt. Bridge inspection and construction respondents preferred other criteria, such as cost and safety, respectively, as the top criteria. Given the hazardous nature of construction, it is not surprising that safety is a priority characteristic when operating instruments in the field.

Accuracy, as the most important factor, remained consistently ranked as a first priority, followed by ease-of-use and safety, with ease-of-use surpassing by a slight margin in Figure 8.8. The ease-of-use was never ranked as the top attribute by any respondent. The heatmap in Figure 8.8 shows the relative importance of other criteria depending on situational or department-specific demands and constraints.

8.1.7 Training Required to Effectively Use NDT Tools

A chart based on the written responses, as shown in Figure 8.9, illustrates the suggested training strategies to properly execute NDT in bridge inspection. The vendor category

Department	Accuracy	Ease of Use	Safety	Cost	Portability
Research	5.00	4.00	1.00	2.00	3.00
Bridge Design	5.00	4.00	2.00	3.00	1.00
Material & Testing	4.50	3.00	3.50	1.50	2.50
Construction	4.30	2.00	4.67	2.00	2.00
Bridge Asset management	4.80	2.40	3.60	2.40	1.80
Bridge Inspection	3.00	3.50	4.00	5.00	2.50
Average	**4.43**	**3.15**	**3.13**	**2.65**	**2.13**

Most Important = 5	Very important = 4	Moderate Important = 3	Less Important = 2	Least Important = 1

Figure 8.8 Key NDT Attributes Ranked by Various Departments.

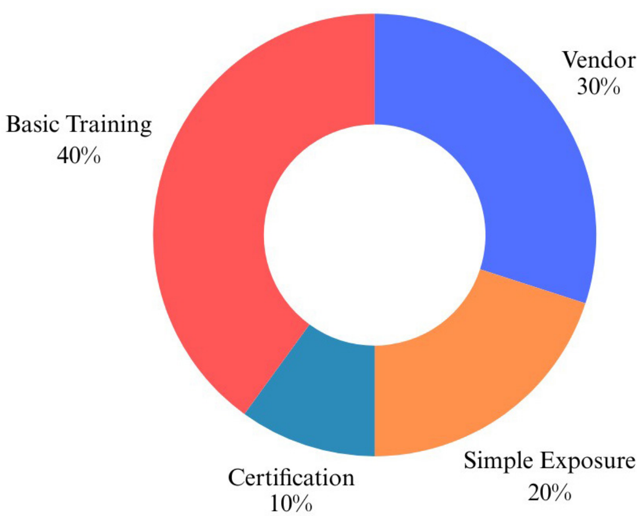

Figure 8.9 Types of Training Required to Use NDT Effectively.

includes responses suggesting that proficiency with NDT tools requires direct consultation with the manufacturer. With 30% of the responses, guidance from the vendor should be considered, given the various NDT tools available. Simple Exposure pertains to activities such as a slideshow of how to operate NDT tools, with 20% believing it is enough.

The Basic Training category includes responses emphasizing the need for hands-on field experience or similarly intensive practice to achieve NDT tool proficiency. Some INDOT respondents (40%) believe basic hands-on operation of NDT tools is required for executing bridge inspections at acceptable proficiency.

Certifications for NDT tools do exist in the ASNT organization, with levels of certification given to competent practitioners in the field of NDT. The survey conducted by FHWA revealed that out of 42 state DOTs, only 14 had ASNT Level III trained experts (Moore et al., 2001). Compared to previous years, a trend showed increasing inclusion of ASNT-certified individuals among the state and country departments. However, with 10% of total INDOT responses, certification was not seen as a necessary level of expertise. The respondents highlight that formal accreditation is not required for operating NDT tools in an acceptable capacity.

Table 8.1 summarizes the type of defect and NDT methods used by INDOT personnel, which were directly resulted from the survey, while CAPO (Cut and Pull-Out Test) is Semi-NDT, and Chloride Content Testing is Destructive.

8.1.8 Conclusion

This survey analysis highlights the complex landscape of NDT tool usage among INDOT personnel who mostly favored NDT, but their experiences expose a spectrum of challenges dampening their confidence. GPR emerged as the standout method, likely due to its unparalleled capability in corrosion

TABLE 8.1
Type of Defect and NDT Methods Used by INDOT Personnel.

Defect Type	NDT Method and Tools Proposed
Concrete delamination, voids, and reinforcement deterioration	IE, GPR, IRT
Rebar cover, reinforcement mapping in new decks	3D GPR, Light Detection and Ranging (LiDAR)
Beam end deterioration	IRT, IE, Schmidt Hammer, GPR
Poor concrete strength in construction	RH, Maturity Meter, Resistivity, Cut and Pull-Out (CAPO) Test (ASTM C900)
Corrosion potential and chloride-induced deterioration	HCP, Chloride Content Testing, IE, GPR
Bridge deck deterioration and delamination (scoping/patching)	IE, GPR, IRT
General deterioration in piers, abutments, RC slabs	GPR, UPV, Acoustic Methods

assessment, one of the most commonly targeted defect types. However, viable methods such as IE and IRT remain underutilized, potentially due to a knowledge gap or performance limitations. Despite GPR's popularity, it is surpassed by IE in terms of perceived performance and is considered the most problematic. The confidence and desirable characteristics of an NDT tool can be further narrowed down to its accuracy. Consistent concerns about the accuracy of NDT tools emphasize the need for standardized training and evaluation protocols, as no confidence can be placed in a tool with false or unreliable readings. While accuracy can be partially addressed, increasing awareness, improving access, and clearly communicating each tool's capabilities could significantly enhance NDT adoption and effectiveness in bridge inspection and maintenance.

8.2 States' DOT Survey

A survey was administered to all DOTs in the US to gather insights into current practices and perceptions regarding NDT. The focus was on RC and prestressed concrete bridge components, excluding bridge decks. The questionnaire aimed to assess participants' familiarity, general knowledge, and experience with various NDT tools, as well as their perspectives on technical considerations, practical applications, performance, training, education, applicable standards, and future developments. The survey consisted of a table in Microsoft Word format designed to elicit detailed feedback on the topics: the active and potential use of various NDT methods and emerging technologies, the types of defects or conditions assessed, the bridge components inspected, and the commercial names of instruments used.

It should be noted that the responses represent the individual views of the participants and may not fully capture the complete range of practices or experiences within DOTs. On June 25, 2025, the survey questionnaire was distributed to DOTs via email as a Microsoft Word document containing a tabular format. The survey was distributed to 50 DOTs, of whom 14 submitted responses. These respondents represented a range of DOTs within the United States, as illustrated in Figure 8.10. The survey period closed on July 31, 2025. A copy of the questionnaire is provided in Appendix A.

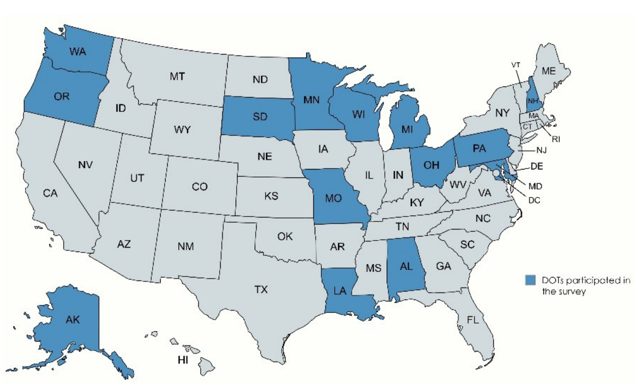

Figure 8.10 The States Participated in the Survey.

8.2.1 NDT Methods and Emerging Technologies in Active Use or Desired

DOT's responses indicate the NDT tools that were in active use and those that were interesting choices for them, as displayed in Table 8.2. Many states actively used NDT. This was particularly about Alabama and New Hampshire, confirming zero and nine NDT methods and emerging technologies, respectively. Half of the states focused primarily on the methods already in use, highlighting opportunities to expand the adoption of additional NDT techniques, which can serve as valuable strategic tools in bridge diagnostics.

Participant state DOTs were asked to indicate which NDT methods and emerging technologies were in active use, with the results shown in Figure 8.11. Each DOT received a predetermined list of typical NDT methods and emerging technologies, as outlined in the questionnaires in Appendix A.

The most frequently used NDT methods were GPR (16.9%) and IRT (13.85%), followed by IE (10.77%), and Ultrasonic methods and HCP (each at 9.32% of total responses). RH and light detection and ranging (LiDAR) methods followed, each with 6.15%. All emerging technologies used alongside NDT methods accounted for less than 5% of the responses.

The adoption rates provide insight into current field practices and institutional preferences. For instance, the prominence of GPR, IE, and IRT reflects their familiarity, availability, and versatility, contributing to their widespread use. These tools are capable of assessing a variety of defects, including delamination, corrosion, and cracking, and are among the most well-known and frequently employed in the field of NDT, making them representative of 'typical' NDT tools.

In contrast, the use of emerging technologies, at less than 5%, may indicate early stages of adoption or limited awareness due to knowledge gaps. Furthermore, these technologies often involve advanced innovations that can face barriers such as limited technological literacy, challenges in integrating with

TABLE 8.2
NDT Methods and Emerging Technologies in Active Use or Desired.

DOT	Total Using	Total Interested
Maryland	4	2
Louisiana	4	0
Alaska	3	0
Michigan	4	1
South Dakota	1	1
Washington	4	0
Wisconsin	5	0
Alabama	0	2
Minnesota	7	5
Missouri	4	0
Ohio	8	0
Pennsylvania	5	0
Oregon	7	3
New Hampshire	9	3

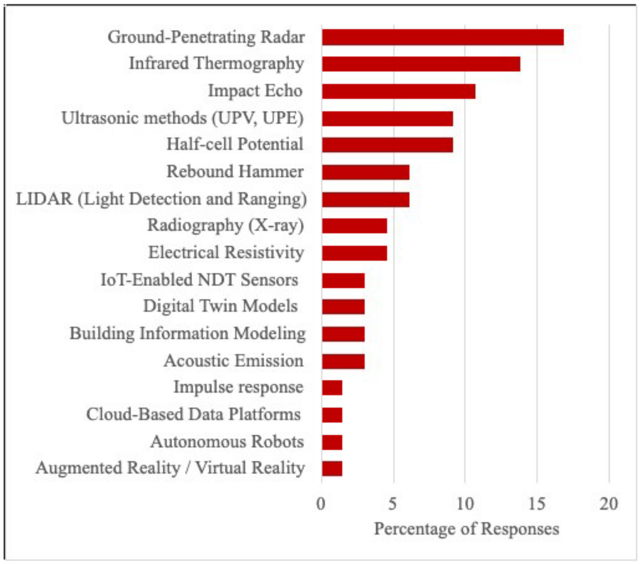

Figure 8.11 NDT Methods and Emerging Technologies Actively Used or Previously Used.

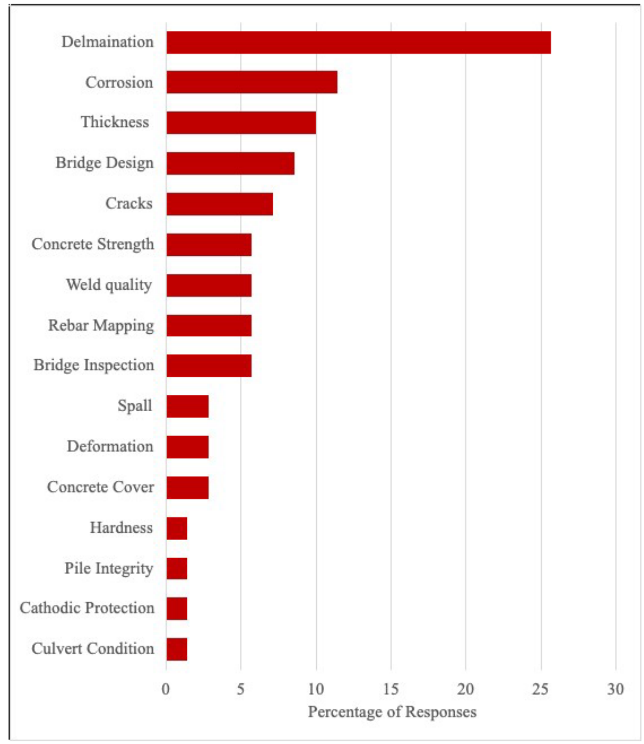

Figure 8.12 Defect Detection or Condition Assessment by NDT Methods.

existing work infrastructure, or high upfront costs. The limited use of emerging technologies, less than 5%, highlights the gap between technological innovation and practical implementation in NDT. This underscores the need for greater exposure, demonstrations, and training to showcase the full capabilities of NDT in conjunction with emerging technologies.

8.2.2 Defect Detection or Condition Assessment by NDT Methods

DOTs were asked to identify the defects or conditions assessed using the NDT methods shown in Figure 8.12. Delamination (25.7%) was the most frequently reported defect, followed by corrosion (11.4%), thickness determination (10%), bridge design (8.57%), cracks (7.14%), and concrete strength estimation (5.7%). These results indicate that delamination may be the primary use case for NDT methods among state DOTs.

Delamination in concrete refers to the separation of layers within the material, typically parallel to the surface, and is often caused by reinforcing steel corrosion, freeze-thaw cycles, or inadequate bonding during placement. While delamination may be visible on the surface, its extent often penetrates deeper than what can be seen. Consequently, NDT tools used for delamination are typically capable of detecting subsurface defects. Notably, 45% of state DOTs reported using IRT for delamination assessment, making it the most common tool for this purpose. GPR accounts for 25% of delamination assessments, while AE and IE contribute approximately 10% and 20%, respectively. Although IRT cannot directly map the subsurface conditions of a structure, it can identify subsurface defects by detecting the thermal anomalies they produce.

Corrosion occurs when metals deteriorate due to exposure to salts, moisture, or weathering. In this study, two-thirds of corrosion assessments by DOTs were conducted using the HCP method. Although other established tools, such as GPR, are available, the Half-Cell method's predominance underscores its practical value. Rebar mapping is done with GPR. The DOTs that use GPR performed reinforcement density, mapping, and thickness scans with GPR alone. Thickness measurements, meanwhile, were performed exclusively using ultrasonic methods such as UPV and UPE.

Regarding estimating compressive strength, the RH stands out as the most widely applied, accounting for 75% of reported cases in primary concrete strength estimation. Most strength assessments remain destructive, typically involving the extraction of cores from the structure. For more accurate estimation of concrete strength, a combination of UPV and RH testing, supported by statistical correlation, is recommended by the ACI code. For mapping or detecting cracking, IE was the most used method, accounting for 50% of reported cases, with the remainder utilizing ultrasonic and radiographic methods. A key strength of NDT tools is their ability to assess multiple types of conditions and defects. This versatility explains why no single tool is used exclusively for a given defect or condition.

8.2.3 Applied Bridge Components with NDT

DOTs were asked to identify the bridge components where NDT methods were applied, as shown in Figure 8.13. The largest share of applications involved bridge deck examinations (38.46%), followed by piers (18.46%), abutments (9.23%), the entire bridge (9.23%), pins (6.15%), and piles (4.6%), with culverts and soffits receiving the fewest mentions.

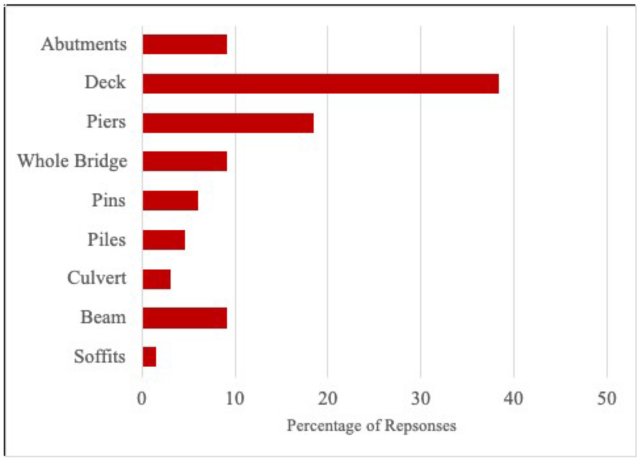

Figure 8.13 Applied Bridge Components With NDT.

TABLE 8.3
Percentage of Defects Assessed for Each Bridge Component.

	Pier	Abutment	Beam End
Delamination	40.00%	38.46%	33.33%
Crack	13.33%	15.38%	8.33%
Corrosion	26.67%	23.08%	33.33%
Concrete strength	20.00%	23.08%	25.00%

Bridge decks consistently receive the greatest attention in NDT applications, followed by piers, which serve as the primary vertical load-bearing elements. Abutments receive a comparable level of attention to that of the bridge as a whole. While the focus on decks is understandable, it is equally important to direct greater attention toward other critical bridge components such as piers, abutments, and beams, which are essential to the structural integrity of the bridge. Overemphasis on decks can obscure the significance of NDT in assessing these vital elements, a gap this study aims to address.

Table 8.3 displays the percentage of attention at the pier, abutment, and beams for a particular defect type. For every instance where a defect was the target, participant DOTs also listed the areas which received attention.

It is worth noting that this analysis accounts only for attention given to piers, abutments, and beams, excluding decks entirely. Percentages sum to 100% for each component. Delamination is the predominant concern across all three elements, with each receiving over one-third of the attention. For beams, corrosion ranks equally with delamination at 33.33% as the primary defect of concern for DOTs. In piers, delamination is strongly associated with 40% of the attention, followed by corrosion at 26.67%. For abutments, corrosion and concrete strength are the leading concerns after delamination.

As load-bearing structures, the concrete in vertical elements is essential for keeping these components upright. However, a clear hierarchy of attention emerges: cracks appear to be a relatively minor concern for the listed bridge elements, showing only a weak association, particularly for beams. This distribution underscores the critical importance of maintaining the concrete integrity of vertical elements such as piers and abutments, as well as prioritizing reinforcement. It may also suggest either a greater tolerance for cracking in beams or a tendency to address delamination as the more immediate issue.

Table 8.3 presents the percentage of attention given to piers, abutments, and beam ends for each NDT method. This focus on specific bridge elements helps identify which methods are most frequently applied to each component. Emerging NDT technologies with less than 5% usage were excluded to keep the discussion centered on widely used methods.

Popular methods for inspecting piers, abutments, and beam ends included GPR, RH, Half-Cell, and IRT. Other techniques such as IE, Ultrasonic (UPV and UPE), ER, and AE were also reported, though their usage varied by component. Piers, in particular, showed a relatively high interest, with a 33.3% likelihood of being scanned using GPR. This reflects a strong association of GPR with assessing potential subsurface degradation, corrosion, and reinforcement mapping.

RH testing was also commonly applied to abutments, tying with GPR at 23.1%. Given that abutments bear substantial vertical loads, assessing subsurface conditions and compressive strength is a sound practice for ensuring their stability. Beam ends, as shown in Table 8.4, received no particular emphasis aside from moderate use of the RH.

Current NDT preferences highlight GPR, RH, and Half-Cell testing as the primary choices for piers and abutments. These methods address key concerns in load-bearing components, including internal condition, concrete strength, and reinforcement corrosion, making them well-suited for these applications. Beams, however, are underrepresented in Table 8.4, indicating a need to promote methods tailored for beam-specific diagnostics.

Table 8.5 shows the type of defect assessed and the NDT method used, which resulted directly from the DOT's survey

8.2.4 Conclusion

Based on the results of the survey, NDT use among state DOTs is common, with GPR, IRT, IE, UPV, UPE, and HCP as the most frequently applied tools for detecting defects, mostly delamination and corrosion. These established methods remain popular due to their proven reliability, versatility, and ease of integration into existing inspection programs. However, emerging

TABLE 8.4
Percentage of NDT Methods Used for Bridge Components.

Method	Pier	Abutment	Beam end
AE	5.6%	7.7%	11.1%
ER	5.6%	7.7%	11.1%
Half-cell	16.7%	15.4%	11.1%
RH	16.7%	23.1%	22.2%
UPV/UPE	5.6%	7.7%	11.1%
IE	5.6%	7.7%	11.1%
IRT	11.1%	7.7%	11.1%
GPR	33.3%	23.1%	11.1%

TABLE 8.5
Type of Defect Assessed and the NDT Method Used, Based on the DOT's Survey.

Type of Defect /Condition Assessed	NDT Method/Tool
Post-tension strand snapping in prestressed members	AE
Delamination	AE, GPR, IRT, IE
Cracking	IE
Resistance of epoxy-coated reinforcing in bridge deck	ER
Corrosion-based deterioration, reinforcement layout, thickness of deck/overlay/cover; Deck defects/delamination, Rebar/Strand depth/location, debonding of overlay	GPR
Cathodic protection effectiveness, Potential for active corrosion in bridge deck, Probability of reinforcement corrosion	HCP
PT force in external PT bars, Subsurface defects	IE
Pile length or integrity	Impulse Response
Concrete strength	RH, Ultrasonic methods (UPV, UPE)

technologies used with NDT methods remain underutilized, often limited by cost, training, and compatibility challenges. Expanding the application of NDT to underrepresented components such as beam ends, alongside targeted training and standardization, could further enhance bridge diagnostics and asset management.

8.3 Experts' Survey

A survey was administered to 65 NDT experts in governmental and private sectors to gather their insights into current practices and perceptions regarding NDT. The focus was on RC and prestressed concrete bridge components, excluding bridge decks. The questionnaire aimed to collect participants' knowledge, experiences, and perspectives on the selection, application, and performance of NDT tools for bridge beam ends, abutments, and piers. It also sought input on relevant case studies, emerging digital technologies, training and certification, applicable standards, documentation practices, and potential areas for future research.

The survey, administered via Google Forms, consisted of nine questions. It should be noted that the responses represent the individual views of the participants. It was distributed to 65 experts, of whom eight submitted responses. These respondents represented a range of governmental and private sectors within the United States, as illustrated in Figure 8.14. The survey was distributed on April 4, 2025, and closed on April 30, 2025. A copy of the questionnaire is provided in Appendix A.

8.3.1 NDT Methods Recommended by Experts

Experts identified several notable NDT methods suitable for beam ends, piers, and abutments as displayed in Figure 8.15. To preserve the originality of the respondents' answers, the terms

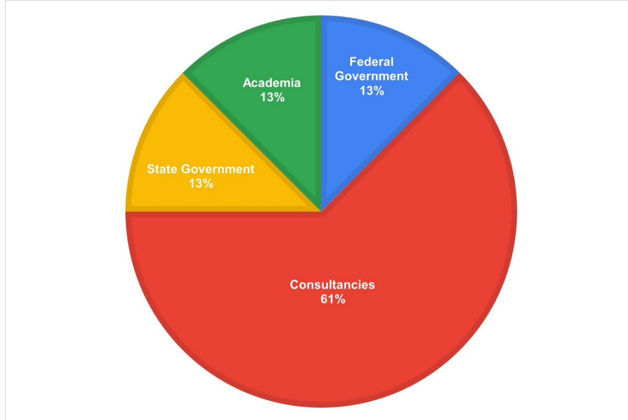

Figure 8.14 Distribution of Survey Participants Across Different Sectors.

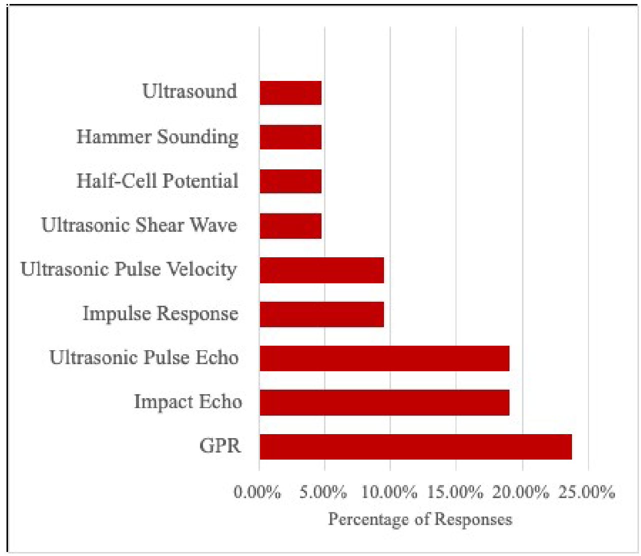

Figure 8.15 Recommended NDT Methods by Experts.

Ultrasonic Pulse Velocity and *Ultrasonic Pulse Echo* were kept separate from ultrasound in Figure 8.15, even though ultrasound is a broad term that encompasses both UPV and UPE. Many of these experts suggested the use of GPR and ultrasonic methods (UPV and UPE) with more than half of the responses as part of these two methods. Notably, respondents frequently identified HCP as a primary corrosion assessment tool when elaborating on the specific tasks for a particular method.

In totality, ultrasonic methods (UPV and UPE) were the most common type of NDT method recommended. UPV is like shouting in a cave and having a friend listen from the other side to gauge how fast the sound travels through the rock, while UPE is like shouting and listening for your own echo. UPE is mentioned more by the experts, potentially due to the versatility of its one-sided sensing methodology. Structures that cannot be accessed from both sides would favor UPE instead of UPV. Practical applications of an NDT method may rely on its versatility as much as its capabilities, as seen in the dynamic between UPV and UPE.

Whenever GPR was mentioned, experts referred to it using its functional terminology. In contrast, UPE was often referred to by its commercial product name, MIRA. This strongly reflects not only the established success of UPE in the field of NDT, but also the prominence of MIRA as the leading device for UPE tomography. Further details on specific NDT projects involving bridge elements could not be obtained, as many of these projects were confidential.

8.3.2 Experts' Perspectives on Advanced Digital Technologies Used with NDT

When asked about the viability of AI, robotics, or drones for the evaluation of bridge elements, more than half of the respondents recognized the potential of drones and robotics. The experts acknowledged that robots and drones can be useful, especially because they can access hard-to-reach areas that humans might not be able to inspect directly, but they also recognized limitations. Specifically, the main output from these tools is visual data (photos, videos, or images), so while they can show what an area looks like, they often cannot by themselves provide deeper diagnostic information (like detecting internal defects) without additional sensors or NDT equipment. One expert describes drones as a tool that is only as good as it is appropriate for a situation. On occasion, respondents suggested equipping drones or robots with infrared cameras to enhance their effectiveness, enabling the detection of surface temperature variations that may reveal moisture intrusion, delamination, or other hidden defects. While robotics may not entirely replace visual inspection, they offer a clear advantage in producing detailed photomosaics. Experts highlighted their wide coverage and scanning capabilities as key strengths, though they agreed that these methodologies still require further innovation. Similarly, AI was acknowledged for its potential, but one respondent expressed limited trust in and interest in its use.

8.3.3 Future of NDT Adoption

Widespread NDT adoption remains as a potential outcome as the innovations to NDTs progress. The DOT survey in Section 8.2 shows increasing rates of desire for NDT, but the actual implementation is believed among experts to be slow. In the expert survey, one respondent highlighted NDE webinars organized by the FHWA for various applications as a valuable resource for increasing awareness of NDT. Another expert explained that while GPR is a well-established method, its images can be significantly improved through MATLAB processing.

8.3.4 NDT Standards and Certification

These NDT experts did not know of a single certification program for data acquisition or analysis for the field of NDT. While several NDT standards exist, there is no professional institutional body dedicated to overseeing the practice of NDT. The absence of a centralized NDT standard remains a significant barrier to widespread NDT implementation. In practice, many organizations rely on standards from ASTM, FHWA, AASHTO, and others as performance or procedural benchmarks; however, no unified standard exists that governs NDT as a whole. Without a body to unify the practice and unlock its potential, NDT remains underutilized.

8.3.5 Conclusion

Expert responses emphasized both the potential and practical applications of NDT. While NDT tools often generate a large volume of data, their value lies in enhancing the available information rather than replacing conventional methods. In some cases, inspectors may arrive at similar rehabilitation strategies using either approach, yet the unique strengths of specific NDT techniques remain well-recognized. For most defects, there is typically a primary method of choice as well as viable alternatives, reflecting the versatility of NDT in addressing a range of inspection needs.

8.4 Comparative Analysis of Indot, Dot, and Expert Survey Results

This section presents a comparative analysis of survey findings from INDOT personnel, state DOT representatives, and industry experts. The combined results offer a comprehensive view of current NDT practices, perceived advantages, and common barriers across these three groups. By examining similarities and differences in method preferences, application trends, and implementation challenges, this analysis highlights areas of consensus, identifies knowledge gaps, and reveals opportunities for advancing NDT use in bridge inspections.

8.4.1 Current Practices and Perspectives on NDT Methods

Among all participants, GPR was the most likely method to be utilized or recommended. It is the topmost NDT strategy, with GPR accounting for above 25% of all popularity measures in the survey, including utilization, recommendation, and preference. This may be due to several factors, including its widespread use in deck assessments and even on piers and abutments. Additionally, its application in various disciplines beyond engineering enhances its appeal across multiple fields.

Despite GPR's status as the leading NDT tool, some within INDOT felt it should be used more often, ranking it just behind IE in methods with the greatest potential for increased application. IE is also widely valued, exchanging positions with IRT between the rankings of INDOT and DOTs. IE and GPR gained this predominance over others as they scan delamination, which was identified as the top concern for various state DOTs. Additionally, IE and GPR may be used in tandem or separately, as one can perform large scans with GPR and localized tests with IE. With such similar characteristics and abilities, IE seems to complement the capabilities of GPR, rather than being a direct competitor.

IRT is a favored method among state DOTs; however, IRT was not recommended by experts in their surveys. This is noteworthy considering that all DOTs assigned IRT as a viable option for NDT inspection, especially for delamination, with a noticeable contribution to addressing delamination on piers. While concerns can be raised as to whether IRT can be effectively replaced by other methods in the assessment of piers, pier caps, beams, and abutments, this gap presents an opportunity to refine or find new approaches to IRT scanning.

HCP and HR appear to be more specialized than other methods. Although neither ranks among the most frequently used tools overall, each maintains a dominant position within its specific niche. HCP was consistently highlighted as the leading corrosion probability tool for the task. Similarly, HR was the primary method for concrete strength determination. Like many defects or condition assessments, other methods were viable, such as GPR for corrosion of rebar and ER for strength and corrosion estimation. Regardless of the availability of such options, HCP and HR can be considered the benchmark for their respective tasks. Furthermore, these two tools are occasionally used to sense piers and abutments, only behind GPR.

Ultrasonic sensing methods (UPV and UPE) were the preferred method of NDT experts and were often applied for measurements of material thickness. However, between the two, UPE was considered a more advantageous option. This does not diminish the value of UPV but reflects the superiority of one-sided echo sensing methods, which are less restrictive than two-sided echo sensing with UPV. In this study, the UPE method is occasionally referred to by the commercial name of the instrument, MIRA, indicating not only a widespread familiarity but also a substantial degree of success and trust in the field. However, UPV and UPE are not the default NDT methods on piers and abutments according to the surveys.

LiDAR, IR, ER, Radiography, and Hammer Sounding were relatively unpopular methods displaying very rare applications among DOTs and expert surveys. Nonetheless, they are still used, which indicates that each occupies a specific niche where it proves effective and appropriate.

8.4.2 Advantages and Strategic Applications of NDT

According to INDOT personnel, the internal damage assessment is a key attribute of NDT tools. This is reflected by state DOTs, which show a high level of attention to delamination and corrosion assessment, defects that are not always externally apparent in severity. A similar sentiment can be seen from the experts who did not recommend a single methodology that did not sense internal features. The most well-known, used, and preferred tools were those that could gather insight into the internal characteristics of a bridge component. It is clear that the value of NDT is in enhancing the data capture from structures.

However, some types of methods, such as LiDAR or other digital photogrammetry methods like aerial drones with optical cameras, compete directly with visual inspection. Despite the superior image capture capabilities of these methods, they do not fulfill this task of internal defect mapping, limiting their adoption to situational tasks. As such, surficial assessment tools remain overlooked. However, according to the INDOT survey, situational tools may have a greater impact and appeal to groups that need them.

Redundancy, or in other words, data fusion, is an essential aspect of NDT methods that is often overshadowed. The use of complementary NDT methods can help overcome the limitations inherent in and significantly improve the reliability of results. For example, pairing UPV and HR offers a robust and valid method for strength estimation. Additionally, GPR and IE delamination detection are excellent combinations to validate readings of subsurface anomalies.

8.4.3 Barriers, Limitations, and Concerns in NDT

There is a strong and growing interest in NDT apparent in the INDOT participants, reflecting an inherent desire to enhance current practices. The viability of NDT is occasionally brought up. Some, like bridge inspectors, believe visual inspection is acceptable. Experts believe drone technology is not adequate to replace visual inspection, despite its ability to maneuver into hard-to-reach places.

In terms of visual assessment and analytical reasoning, the survey's results show that NDT tools tend to provide additional data rather than transformative insights that could fundamentally challenge established methods. This does not imply that the survey respondents see no value in NDT; rather, they perceive its capabilities as comparable to those already achievable through conventional approaches. Consequently, NDT is viewed less as a replacement for existing practices and more as a complementary enhancement that can be used alongside them to improve overall inspection effectiveness.

Accuracy consistently emerged as the foremost concern among respondents in the INDOT survey, ranking above ease-of-use and safety. To address accuracy concerns, the strategic use of multiple, complementary NDT methods remains a possible route to improve confidence in readings. However, as INDOT personnel have pointed out, environmental conditions, moisture, surface conditions, and other factors will be obstacles for accurate data capture for any NDT. However, some methods have clearly shown noteworthy practical success in the field, as indicated by the trust seen for GPR, IE, UPE, and IRT in the DOTs and experts' surveys.

The concerns for accuracy due to external, environmental, or worksite issues are not irregular or specific barriers to NDT. These concerns may be attributed to a larger gap in unified standards for NDT. While it does not require a highly trained operative to execute NDT, as suggested by the INDOT survey, the operators who do use NDT do not always have high confidence in either their readings or perhaps their own judgment because of this issue.

Most of the participants in the expert survey confirmed that no quality certification program exists for NDT in terms of data acquisition and analysis. This leaves current operators as pioneers who only have their own judgment or what limited standards exist for NDT to guide them. Without a greater body to orient readings, confirm accuracy, and stand as a benchmark, the operators who wish to integrate NDT will struggle to rely on it.

Ultimately, integrating multiple NDT methods and addressing these institutional and practical barriers can unlock the full potential of NDT, leading to more accurate, efficient, and effective structural assessments.

9. SELECTION OF SUITABLE NDT METHODS FOR REINFORCED AND PRESTRESSED CONCRETE BRIDGE COMPONENTS (EXCLUDING DECK)

The selection of appropriate NDT methods for reinforced and prestressed concrete bridge components is a complex task that requires careful consideration of multiple interrelated factors. NDT is a highly conditional field, involving numerous "if-then" scenarios at every step of the inspection process. For example, if the material is aged concrete, then certain methods are more suitable; if the reinforcement density is high, meaning the steel bars are closely spaced or layered, then certain NDT methods may face limitations, as the dense steel can block, distort, or scatter signals, making it more difficult to detect flaws or interpret the results accurately. Even within a single method, decisions regarding test frequency, resolution, and data interpretation often vary based on environmental conditions, material properties, and the structural characteristics of the component being inspected. This layered and conditional nature makes it difficult to offer straightforward, one-size-fits-all solutions to many NDT-related challenges, particularly in complex structures like bridges.

This chapter presents tables for each reinforced and prestressed concrete bridge component, beam ends, abutments, piers, and pier caps. For each component, the common defects are matched with appropriate NDT methods, including their advantages and limitations. The tables are developed based on relevant standards, published literature, case studies, multiple survey responses, and expert opinions.

Each bridge component faces distinct loading conditions, exposure environments, and defect mechanisms. For clarity, each table links common defects specific to the component with appropriate NDT methods, outlining their advantages and limitations. While the tables are component-specific, some overlaps naturally occur, since defects such as cracking, corrosion, moisture ingress, and honeycombing are common across multiple bridge components. In these cases, the same NDT methods may appear in more than one table, but their relevance, effectiveness, and limitations are explained in the context of the specific structural role, geometry, and environmental exposure of the component.

A detailed framework for core sampling, test-location planning, and grid-mapping strategies used in this study is provided in Appendix C, including guidance based on ACI 228.1R/228.2R, EN 13791 (EN, 2019), ASTM C823, and ASTM E122. Readers are referred to this appendix for the principles governing lot definition, test density, and sampling design, which form the basis for selecting appropriate NDT methods for various bridge components.

9.1 Beam Ends

TABLE 9.1
Common Types of Defects and Conditions in Beam Ends Linked to Suitable NDT Methods With Pros and Cons.

	Type of Defect or Condition in Beam Ends	Suitable NDT Methods (With Pros and Cons)
1	Subsurface cracks, fatigue cracks in stress concentration zones	**UPV:** High sensitivity to internal cracks; Requires two-sided access for best accuracy. **AE:** Monitors live crack propagation under load, in real time. Needs continuous monitoring; background noise can interfere. **IE:** Detects larger cracks and evaluates depth and extent. May miss microcracks.
2	Delamination (near reinforcement or joint zones)	**UPE:** One-sided access; identifies depth of delamination. Interpretation requires skilled operators. **IE:** Identifies delamination at depth with good accuracy. Limited resolution for near-surface delamination. **GPR:** Rapid mapping of delaminated zones and rebar. Reduced accuracy in wet or chloride-contaminated environments. **IRT:** Detects near-surface delamination due to moisture or thermal contrast. Weather-dependent; limited penetration depth.
3	Spalling, surface scaling	**RH:** Identifies surface hardness (concrete strength) loss quickly. It provides a qualitative indication of surface hardness and strength. **IRT:** Reveals shallow spalls by thermal signature. Only detects near-surface issues.
4	Corrosion of reinforcement or tendons	**HCP:** Identifies probability of corrosion activity. Low-cost, simple setup. Provides probability, not corrosion rate. **GPR:** Locates rebar or tendon ducts and detects corrosion-prone anomalies. Accuracy is reduced in saturated zones. **UPE:** Identifies voids around corroded steel. Accuracy depends on how well the ultrasonic transducer is connected to the concrete surface.
5	Moisture ingress, joint leakage	**GPR:** Detects moisture-related anomalies around rebar and ducts. Rapid scanning. Limited penetration in saturated environments. **IRT:** Non-contact detection of moisture through surface temperature variation. Requires a strong thermal gradient.
6	Voids, honeycombing	**UPE:** Detects internal voids and honeycombs with one-sided access. Requires experience for interpretation. **IE:** Detects large voids and thickness variation. Not sensitive to very small voids (less than 5 mm).

(*Continued*)

TABLE 9.1
Common Types of Defects and Conditions in Beam Ends Linked to Suitable NDT Methods With Pros and Cons. (*Continued*)

	Type of Defect or Condition in Beam Ends	Suitable NDT Methods (With Pros and Cons)
7	Debonding of prestressing tendons or duct defects	**GPR:** Maps tendon ducts, identifies anomalies around ducts. Can struggle in chloride-contaminated or saturated ducts. **UPE or UPV:** Detect voids or debonding around tendons. Requires high expertise for interpretation. **AE:** Detects active tendon cracking under load. Requires continuous monitoring equipment.
8	Surface Deterioration, in-place concrete strength	**UPV:** Estimates in-place compressive strength, highlights degraded concrete zones. Requires opposite-side access or semi-direct setup. **RH:** Quick check for surface hardness uniformity. Limited penetration; must be correlated with other methods.

9.2 Abutment

TABLE 9.2
Common Defects and Conditions in Abutments and Suitable NDT Methods With Pros and Cons.

No.	Common Defect, Condition in Abutments	Suitable NDT Methods with Pros and Cons
1	Subsurface cracks (due to earth pressure or settlement)	**UPE:** One-sided inspection of abutments; detects deep cracks and delamination. Requires skilled interpretation. **AE:** Monitors real-time crack propagation during loading. Continuous monitoring needed; background noise interference.
2	Delamination (freeze–thaw, moisture, thermal cycles)	**IE:** Locates delamination depth and extent. **IRT:** Detects shallow delamination via temperature contrasts. Sensitivity to environmental factors such as sun and wind
3	Voids and honeycombing (poor compaction during casting)	**UPE:** Detects internal voids or honeycombing with one-sided access, suitable for massive abutment sections. Accuracy decreases in very thick or highly reinforced zones. **IE:** Detects large voids and thickness variation. Not sensitive to very small voids (less than 5 mm).
4	Moisture Ingress/poor drainage effects	**GPR:** Maps moisture pathways, rebar corrosion risk, and subsurface voids. Accuracy is reduced in saturated or chloride-contaminated environments. **IRT:** Detects near-surface moisture anomalies.
5	Surface Deterioration, strength loss (weathering, abrasion, shrinkage), concrete strength estimation	**RH:** Provides a quick, low-cost assessment of surface hardness or strength. Limited to surface measurements and requires calibration for accuracy.
6	Corrosion of reinforcement (chloride ingress from deicing salts, splash zones, or soil contact)	**HCP:** Identifies probability of corrosion activity. Low-cost, simple setup. Provides probability, not corrosion rate. **GPR:** Maps reinforcement layout, cover depth, and moisture-related anomalies that indicate corrosion-prone areas. Accuracy is reduced in saturated or highly conductive environments.
7	Foundation settlement, tilting, leading to stress cracks	**AE:** Detects active crack growth due to foundation movements. It requires long-term monitoring. **UPV:** Assesses internal cracking associated with differential settlement. Requires two-sided or semi-direct access.

9.3 Pier

TABLE 9.3
Common Defects and Conditions in Piers and Suitable NDT Methods With Pros and Cons.

No.	Common Defect, Condition in Piers	Suitable NDT Methods with Pros and Cons
1	Subsurface cracks (due to axial or flexural load, settlement)	**UPE**: One-sided access in thick piers. It detects deep cracks. **AE**: Monitors live crack propagation under service loads. It requires continuous monitoring. **IE**: Estimates crack depth and extent but may miss microcracks.
2	Delamination (freeze–thaw, moisture, thermal cycles near waterline)	**IE**: Locates delamination depth in thick pier faces. **IRT**: Detects shallow delamination via thermal contrast; weather-dependent. **GPR**: Maps delamination near rebar. Its effectiveness is reduced in saturated zones.
3	Corrosion of reinforcement (water or splash zone exposure)	**HCP**: Detects probability of corrosion. It does not quantify rate. **GPR**: Maps rebar cages, cover depth, anomalies. Its accuracy is reduced in wet conditions. **UPE**: Detects voids around corroded bars. It requires skilled operation.
4	Moisture ingress and saturation	**GPR**: Detects subsurface moisture pathways; less effective in highly saturated zones. **IRT**: Maps near-surface moisture anomalies through temperature variation.
5	Voids, honeycombing (poor compaction during casting)	**UPE**: Detects voids and honeycombing with one-sided access. **IE**: Identifies large voids and thickness variation. It is not sensitive to very small voids (less than 5 mm).
6	Foundation settlement, scour, tilting cracks	**AE**: Detects live crack growth during scour or settlement. Requires long-term monitoring. **UPV**: Assesses internal cracking associated with differential settlement. Requires two-sided or semi-direct access.
7	Surface deterioration, strength loss, concrete strength estimation	**UPV**: Estimates residual strength and degraded zones in piers. Two-sided access required. **RH**: Quick check for surface hardness uniformity; must be correlated with other methods.

9.4 Pier Cap

TABLE 9.4
Common Defects and Conditions in Pier Caps and Suitable NDT Methods With Pros and Cons.

No	Common Defect, Condition in Pier Caps	Suitable NDT Methods with Pros and Cons
1	Subsurface cracks (due to girder reactions, shear, or settlement)	**UPE:** One-sided detection of internal cracks near girder seats. It requires skilled interpretation. **AE:** Captures live crack propagation under service loads. Continuous monitoring is needed. **IE:** Detects deeper cracks and estimates depth. It is less sensitive to microcracks.
2	Delamination (bearing zones, leakage effects)	**UPE:** One-sided access to bearing seat delamination. A skilled operator is needed. **IE:** Identifies deeper delamination within pier caps. **GPR:** Maps shallow delamination near rebar cages. Accuracy is reduced in saturated conditions. **IRT:** It detects near-surface delamination from leakage and moisture. It is weather-dependent.
3	Spalling, surface scaling	**RH:** It provides a quick check of surface hardness loss at bearing seats. **IRT:** It detects shallow spalls via heat contrast and is limited to near-surface defects.
4	Corrosion of reinforcement (chlorides from leakage, splash)	**HCP:** It identifies the probability of corrosion activity and is low-cost, but provides only the probability. **GPR:** It locates rebar, cover depth, and corrosion anomalies. Accuracy is reduced in wet conditions. **UPE:** It detects voids around corroded bars near accessible faces.
5	Moisture ingress (from leaking joints, ponding at girder seats)	**GPR:** It maps moisture pathways and subsurface voids. It is less effective in highly saturated conditions. **IRT:** It detects near-surface moisture patches and has a limited penetration depth.
6	Voids, honeycombing (poor compaction in congested bearing zones)	**UPE:** One-sided detection of voids and honeycombing in congested reinforcement regions. **IE:** It identifies large voids and thickness variations. It is not sensitive to very small voids (less than 5 mm).
7	Settlement or support-related stress cracks (column–pier cap interface)	**AE:** It detects live crack propagation due to settlement or tilting. It needs long-term monitoring. **UPV:** It assesses internal cracking and requires two-sided or semi-direct access.
8	Surface deterioration, in-place strength estimation	**UPV:** It estimates residual strength and degraded concrete zones. It requires opposite or semi-direct access. **RH:** It is a quick, low-cost check of surface hardness uniformity.

9.5 Conclusion

Selecting NDT for reinforced and prestressed concrete bridge components is not a one-click choice; it is a system-level decision. The tables in this chapter translate the conditional reality of field inspection into a clear, component-specific playbook: beam ends where joint leakage and anchorage effects dominate; abutments where soil interaction, drainage, and settlement rule; piers where saturation, freeze–thaw, and scour shape deterioration; and pier caps where bearing seats, reinforcement congestion, and persistent moisture drive damage patterns. Across these elements, recurring defect families: cracking, delamination, corrosion, moisture ingress, and honeycombing, reappear, but their best diagnostic tools shift with geometry, access, and exposure. The practical takeaway is threefold: (1) start with the component-tailored table to shortlist feasible methods; (2) combine complementary tools to balance depth, coverage, and speed (e.g., GPR or IRT for moisture pathways plus UPE or IE for depth and UPV or RH for material condition); and (3) calibrate interpretations to site conditions and constraints. Used this way, the tables are not a checklist but a decision framework. They help inspectors justify choices, triage risks, and focus rehabilitation where it matters most. No single method is sufficient; intelligent combinations, grounded in the context of each bridge component, deliver the most reliable and defensible assessments.

10. CONCLUSIONS, RECOMMENDATIONS, BENEFITS, AND IMPLEMENTATION

10.1 Summary of Research Findings

This research was conducted on the basis of existing literature and expert opinion. The key findings are summarized below:

- Integrating multiple NDT methods is the key to enhance accuracy.
- Accurate and efficient NDT for reinforced and prestressed concrete bridge requires the integration of core sampling, statistically planned test locations, and method-specific grid mapping.
- Selecting NDT methods for reinforced and prestressed concrete bridge components must be tailored to exposure conditions, geometry, accessibility, functionality, expected defect types, and cost.
- Each bridge component, pier, abutment, beam end, and pier cap, has distinct structural functions, load paths, exposure conditions, and accessibility challenges that influence inspection and maintenance strategies; therefore, the selection of suitable NDT methods should be based on these attributes.
- This research provides four comprehensive tables (9.1–9.4) that align specific defects with the most suitable NDT methods for each bridge component, beam ends, abutments, piers, and pier caps, along with the advantages and limitations of each method.

10.2 Expected Benefits, Deliverables, and Implementation

This research has contributed to the current INDOT strategic priorities as described in Table 10.1.

Table 10.2 is the consolidated master table that merges and summarizes the information from Tables 9.1–9.4 (Beam Ends,

TABLE 10.1
Research Contributions to INDOT Strategic Priorities.

INDOT Strategic Priority	Research Contribution
Time Savings	Provides ready-to-use, component-specific NDT selections from Tables 9.1–9.4 that INDOT can apply directly or share with consultants, greatly reducing planning time, eliminating trial-and-error, and accelerating overall inspection schedules.
Cost Savings	INDOT can benefit from using the NDT selection guidance in Tables 9.1–9.4, supported by the commercial names and instrument functionalities provided in Appendix B, to reduce costs by avoiding inappropriate or redundant methods and equipment. This guidance can be applied in-house or recommended to consultants to ensure consistent, efficient, and cost-effective inspections.
Safety	Using the guidance tables in Chapter 9, INDOT can enhance early detection of hidden defects in critical bridge elements, enabling timely repairs and reducing risks to both road users and inspection crews, whether the work is performed in-house or by supervised consultants.
Mobility/Reduced Congestion	Bridge component accessibility such as height, one- or two-sided access, and underside-of-beam conditions is incorporated into the guidance tables (Tables 9.1–9.4), enabling optimized inspection planning that minimizes lane closures, reduces traffic congestion, and limits inspector mobility requirements.
Quality	By aligning each bridge component's specific attributes, such as geometry, exposure, accessibility, and expected defect types, with the suitable NDT methods, inspectors can ensure more thorough and targeted evaluations, which enhance the quality of inspection.

Abutments, Piers, and Pier Caps). It lists major common defects and conditions found in reinforced or prestressed concrete bridge components (excluding decks) and their corresponding suitable NDT methods.

The findings of this research have resulted in five guideline tables (Tables 9.1–9.4) for INDOT to determine the most suitable NDT methods for reinforced and prestressed concrete bridge components, piers, pier caps, beam ends, and abutments. These tables integrate best practices from AASHTO, ASTM, ACI, and other relevant standards, combined with insights from INDOT staff, other DOTs, and industry experts. By implementing these findings, INDOT can directly apply the tables in-house or recommends consultants to follow them, ensuring a consistent, systematic, and standards-based approach while reducing reliance on trial-and-error methods.

INDOT can embed Tables 9.1–9.4 into existing inspection manuals, bridge condition rating protocols, and consultant contract requirements. This ensures that NDT method selection is not left to individual judgment but follows a structured, agency-wide standard. INDOT can require consultants to document their selected NDT methods and tools, cross-referencing them with the guideline tables (9.1–9.4) to ensure oversight of inspection reports and provide justification for maintenance planning decisions.

The guideline tables serve as quick-reference tools for developing component-specific, multi-method inspection plans, confirming that no single NDT method is sufficient. Instead, strategic combinations of complementary techniques deliver the most accurate, reliable, and cost-effective results for actionable bridge condition assessments. Applying these resources early in the inspection planning phase allows INDOT to streamline NDT method selection, minimize unnecessary fieldwork, improve inspection quality, and enhance the reliability of collected data.

TABLE 10.2
Consolidated Summary of Common Defects and Conditions in Reinforced and Prestressed Concrete Bridge Components and Suitable NDT Methods.

No.	Common Defect/Condition	Suitable NDT Methods with Key Notes on Use
1	Subsurface cracks (from stress, load, or settlement)	**Ultrasonic Pulse Echo (UPE):** One-sided detection of deep internal cracks; good for massive/inaccessible members. **Impact-Echo (IE):** Estimates crack depth/extent in thick sections. **Acoustic Emission (AE):** Monitors live crack propagation during service loads. **Ultrasonic Pulse Velocity (UPV):** Bulk integrity/residual strength when two-sided or semi-direct access exists.
2	Delamination (near reinforcement, joints, freeze–thaw zones, bearing seats)	**UPE:** One-sided depth/location of delamination. **IE:** Deeper delamination in thick members. **Ground-Penetrating Radar (GPR):** Rapid mapping near reinforcement, limited in saturated/chloride-contaminated concrete. **Infrared Thermography (IRT):** Near-surface delamination via thermal contrast, weather dependent.
3	Spalling/surface scaling	**Rebound Hammer (RH):** Quick qualitative check of surface hardness/local strength loss. **IRT:** Highlights shallow spalls or scaled areas by showing temperature contrasts on the surface that indicate underlying defects.
4	Corrosion of reinforcement or prestressing tendons	**Half-Cell Potential (HCP):** Probability of active corrosion (does not give rate). **GPR:** Maps bars/ducts, cover, corrosion-prone anomalies. **UPE:** Voids/debonding around corroded bars/tendons. **AE:** Active cracking in concrete and fracture of prestressing tendons under load.
5	Moisture ingress/joint leakage/poor drainage/saturation	**GPR:** Moisture pathways and subsurface anomalies. Its effectiveness is limited in highly saturated zones. **IRT:** Non-contact mapping of surface moisture or leakage using temperature gradients.

(*Continued*)

TABLE 10.2
Consolidated Summary of Common Defects and Conditions in Reinforced and Prestressed Concrete Bridge Components and Suitable NDT Methods. (*Continued*)

No.	Common Defect/Condition	Suitable NDT Methods with Key Notes on Use
6	Voids/honeycombing (due to poor compaction)	**UPE:** Localized voids/honeycombing with one-sided access. It is good in congested reinforcement. **IE:** Large voids and thickness variation. It is not sensitive to micro-voids (< ~5 mm).
7	Debonding of prestressing tendons/duct defects	**GPR:** Maps ducts and highlights anomalies at anchorage/tendon zones. **UPE/UPV:** Detect loss of bond or voids around tendons. **AE:** Monitors cracking/slip under service loads.
8	Surface deterioration/in-place concrete strength estimation	**UPV:** Residual strength/degraded zones. It needs two-sided or semi-direct access. **RH:** Fast, low-cost surface hardness check. It correlates with other NDT for strength.
9	Freeze–thaw damage (delamination, scaling, cracking)	**IE:** Depth/extent of delamination from freeze–thaw. **IRT:** Maps shallow thermal anomalies. **RH:** Screens surface hardness reduction due to scaling.
10	Foundation settlement/tilting/scour-induced stress cracking	**AE:** Live crack activity from differential movement or scour. **UPV:** Internal cracking/strength loss (needs semi-direct access). **UPE:** Useful when only one face is accessible in massive sections.
11	Soil–structure interaction effects (earth pressure, buried faces)	**UPE:** One-sided deep flaw detection on accessible faces. **AE:** Stress-related crack activity from earth pressure. **HCP/GPR:** Corrosion risk mapping and bar layout where accessible.
12	Settlement-related delamination or joint defects (bearing/pier or abutment interfaces)	**AE:** Live crack growth at bearing seats or pier/abutment interfaces. **UPV:** Internal cracking continuity across interfaces (requires access).
13	Scour or waterline deterioration in piers	**AE:** Monitors cracking due to scour-induced instability. **GPR:** Subsurface voids/washout zones. **IRT:** Moisture saturation bands near waterlines.
14	General weathering/aging/shrinkage cracking	**RH and UPV combo:** Surface vs in-depth degradation. **UPE and IE:** Internal cracks or shrinkage-related delamination.

Whether used by INDOT personnel or supervised consultants, this implementation ensures higher-quality evaluations, better maintenance decisions, and ultimately improved bridge safety and longevity.

10.3 Gaps and Future Studies

10.3.1 Technical Gaps in NDT Methods

10.3.1.1 Accuracy and Reliability. While many advanced NDT instruments are available today, the accuracy and reliability of their results remain a concern. Findings from this research highlight that integrating multiple NDT methods can improve accuracy. However, selecting an appropriate set of advanced instruments for detecting specific defects or conditions requires further experimental research. Achieving this goal necessitates a deeper understanding of the capabilities of new and advanced NDT instruments. Appendix B of this report provides a list of these instruments along with a summary of their capabilities obtained from their manufacturer. For instance, whether a combination of iCOR and Profometer PM8000 is practically suitable for corrosion assessment in concrete bridges needs experimental research.

10.3.1.2 Depth and Defect Characterization. UPE and IRT are effective for detecting anomalies within concrete; however, both methods are constrained by limited penetration depth and by difficulties in reliably identifying the type of defect: crack, void, or delamination. To address these limitations, further experimental research is needed on the inclusion of advanced imaging techniques. Advanced imaging enables the generation of detailed 3D or tomographic views of the internal condition of concrete. For instance, ultrasonic tomography (e.g., A1040 MIRA) can produce volumetric, high-resolution images of defects, allowing inspectors to visualize not only the presence of an anomaly but also its shape, orientation, and extent.

10.3.1.3 Integration of Emerging Technologies. While drones, LiDAR, VR/AR, and robotics are being applied, they remain primarily surficial or complementary tools. Their ability to advance NDT inspection when integrated with NDT instruments is still underdeveloped. For instance, the feasibility of mounting an NDT instrument on a climbing robot for inspection of hard-to-reach bridge components, such as tall piers or abutments, and the underside of beams should be further explored and researched.

10.3.1.4 Concrete Strength Estimation in Aged Concrete Bridges. While this research recommends the use of UPV or UPE in combination with RH for concrete strength estimation in aged concrete bridges, further experimental data is needed to refine this strategy and establish robust correlations between UPV results and compressive strength. The current body of experimental data in the literature is limited, underscoring the need for additional targeted experiments.

10.3.1.5 Standardized Grid Mapping and Core Correlation. Further research is needed to establish standardized approaches for grid design and statistically planned test locations to ensure consistent and representative data collection. Current practices often rely on inspector judgment, which can lead to biased sampling and variability in results. Developing systematic grid mapping strategies would improve the spatial reliability of NDT measurements and reduce the risk of overlooking critical defects.

10.3.2 Institutional and Practice Gaps

10.3.2.1 Lack of Unified NDT Certification and Training. Further research is needed to identify the most appropriate NDT certification programs and the organizations that provide them. While various NDT equipment manufacturers supply their own user manuals and data interpretation procedures, inspectors are still required to follow established standards and guidelines such as those from ASTM and ACI. This dual requirement can lead to inconsistencies in the inspection strategies applied, particularly when manufacturer-recommended practices differ from standardized procedures. Clarifying certification pathways, harmonizing training requirements, and aligning manufacturer protocols with recognized standards would help ensure consistency, reliability, and regulatory compliance in NDT applications.

10.3.3 Gaps in Standards and Guidelines

10.3.3.1 Fragmented Standards Across Organizations. Standards and guidelines for NDT of RC bridges are currently distributed across several professional organizations, including ACI, AASHTO, ICRI, ASTM, and ISO. Each body emphasizes different aspects of inspection, testing, and asset management, resulting in a fragmented framework. This patchwork creates inconsistencies in how inspections are conducted, how data are interpreted, and how decisions are made across agencies. To address this gap, further research is needed to develop harmonized frameworks and propose a unified guideline that consolidates the strengths of existing standards while focusing specifically on the unique requirements of RC bridge assessment.

10.3.3.2 Limited Coverage of Emerging Technologies. Current codes and guidelines, such as ACI, AASHTO, and ICRI, provide some recognition of established NDT methods. However, their coverage is limited to conventional NDT applications and does not adequately address the rapid evolution of emerging technologies. The key gaps are integration of real-time monitoring systems, AI and machine learning applications, data fusion and digital twins, advanced imaging and robotics. Future research should focus on developing and proposing performance-based guidelines that incorporate emerging technologies into established standards.

10.3.3.3 Case Study Deficiency. Current standards and guidelines for NDT rarely include detailed field case studies showing how these methods perform under real-world bridge conditions. This is a critical shortcoming because many NDT methods are validated under laboratory conditions, where variables such as temperature, moisture, surface roughness, and traffic vibration are controlled. In the field, however, these factors can significantly influence test reliability and data quality. RC bridges vary widely in age, construction type, reinforcement detailing, environmental exposure, and deterioration mechanisms. Without documented case studies, inspectors lack guidance on how an NDT method might perform on, for instance, a 60-year-old prestressed girder bridge versus a newer post-tensioned box girder. The absence of comprehensive case studies prevents practitioners from understanding failure modes, limitations, calibration requirements, and interpretation challenges that arise during field deployment. Agencies may hesitate to adopt advanced NDT technologies without practical examples that demonstrate cost-effectiveness, repeatability, and integration with asset management decisions.

In this report, seven case studies are presented to illustrate the application of NDT in diverse contexts. However, further research should systematically document and analyze more field-based case studies that apply different NDT techniques across diverse bridge types and deterioration scenarios. These studies should capture not only successes but also limitations, lessons learned, and best practices. Incorporating such case studies into standards would make guidelines more practical, field-relevant, and implementable for state DOTs.

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APPENDICES

Appendix A. Survey's Questionnaires

Appendix B. Commercial Names and Applications of NDT Instruments for Concrete Structures

Appendix C. Core Sampling, Test Location Planning, and Grid Design for NDT

APPENDIX A. Survey's Questionnaires

A.1 INDOT SURVEY QUESTIONNAIRE

Personal Information

Full name:
Email address:

General Knowledge and Experience

1. Do you see any value in using NDT tools for Beams, Piers, Abutments, RC Slab (reinforced concrete/prestressed components)? Please explain.

2. Which NDT tools applicable to Beams, Piers, Abutments, and RC Slabs (reinforced concrete/prestressed components) are you familiar with, have you used, or have you overseen? Please include those even learnt from seminars, conferences…

3. Have you been involved in any INDOT project where a contractor or consultant used NDT tools on beams, piers, abutments, and bottom of RC Slab? If yes, share details.

Technical Insights

1. If you are in a position of choosing or using the results of NDT method for concrete bridge components, what criteria would you consider most important? Please rank these (accuracy, cost, ease of use, portability, safety) in order of priority from highest to lowest.

2. Are there any particular NDT tools or technologies you believe are currently underutilized or overlooked in bridge inspections or other projects involving NDT?

3. Have you encountered any technical challenges or limitations in applying NDT methods to applicable INDOT projects? If so, what are these challenges?

Practical Application and Performance

1. Based on your experience, what are the primary barriers or limitations to adopting or implementing new NDT technologies within bridge inspection projects or other projects that involve the use of NDT to investigate a specific issue?

2. Can you describe any specific projects, scenarios, or conditions where certain NDT methods performed exceptionally well or poorly?

Training and Education

1. What specific training do you consider essential for engineers or technicians to properly implement and interpret the results of NDT methods?

2. Do you believe current educational resources or training programs in NDT are adequate? If not, what improvements or additions would you recommend?

Regulations, Standards, and Guidelines

1. Do you follow specific guidelines or standards (e.g., ASTM, ACI, AASHTO) when implementing NDT methods?

2. Do you believe the existing NDT standards and guidelines sufficiently cover all practical scenarios encountered in the field? If not, what additional guidance would you find beneficial?

Future Perspectives and Recommendations

1. Are there any emerging or advanced NDT technologies you think INDOT should explore further for bridge assessments?

2. What suggestions would you have for researchers or manufacturers to enhance current NDT methods and tools?

Contacts

1. Could you please recommend any other experts or companies we could contact for our research?

A.2 DOTS SURVEY QUESTIONNAIRE

Full Name:

Email address:

Phone number:

Job title:

State DOT:

Can we contact you by email or phone if further discussion is needed? If yes, which of email or phone call do you prefer?

Please type your answer in the table below regarding NDT methods, and emerging technologies used with them. If any sections don't apply to you, please leave them blank.

	NDT Method/Technology	Actively using	Agency is interested, but not actively using	Brief description of what defects or conditions are being assessed.*	What bridge component(s) is the method / technology being used on?	Commercial name of instrument used, if known
NDT methods	Rebound Hammer	-	-	-	-	-
	Ultrasonic methods (UPV, UPE)	-	-	-	-	-
	Impact Echo	-	-	-	-	-
	Acoustic Emission	-	-	-	-	-
	Ground-Penetrating Radar	-	-	-	-	-
	Impulse response	-	-	-	-	-
	Half-cell Potential	-	-	-	-	-
	Electrical Resistivity	-	-	-	-	-
	Ultrasonic Surface Waves (USW)	-	-	-	-	-
	Ultrasonic Tomography	-	-	-	-	-
	Radiography (X-ray)	-	-	-	-	-
	Infrared Thermography	-	-	-	-	-
Emerging technologies used with NDT	Artificial Intelligence	-	-	-	-	-
	Digital Twin Models	-	-	-	-	-
	Augmented Reality / Virtual Reality	-	-	-	-	-
	Autonomous Robots	-	-	-	-	-
	3D Imaging / Tomography	-	-	-	-	-
	LIDAR (Light Detection and Ranging)	-	-	-	-	-
	IoT-Enabled NDT Sensors	-	-	-	-	-
	Cloud-Based Data Platforms	-	-	-	-	-
	Building Information Modeling	-	-	-	-	-

*Defects or Conditions: Thickness, Depth, Voids, Cracks, Rebar Corrosion, Delamination (Shallow/Deep), Deterioration (such as Sulfate, Freeze-Thaw), Bonding Issues, Strength Estimation, Fire Damage, etc.

A.3 EXPERTS' SURVEY QUESTIONNAIRE

Full name:

Email address:

1. Given the various types of defects and different NDT tools, could you identify the most suitable NDT tools for evaluating the condition of bridge beam ends, abutments, and piers? (focusing on reinforced/prestressed concrete components?)

2. Could you please recommend any other experts/companies we could reach out to that would be beneficial to our research?

3. Please provide any experience/thoughts on using advanced digital technologies, such as AI, robotics, or drones, in the context of NDT inspections explored for condition evaluation of bridge beam ends, abutments, and piers (focusing on reinforced/prestressed concrete components).

4. Do you know of any case studies or real-life bridge projects that involved NDT of bridge beam ends, abutments, and piers (focusing on reinforcing/prestressed concrete components)? If so, do you have any documents about it?

5. Do you know of any NDT certification for data acquisition/analysis?

6. In your experience, do you see more DOTs adapting NDT now? Do you have any documentation on this to help us?

7. Which DOTs do you think have more experience with NDT? Do you have any documents on this to help us?

8. Do you have documents/templates to help DOTs to use when contracting NDT services, ensuring that all important requirements and expected outputs from the contractor or consultant are clearly defined in the procurement documents?

9. Please kindly let us know any areas you think could help us to explore as part of this research study.

APPENDIX B. Commercial Names and Applications of NDT Instruments for Concrete Structures

B.1 MECHANICAL AND ACOUSTIC METHODS

B.1.1 Impact Echo:

Commercial Name of the NDT Instrument: DOCter

- Manufacturer's Name: Germann Instruments
- Main Applications:
    - Measure the thickness of plate-like concrete elements like slabs or walls.
    - Detects the presence and depth of voids and honeycombing.
    - Delamination surveys of bridge decks, piers, cooling towers, and chimneystacks.
    - Estimates early-age strength development.
- Link to website

Figure 1 Germann Instruments, DOCter

Commercial Name of the NDT Instrument: Pundit Impact Device

- Manufacturer's Name: Proceq also known as Screening Eagle
- Main Applications:
    - Concrete slab testing, thickness measurement, and defect detection.
    - Testing of piles and concrete plates.
    - Pile length assessment, detection of internal defects like voids and delamination, as well as mapping concrete plate thickness.
    - Asset inspection of buildings, bridges, and piles.
- Link to website

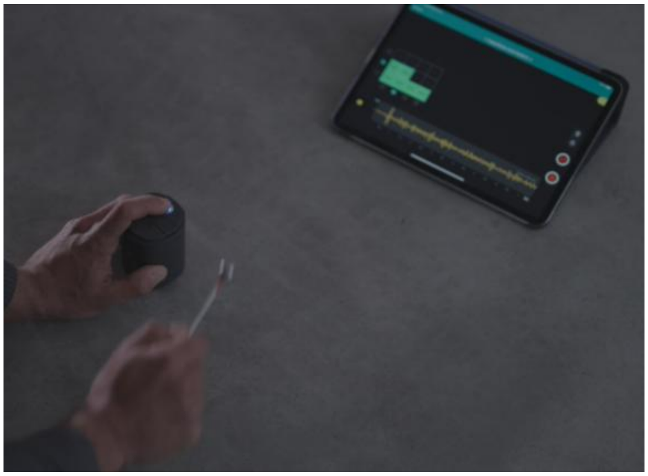

Figure 2 Proceq, Pundit Impact Device

Commercial Name of the NDT Instrument: Impact-Echo Testers, "Impact Echo 1 & 2"

- Manufacturer's Name: Olson Instruments
- Main Applications:
    - Impact Echo 1:
        - Tests concrete between 3.2" to 6 ft. Includes impactor solenoid and displacement transducer.
        - Applicable on beams, columns, walls, decks, etc.
        - Tests for cracks, delamination, honeycombing, thickness, and voids.
    - Impact Echo 2:
        - In addition to impactor solenoid and displacement transducer, accelerometer for testing up to 12 ft.
        - Applicable on beams, columns, walls, decks, etc.
        - Tests for cracks delamination, honeycombing, thickness, and voids.
- Link to website

Figure 3 Olson Instruments, Impact-Echo Testers

Commercial Name of the NDT Instrument: NDE 360

- Manufacturer's Name: Olson Instruments

- Main Applications:
  - Used on beams, bridge decks, columns, dams, and walls for detection of cracks, delamination, honeycombing, voids, and thickness.
- Link to website

Figure 4 Olson Instruments, NDE 360

Commercial Name of the NDT Instrument: Pistol Transducer and WaveSpeed Transducer

- Manufacturer's Name: Impact Echo Instruments
- Main Applications:
  - Has 6 recommended configurations for an impact-echo test system depending on the type of tests to be performed.
  - System A: A comprehensive system having three transducers including two cylindrical or two pistol grip or one of each, plus a dual-head transducer. The cylindrical and pistol grip transducers can be used for testing, with a backup available in case one is lost or damaged. Determining the depth of surface-opening cracks requires two transducers and is most convenient using two cylindrical or two pistol grip transducers, or one of each. The dual-head transducer is used for independent measurements of wave speed.
  - System B: A system that includes the pistol transducer for testing and the dual-head transducer for wave speed measurements. This will cover all possible testing needs. For determining the depth of surface opening cracks, one end of the dual head transducer can be used in conjunction with the pistol transducer. The dual head transducer is used for independent measurements of wave speed.
  - System C: A system that includes only one transducer, either cylindrical or pistol grip. This system is suitable for routine testing where wave speed is estimated or measured. Wave speed can be measured only if tests can be performed on slabs of known thickness in the regions where testing is to be performed.
- Link to website

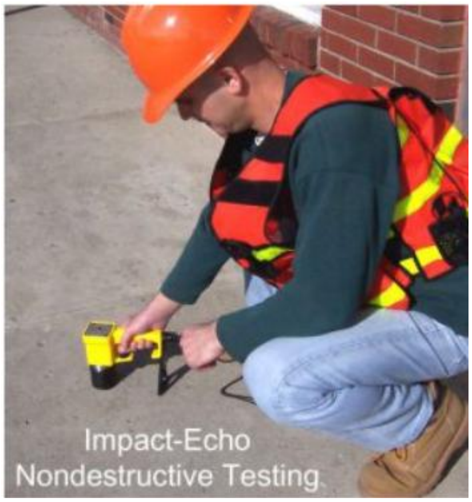

Figure 5 Impact Echo Instruments, Pistol Transducer

Figure 6 Impact Echo Instruments, WaveSpeed Transducer

Commercial Name of the NDT Instrument: Impact Echo

- Manufacturer’s Name: FPrimeC Solutions
- Main Applications:
    - Detects voids in grouted tendon ducts in post-tensioned elements.
    - Can be conducted in structural assessment.
    - Has augmented reality.
- Link to website

Figure 7 FPrimeC Solutions, Impact Echo

B.1.2 Ultrasonic Pulse Velocity:

Commercial Name of the NDT Instrument: V-Meter MK IV

- Manufacturer's Name: James Instruments
- Main Applications:
    - Locates cracks in concrete, ceramics, masonry or stone.
    - Determines fire damage extent in concrete or masonry.
    - Crack depth determination.
    - Widely used and accepted for quality control and inspection of concrete. It can measure and correlate concrete strength to standard strength measurement, permitting non-destructive testing of complete structures.
    - Identify honeycombs, voids, frozen concrete, cracks and other non-homogenous conditions in concrete.
    - Ultrasonic testing can be applied to new and old structures, slabs, columns, walls, fire damaged areas, hydroelectric structures, pipe, prefab and pre-stressed beams, cylinders and other concrete forms.
- Link to website

Figure 8 James Instruments, V-Meter MK IV

Commercial Name of the NDT Instrument: Pundit Lab and Pundit Plus

- Manufacturer's Name: Proceq also known as Screening Eagle
- Main Applications:
    - Correlation of compressive strength of concrete and rocks.
    - Mapping homogeneity of concrete.
    - Concrete strength estimation using the SONREB method.
- Link to website

Figure 9 Proceq, Pundit Plus

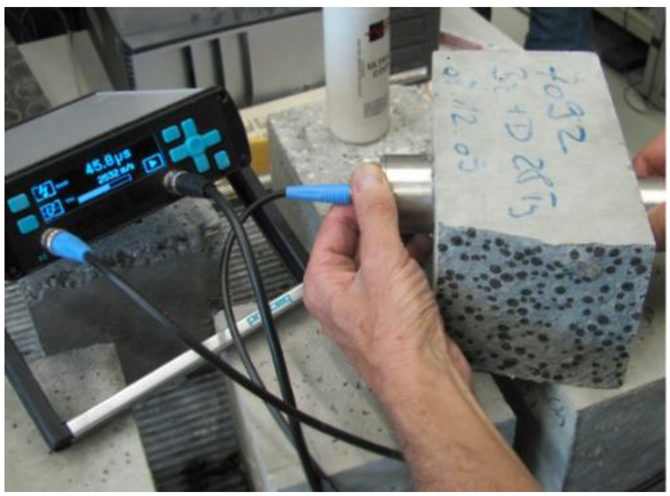

Figure 10 Proceq, Pundit Lab

Commercial Name of the NDT Instrument: UPV-1 Model

- Manufacturer's Name: Olson Instruments
- Main Applications:
    - Applicable on beams, beam intersections, columns, complex geometries, shaft tops, walls, bridge decks, and elevated slabs.
- Link to website

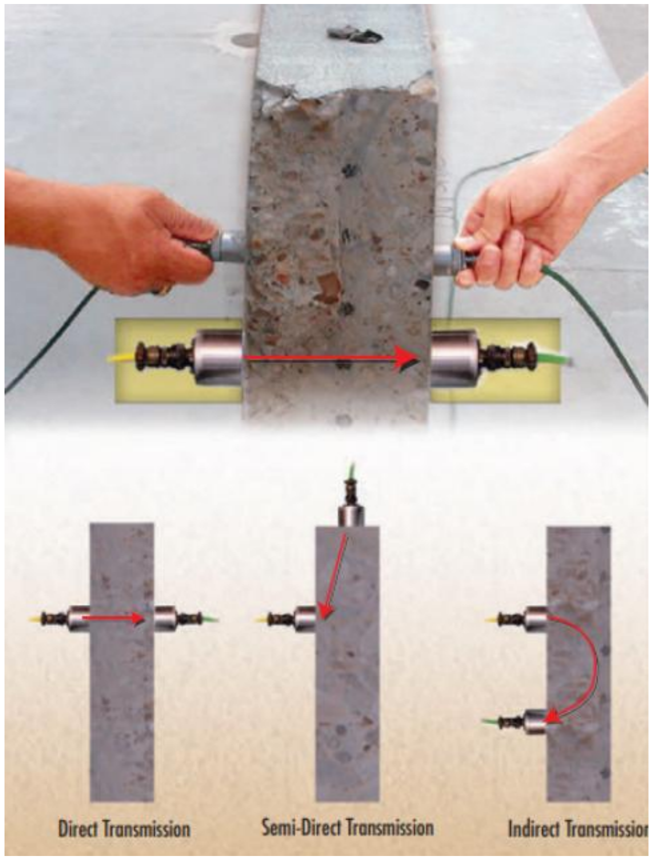

Figure 11 Olson Instruments, UPV-1 Model

Commercial Name of the NDT Instrument: PULSONIC, Ultrasonic Pulse Analyzer

- Manufacturer's Name: Controls
- Main Applications:
  - Used for measuring the velocity of ultrasonic pulses through a concrete section providing information on cracks, voids, strength, and giving quick estimates of dynamic modulus of elasticity on site or in the laboratory.
- Link to website

Figure 12 Controls, PULSONIC Ultrasonic Pulse Analyzer

Commercial Name of the NDT Instrument: Ultrasonic Pulse Velocity Tester

- Manufacturer's Name: Humboldt
- Main Applications:
  - Used to determine the presence of faults, voids, and cracks in in-situ or precast concrete and for long-term monitoring of structures subject to environmental conditions.
- Link to website

Figure 13 Humboldt, Ultrasonic Pulse Velocity Tester

Commercial Name of the NDT Instrument: A1410 Pulsar, Ultrasonic Pulse Velocity Tester

- Manufacturer's Name: Acoustic Control Systems, ACS
- Main Applications:
  - Measures a maximum thickness of inspection object up to 2.5 meters.
  - Provides accurate crack evaluation.
- Link to website

Figure 14 Acoustic Control Systems, A1410 Pulsar

Commercial Name of the NDT Instrument: A1220 Monolith, Ultrasonic Pulse Velocity Tester

- Manufacturer's Name: Acoustic Control Systems, ACS
- Main Applications:
  - Suitable for compressive strength evaluation of concrete, estimation of the open crack depth, and evaluation of elastic properties.
- Link to website

Figure 15 Acoustic Control Systems, A1220 Monolith

Commercial Name of the NDT Instrument: UK1401 Surfer, Ultrasonic Pulse Velocity Tester

- Manufacturer's Name: Acoustic Control Systems, ACS
- Main Applications:
  - Evaluation of the depth of the outcrop cracks
  - Evaluation of the durability of concrete
  - Evaluation of the load-carrying ability of concrete backbones and posts.
- Link to website

Figure 16 Acoustic Control Systems, UK1401 Surfer

B.1.3 Ultrasonic Pulse Echo:

Commercial Name of the NDT Instrument: Pundit Ultrasonic Pulse Echo PF8050

- Manufacturer's Name: Proceq, also known as Screening Eagle
- Main Applications:
  - Location of subsurface defects of concrete.
  - Measurement of thickness of concrete elements.
  - Determination of concrete pulse velocity for homogeneity and strength estimation.
- Link to website

Figure 17 Pundit Ultrasonic Pulse Echo PD8050

Commercial Name of the NDT Instrument: A1040 MIRA, Ultrasonic Tomograph

- Manufacturer's Name: Acoustic Control Systems, ACS
- Main Applications:
  - Inspection of concrete constructions up to 2500 mm thickness.
  - Inspection of reinforced concrete constructions up to 800 mm thickness for the purpose of evaluation of consistency of the construction.

- Evaluation of condition of the channels with stressed reinforcement in reinforced concrete bridges.
    - Estimation of the thickness of the concrete cover and depth of coverage reinforcement.
    - Thickness measurement of the testing object at one-sided access.
- Link to website

Figure 18 Acoustic Control Systems, A1040 MIRA

Commercial Name of the NDT Instrument: A1220 Monolith, 3D Ultrasonic Pulse Echo Tester

- Manufacturer's Name: Acoustic Control Systems, ACS
- Main Applications:
    - Thickness measurement of concrete objects up to 3000 mm and reinforced concrete objects up to 600 mm thick.
    - Allows operators to search for internal foreign inclusions, cavities, voids and cracks of reinforced concrete constructions.
- Link to website

Figure 19 Acoustic Control Systems, A1220 Monolith

B.1.4 Impulse Response:

Commercial Name of the NDT Instrument: Freedom Data PC

- Manufacturer's Name: Olson Instruments
- Main Applications:
    - Tests for cracks, deep foundation depths, diameter changes (bulb or necking), soil intrusions, uncured or weak concrete, voids on auger cast, concrete pile bridge abutments, drilled shafts (bored piles), driven concrete piles, and wall piers.
- Link to website

Figure 20 Olson Instruments, Freedom Data PC

Commercial Name of the NDT Instrument: Slab Impulse Response

- Manufacturer's Name: Olson Instruments
- Main Applications:
    - Identifies subgrade voids below slabs-on-grade less than two feet thick.
    - Can be used on other concrete structures to quickly locate areas with delamination or voids in the concrete, if the damage is relatively shallow.
- Link to website

Figure 21 Olson Instruments, Slab Impulse Response

Commercial Name of the NDT Instrument: s'MASH

- Manufacturer's Name: Germann Instruments
- Main Applications:
    - Detecting voids beneath concrete slabs in highways, spillways, and floors
    - Locating delamination and honeycombing in bridge decks, slabs, walls and large structures such as dams, chimney stacks, and silos.
    - Evaluating the integrity of anchoring systems of wall panels.
    - Evaluating the effectiveness of the load transfer system in transmitting forces across joints in concrete structures.
- Link to website

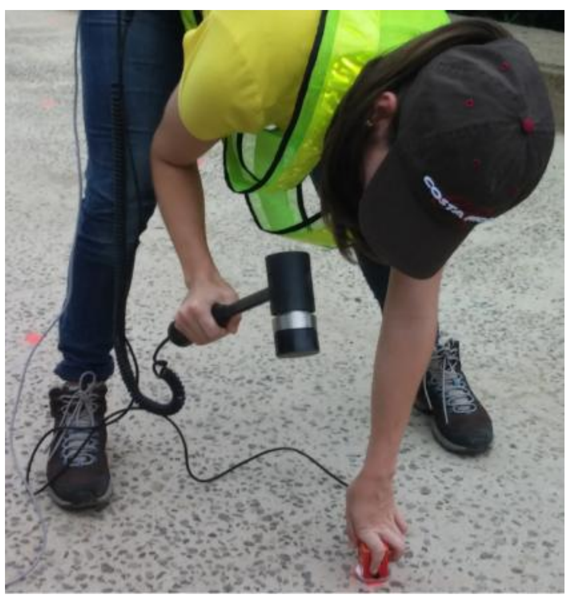

Figure 22 Germann Instruments, s'MASH

B.1.5 Acoustic Emission:

Commercial Name of the NDT Instrument: AMSY-6

- Manufacturer's Name: Vallen Systeme
- Main applications:

- It can be used for non-destructive inspection of small and large-sized structures, such as pressure vessels, pipelines, bridges, storage tanks, and for other components for which the early detection of reduced structural integrity is important.
- It can also be used to detect, measure and locate AE sources such as material failure on a microscopic level, corrosion, leakage, partial discharge, friction and wear as well as particle impact.

- Link to website

Figure 23 Vallen Systeme, AMSY-6

Commercial Name of the NDT Instrument: Sensor Highway III

- Manufacturer's Name: MISTRAS Data Solutions also known as Physical Acoustics Corporation
- Main Applications:
  - Developed for continuous outdoor, Acoustic Emission (AE), Structural Health Monitoring (SHM) and Sensor Fusion applications.
- Link to website

Figure 24 MISTRAS Data Solutions, Sensor Highway III

Commercial Name of the NDT Instrument: Micro-SHM

- Manufacturer's Name: Physical Acoustics Corporation
- Main Applications:
  - Standalone AE system for isolated objects, such as bridge components, pressure vessels, pipelines, slow-speed bearings, and machine monitoring.
- Link to website

Figure 25 Physical Acoustics Corporation, Micro-SHM

B.1.6 Rebound Hammer:

Commercial Name of the NDT Instrument: Silver Schmidt OS8200

- Manufacturer's Name: Proceq, also known as Screening Eagle
- Main applications:
  - Estimation of compressive strength of concrete
  - Mapping of concrete uniformity
  - Estimation of compressive strength of high strength concrete
- Link to website

Figure 26 Proceq, Silver Schmidt OS8200

Commercial Name of the NDT Instrument: Digi-Schmidt Hammer

- Manufacturer's Name: Proceq also known as Screening Eagle
- Main Applications:
  - Non-destructive measurement of the concrete compressive strength and control of the uniform concrete quality (ND type hammer) for use on concrete components of 100 mm thickness or more.
- Link to website

Figure 27 Proceq, Digi-Schmidt Hammer

Commercial Name of the NDT Instrument: Concrete Test Hammer

- Manufacturer's Name: Controls
- Main Applications:
    - The concrete test hammer is used to evaluate strength of hardened concrete in various parts of a built structure.
- Link to website

Figure 28 Controls, Concrete Test Hammer

Commercial Name of the NDT Instrument: Concrete Rebound Hammer

- Manufacturer's Name: Humboldt
- Main Applications:
    - Designed for testing concrete 4" or more in thickness with a max particle size less than or equal to 1.25".
    - Compressive strength range of 1450 to 9000 psi.
- Link to website

Figure 29 Humboldt, Concrete Rebound Hammer

Commercial Name of the NDT Instrument: Digital Rebound Hammer

- Manufacturer’s Name: James Instruments
- Main Applications:
    - For concrete compressive strength analysis in the field and material hardness testing.
- Link to website

Figure 30 James Instruments, Digital Rebound Hammer

Commercial Name of the NDT Instrument: Original Schmidt OS8000

- Manufacturer’s Name: Proceq also known as Screening Eagle
- Main Applications:
    - Estimation of compressive strength of concrete.
    - Mapping concrete uniformity
- Link to website

Figure 31 Proceq, Original Schmidt OS8000

B.2 ELECTROMAGNETIC METHODS

B.2.1 Ground Penetrating Radar:

Commercial Name of the NDT Instrument: Mala ConcreteExplorer / CX System

- Manufacturer's Name: Guideline Geo
- Main applications:
    - 3D and 2D scanning for concrete investigations, reinforcement studies, void detection, civil engineering, infrastructure, construction, military and police investigations.
- Link to website

Figure 32 Guidline Geo, Mala ConcreteExplorer / CX System

Commercial Name of the NDT Instrument: StructureScan Mini XT

- Manufacturer's Name: GSSI
- Main Applications:
    - Locate the position and depth of metallic and non-metallic objects in concrete structures, including rebar, conduit, post-tension cables, pan decking, voids and service utilities.
- Link to website

Figure 33 GSSI, StructureScan Mini XT

Commercial Name of the NDT Instrument: Aladdin

- Manufacturer's Name: IDS GeoRadar
- Main Applications:
  - For examining the internal structure and features, both near the surface and at depth, within concrete and masonry.
- Link to website

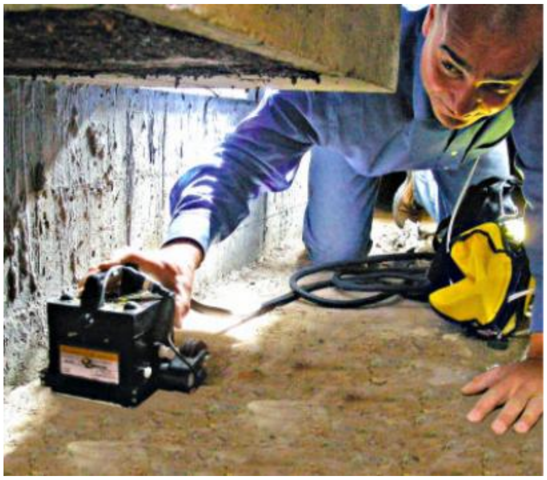

Figure 34 IDS GeoRadar, Aladdin

Commercial Name of the NDT Instrument: GP8800

- Manufacturer's Name: Proceq also known as Screening Eagle
- Main Applications:
  - Concrete inspection and structural monitoring. 25.6 in penetration.
  - Also has Time-Slice view. Pro 3D view, and Augmented Reality (AR).
  - Can be used for irregular and curved surfaces.
  - Can also be used for congested rebar configurations
- Link to website

Figure 35 Proceq, GP8800

Figure 36 Proceq, GP8800

Commercial Name of the NDT Instrument: Mala ConcreteExplorer

- Manufacturer’s Name: Mala
- Main Applications:
    - Condition assessment
    - Inspection of reinforced concrete structures
    - Structure inspection
    - Void detection and location
- Link to website

Figure 37 Mala, ConcreteExplorer

Commercial Name of the NDT Instrument: GP8000

- Manufacturer's Name: Proceq also known as Screening Eagle
- Main Applications:
    - Investigation of pavement and bridge decks
    - Locating rebar and live wires before drilling
    - Concrete quality assessment
- Link to website

Figure 38 Proceq, GP8000

Commercial Name of the NDT Instrument: PS 1000 X-Scan

- Manufacturer's Name: Hilti
- Main Applications:
    - Efficient concrete scanner for structural analysis and to locate embedded objects in multiple layers.
- Link to website

Figure 39 Hilti, PS 1000 X-Scan

Figure 40 Hilti, PS 1000 X-Scan

Commercial Name of the NDT Instrument: PS 300 Ferroscan

- Manufacturer's Name: Hilti
- Main Applications:
    - Concrete detector for rebar localization, depth measurement and size estimation in structural analysis.
- Link to website

Figure 41 Hilti, PS 300 Ferroscan

Figure 42 Hilti, PS 300 Ferroscan

Commercial Name of the NDT Instrument: GP8100

- Manufacturer's Name: Proceq also known as Screening Eagle
- Main Applications:
  - Concrete inspection of large areas in all buildings or bridge decks.
  - GPR data collection for concrete structural assessment and post-processing data.
  - Concrete quality assessment.
- Link to website

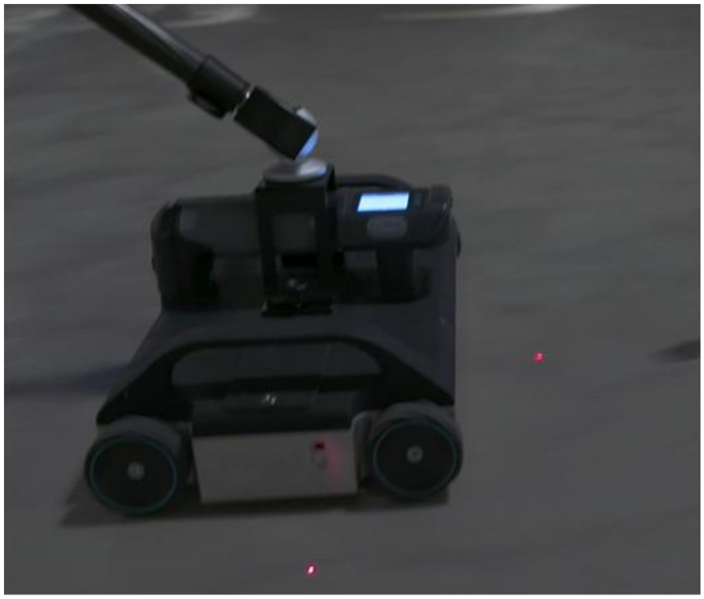

Figure 4343 Proceq, GP8100

Commercial Name of the NDT Instrument: C-thrue

- Manufacturer's Name: IDS GeoRadar
- Main Applications:
  - Device that can locate and identify shallow and deep targets. It has real time data processing and a representation of results in augmented reality.
- Link to website

Figure 44 IDS GeoRadar, C-thrue

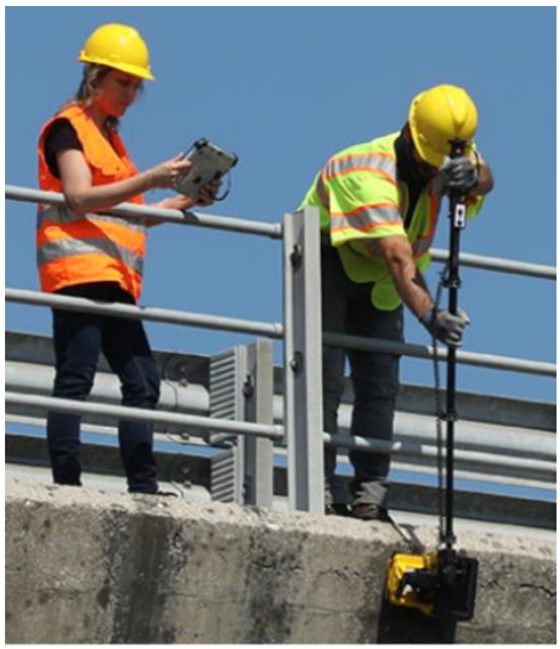

Figure 45 IDS GeoRadar, C-thrue

Commercial Name of the NDT Instrument: C-thrue XS

- Manufacturer's Name: IDS GeoRadar
- Main Applications:
  - Quickly located rebars, voids, post-tension cables, cavities, conduits, and any other object buried in the structure.
- Link to website

Figure 46 IDS GeoRadar, C-thrue XS

B.2.2 Covermeters (Rebar locators):

Commercial Name of the NDT Instrument: Profometer PM8000

- Manufacturer’s Name: Proceq also known as Screening Eagle
- Main applications:
  - Durability and structural resistance assessment of existing concrete structures
  - Rebar location
  - Minimum cover check
- Link to website

Figure 47 Proceq, Profometer PM8000

Commercial Name of the NDT Instrument: PS 250 Ferroscan Detection System

- Manufacturer’s Name: Hilti Oman
- Main Applications:
  - Designed to find and estimate the size of rebar in concrete structures and estimate the depth of concrete cover.
- Link to website

Figure 48 Hilti, PS 250 Ferroscan Detection System

Commercial Name of the NDT Instrument: Concrete Covermeter

- Manufacturer's Name: Elcometer
- Main Applications:
    - Quickly and accurately locates, orientates and measures the depth of cover over reinforcement bars.
- Link to website

Figure 49 Elcometer, Concrete Covermeter

Commercial Name of the NDT Instrument: R-Meter Mk III

- Manufacturer's Name: James Instruments
- Main Applications:
    - Utilizes the latest in eddy current sensing and micro-processor technology to accurately locate determine depth and estimate diameter of metal objects in concrete.
- Link to website

Figure 50 James Instruments, R-Meter Mk III

B.3 ELECTRICAL METHODS

B.3.1 Eddy Current Testing:

Commercial Name of the NDT Instrument: Elcometer 500

- Manufacturer’s Name: Elcometer USA
- Main Applications:
  - Accurately measures the thickness of coatings on concrete and other similar substrates, non-destructively.
- Link to website

Figure 51 Elcometer USA, Elcometer 500

B.3.2 Half-Cell Potential Measurement:

Commercial Name of the NDT Instrument: Profometer PM8500

- Manufacturer's Name: Proceq also known as Screening Eagle
- Main applications:
    - Identifying areas of corrosion in reinforced concrete structures
    - Estimation of corrosion potential of rebars
    - Estimation of concrete durability
    - Investigation of structural failures
    - Evaluation of effectiveness of corrosion repairs
- Link to website:

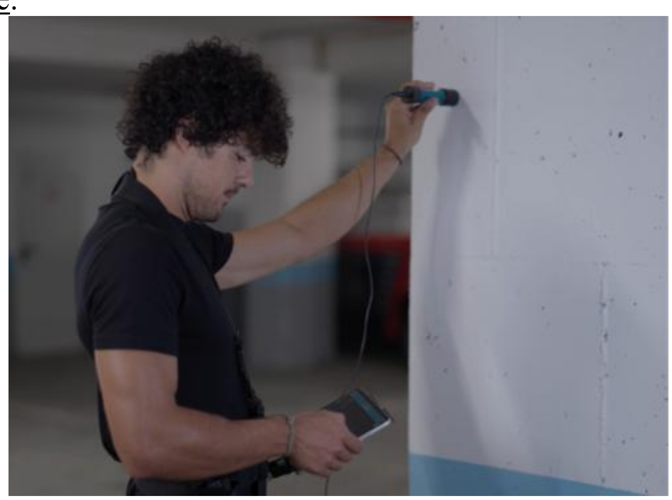

Figure 52 Proceq, Profometer PM8500

Commercial Name of the NDT Instrument: Profometer Corrosion

- Manufacturer's Name: Proceq also known as Screening Eagle
- Main Applications:
    - Advanced half-cell measuring instrument for on-site mapping of the corrosion potential.

- Link to website

Figure 53 Proceq, Profometer Corrosion

Commercial Name of the NDT Instrument: Galvapulse

- Manufacturer's Name: Germann Instruments
- Main Applications:
    - Monitoring corrosion activity in reinforced concrete structures.
    - Service life estimation.
    - Condition surveys of suspect reinforced structures, especially in wet environments where the classic half-cell potential mapping may provide misleading or insufficient information.
    - Measuring corrosion activity in repaired areas.
- Link to website

Figure 54 Germann Instruments, Galvapulse

Commercial Name of the NDT Instrument: XCell

- Manufacturer's Name: Giatec
- Main Applications:
    - Detection of corrosion in reinforcement, measurement of rebar corrosion rate.
    - Evaluation of corrosion potential of rebar.

    - Measurement of in-situ electrical resistivity.
    - Assessment of concrete durability.
    - Rehabilitation and repair of concrete structures.
- Link to website

Figure 55 Giatec, XCell

Commercial Name of the NDT Instrument: GEOCOR 8

- Manufacturer's Name: James Instruments
- Main Applications:
    - Corrosion rate analysis, structural service life analysis, as well as repair cost estimation.
- Link to website

Figure 56 James Instruments, GEOCOR 8

B.3.3 Electrical Resistivity Measurement:

Commercial Name of the NDT Instrument: iCOR

- Manufacturer's Name: Giatec
- Main applications:
    - Detection of corrosion in reinforcement
    - Measurement of rebar corrosion rate
    - Evaluation of corrosion potential of rebar
    - Measurement of in-situ electrical resistivity

    - Assessment of concrete durability
    - Rehabilitation and repair of concrete structures
- Link to website

Figure 57 Giatec, iCOR

Figure 58 Giatec, iCOR

Commercial Name of the NDT Instrument: Resipod

- Manufacturer's Name: Proceq also known as Screening Eagle
- Main Applications:
    - A comprehensive solution for measuring the electrical resistivity of concrete.
- Link to website

Figure 59 Proceq, Resipod

Commercial Name of the NDT Instrument: OhmCorr Test System Resistivity Meter for Concrete

- Manufacturer's Name: James Instruments
- Main Applications:
    - Assesses damaging corrosion currents in concrete.
- Link to website

Figure 60 James Instruments, OhmCorr Test Resistivity Meter for Concrete

B.4 THERMAL AND INFRARED METHODS

B.4.1 Infrared Thermography (IRT):

Commercial Name of the NDT Instrument: Testo 883-2 Kit Thermal Imager

- Manufacturer's Name: Testo
- Main applications:
    - Detects any potential structural defects
    - Preventative maintenance
- Link to website

Figure 61 Testo, Thermal Imager

Commercial Name of the NDT Instrument: Reveal 300

- Manufacturer's Name: Seek Thermal
- Main Applications:
  - With Seek's proprietary SV1 Image Optimization, Reveal 300 provides unmatched clarity and detail in any situation.
- Link to website

Figure 62 Seek Thermal, Reveal 300

Commercial Name of the NDT Instrument: PT-C Thermal Camera

- Manufacturer's Name: Hilti
- Main Applications:
  - Concrete scanner and sensor, but noted more for inspecting electrical, mechanical, piping, and HVAC applications.
- Link to website

Figure 63 Hilti, PT-C Thermal Camera

Commercial Name of the NDT Instrument: ImageIR 6300

- Manufacturer's Name: InfraTec
- Main Applications:
  - Thermal camera with integrated operating system.
- Link to website

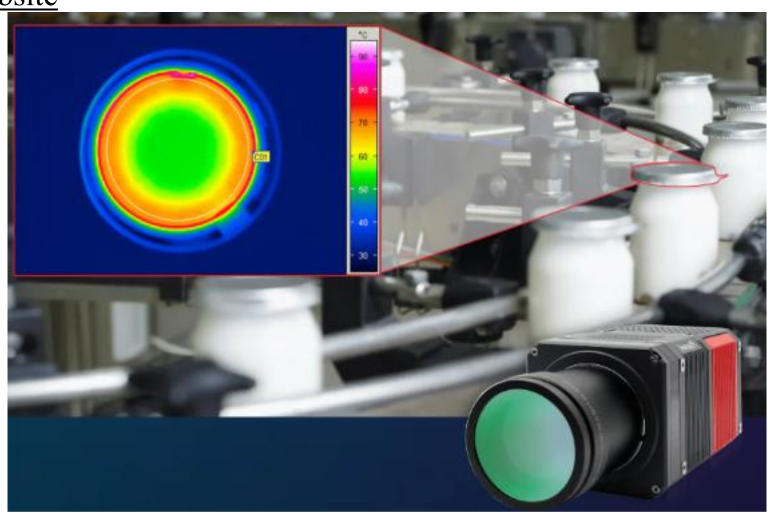

Figure 64 InfraTec, ImageIR 6300

Commercial Name of the NDT Instrument: FLIR Infrared Cameras, E-Series

- Manufacturer's Name: FLIR
- Main Applications:
  - Quickly pinpoint hot spots and easily identify problems with vibrant thermal imagery.
- Link to website

Figure 65 FLIR, E-Series

Commercial Name of the NDT Instrument: FLIR Infrared Cameras, T-Series

- Manufacturer's Name: FLIR
- Main Applications:
    - Comfortably survey equipment both indoors or outdoors and seek out signs of failure all day long.
- Link to website

Figure 66 FLIR, T-Series

Commercial Name of the NDT Instrument: Fluke Infrared Thermal Imagers

- Manufacturer's Name: Fluke
- Main Applications:
    - Offer a large rotating screen so you can comfortably view and inspect hard to reach areas.
- Link to website

Figure 67 Fluke, Fluke Infrared Thermal Imagers

B.5 CHEMICAL AND ELECTROCHEMICAL METHODS (SEMI-DESTRUCTIVE/MINIMALLY INVASIVE)

B.5.1 Carbonation Depth Testing:

Commercial Name of the NDT Instrument: Carbo Detect

- Manufacturer's Name: Humboldt
- Main applications:
  - The reagent will change to pink in uncarbonated concrete and remain colorless when sprayed on carbonated concrete.
- Link to website

Figure 68 Humboldt, Carbo Detect

Commercial Name of the NDT Instrument: Phenolphthalein Solution, 30 mL

- Manufacturer's Name: Home Science Tools
- Main Applications:
  - Indicator in acid-base titrations, component of universal indicator, etc.
- Link to website

Figure 69 Phenolphthalein Solution

Commercial Name of the NDT Instrument: Measur Carbonation Test Set

- Manufacturer's Name: Measur USA
- Main Applications:
    - Determination of carbonation depth of the carbonated layer near the surface of hardened concrete.
    - This is not suitable for concrete made with calcium aluminate cement. The set consists of two 250 mL washing bottles containing distilled water and phenolphthalein solution, and a ruler for depth of carbonation.
- Link to website

Figure 70 Measur USA, Measur Carbonation Test Set

Commercial Name of the NDT Instrument: ASR Detect

- Manufacturer's Name: Humboldt
- Main Applications:
    - By identifying alkali silica deterioration in its earliest stages, the ASR Detect facilitates the problem being identified when remediation techniques can be applied; for example, treating the concrete with a lithium-bearing solution to inhibit further deterioration. Where deterioration is advanced, ASR detect provides a clear picture of the extent and depth of the damage.
- Link to website

Figure 71 Humboldt, ASR Detect

B.5.2 Chloride Content Measurement:

Commercial Name of the NDT Instrument: Profile Grinder

- Manufacturer's Name: Germann Instruments
- Main applications:
  - A high-performance grinding bit (18 mm in diameter) attached to a grinding machine, pulverizes the concrete into a fine powder at exact depth increments.
- Link to website

Figure 72 German Instruments, Profile Grinder

Commercial Name of the NDT Instrument: Chlorimeter

- Manufacturer's Name: James Instruments
- Main Applications:
  - A field test system to determine the chloride ion concentration in wet or dry concrete, and other construction materials.
- Link to website

Figure 73 James Instruments, Chlorimeter

Commercial Name of the NDT Instrument: Rapid Chloride Test Kits, RCT

- Manufacturer's Name: Germann Instruments
- Main Applications:
    - RCT is a portable kit to accurate and immediate determination of chloride ion content in concrete powder samples.
- Link to website

Figure 74 Germann Instruments, Rapid Chloride Test Kits

Commercial Name of the NDT Instrument: Giatec Perma2 Rapid Chloride Permeability

- Manufacturer's Name: Humboldt
- Main Applications:
    - Perma2™ is a laboratory test device for measuring the electrical resistance of concrete against the penetration of chloride (RCPT) according to the standard methods such as ASTM C1202, AASHTO T277 and ASTM C1760.
- Link to website

Figure 75 Humboldt, Giatec Perma2

B.6 VIBRATION-BASED METHODS

B.6.1 Modal Analysis and Dynamic Testing (Vibration Analysis):

Commercial Name of the NDT Instrument: Bruel & Kjaer 2270 Sound Level Meter and Vibration Analyzer

- Manufacturer's Name: Avalon Test Equipment
- Main applications:
    - Handheld vibration and sound measurement device with a dynamic range of over 120 dB and a linear frequency range of 3 Hz to 20 Hz..
    - Applications include frequency analysis, logging or profiling, and signal recording.
- Link to website

Figure 76 Avalon Test Equipment, Bruel & Kjaer 2270 Sound Level Meter and Vibration Analyzer

- Commercial Name of the NDT Instrument: Accelerometers
- Manufacturer's Name: PCB Piezotronics
- Main Applications:

  - Wide Dynamic Measurement Ranges from 1 mcg to 200,000 g.
  - Wide Frequency Response from 0 to 60 kHz.
- Link to website

Figure 77 PCB Piezotronics, Accelerometers

Commercial Name of the NDT Instrument: Dytran 7603B, High Precision Triaxial MEMS Accelerometer

- Manufacturer's Name: A-Tech Instruments
- Main Applications:
  - Triaxial variable capacitance (VC) accelerometer for shock and vibration measurements.
- Link to website

Figure 78 A-Tech Instruments

Commercial Name of the NDT Instrument: Data Acquisition, DAQ

- Manufacturer's Name: National Instruments Corp, NI
- Main Applications:
  - Data acquisition (DAQ) is the process of measuring an electrical or physical phenomenon, such as voltage, current, temperature, pressure, or sound.
- Link to website

Figure 79 National Instruments Corp, DAQ

Commercial Name of the NDT Instrument: mioDAQ USB Data Acquisition Devices

- Manufacturer's Name: National Instruments Corp, NI
- Main Applications:
  - The data acquisition devices capabilities are as follows: measuring: ±10 V signals, sensors that output ±10 V, voltage drops across shunt resistors, battery cell voltages (±10 V peak cell measurement), power rails on USB or battery-powered electronic designs, pulse and event counting, quadrature encoders, resolvers string potentiometers, low-voltage current sensors, as well as low-voltage potential transformers.
- Link to website

Figure 80 National Instruments Corp, mioDAQ

Commercial Name of the NDT Instrument: LMS SCADAS

- Manufacturer's Name: Siemens
- Main Applications:
  - Data acquisition system. Works autonomously as a blind recorder, tablet-operated recorder or a front-end system for a laptop or PC.
- Link to website

Figure 81 Siemens, LMS SCADAS

Commercial Name of the NDT Instrument: SIRIUS R1DB/R2DB Portable Data Acquisition (DAQ) Systems

- Manufacturer's Name: DEWESoft
- Main Applications:
    - o Compact, mobile, and portable data acquisition systems that feature a built-in data logger, powerful data processing computer, multi-touch display, and internal batteries for maximum portability.
- Link to website

Figure 82 DEWESoft, SIRIUS R1DB/R2DB

Commercial Name of the NDT Instrument: CR1000 Measurement and Control Datalogger

- Manufacturer's Name: Campbell Scientific
- Main Applications:
    - o The CR1000 is our most widely used data logger. It can be used in a broad range of measurements and control functions.
    - o Rugged enough for extreme conditions and reliable enough for remote environments, it is also robust enough for complex configurations.
    - o Used in applications all over the world, it will be a powerful core component for your data-acquisition system.
- Link to website

Figure 83 Campbell Scientific, CR1000 Measurement and Control Datalogger

Commercial Name of the NDT Instrument: Electrodynamic Shakers

- Manufacturer’s Name: Unholtz-Dickie Corp.
- Main Applications:
  - The S-Series Vibration Test Systems cover a wide range of force output [300 to 6,000 lbf (1.3 - 26.7 kN)] in support of small to moderately large payloads.
- Link to website

Figure 84 Unholtz-Dickie Corp, Electrodynamic Shakers

Commercial Name of the NDT Instrument: Emerson CSI 2140 Machinery Health Analyzer

- Manufacturer’s Name: Advanced Test Equipment Corp.
- Main Applications:
  - Measures frequency vibrations accurately across a range from 10 Hz to 80 kHz.
- Link to website

Figure 85 Advanced Test Equipment Corp, Emerson CSI 2140 Machinery Health Analyzer

Commercial Name of the NDT Instrument: ARTeMIS Modal

- Manufacturer's Name: Structural Vibration Solutions
- Main Applications:
  - Ambient vibration analysis of large structures like bridges and buildings.
  - Vibration testing software designed for OMA, EMA, ODS and SHM analysis.
- Link to website

Figure 86 Structural Vibration Solutions, ARTeMIS Modal

B.7 FIBER-OPTIC AND STRAIN-BASED TECHNIQUES

B.7.1 Fiber Optic Sensors (FOS) and Distributed Fiber Optic Sensing (DFOS):

Commercial Name of the NDT Instrument: HYPERION Single Board Interrogator

- Manufacturer's Name: Luna Innovations

- Main applications:
    - Structural Health Monitoring in civil engineering and geotechnical structures
    - Structural test and model validation
- Link to website

Figure 87 Luna Innovations, HYPERION Single Board Interrogator

Commercial Name of the NDT Instrument: Distributed Fiber Optic Sensor Analyzers Luna Innovations, ODiSI 7100

- Manufacturer's Name: Luna Innovations
- Main Applications:
    - Characterize strain in new materials and complex structures, profile temperature in-situ to maximize the efficiency of critical processes, measure two- and three-dimensional strain fields to validate FE models, evaluate multi-material joining, detect small cracks and defects in critical structures.
- Link to website

Figure 88 Luna Innovations, ODiSI 7100

Commercial Name of the NDT Instrument: Fiber Bragg Grating, FBG

- Manufacturer's Name: Fibercore
- Main Applications:
    - Used for temperature sensing, strain sensing, hydrophone and geophone acoustic sensing, laser wavelength locking, and wavelength division multiplexing.
- Link to website

Figure 89 Fibercore, Fiber Bragg Grating

Commercial Name of the NDT Instrument: Fiber-Bragg Grating Sensors

- Manufacturer's Name: Micron Optics
- Main Applications:
    - Optical sensors provide an alternative to traditional electrical sensors for many applications, with high accuracy, long term stability, streamlined installation, and premium performance under harsh environmental conditions. These optical sensors offer immunity to EMI and extraordinary resistance to mechanical fatigue.
- Link to website

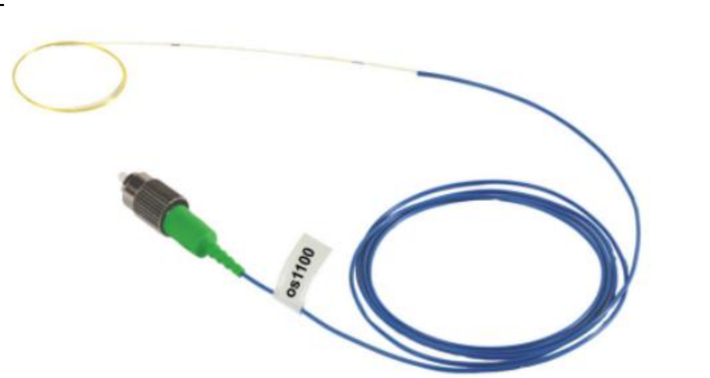

Figure 90 Micron Optics, Fiber-Bragg Grating Sensors

Commercial Name of the NDT Instrument: OEP-C Fiber Optic Extensometer Sensor

- Manufacturer's Name: Opsens Solutions
- Main Applications:
    - Not affected by transverse strain and without drifting over time, the concrete embeddable extensometer is perfectly tailored for permanent monitoring of infrastructure, and provides continuous reliable measurements in almost any conditions.
- Link to website

Figure 91 Opsens Solutions, OEP-C Fiber Optic Extensometer Sensor

B.8 MAGNETIC METHODS

B.8.1 Magnetic Flux Leakage (MFL):

Commercial Name of the NDT Instrument: Schonstedt Magnetic Rebar Locator

- Manufacturer's Name: Exploration Instruments
- Main applications:
    - Accurately locates rebar within concrete structures using a high-resolution sensor.
    - Automatically rejects non-ferrous metals so that rebar is the only thing mapped.
- Link to website

Figure 92 Exploration Instruments, Schonstedt Magnetic Rebar Locator

APPENDIX C. Core Sampling, Test Location Planning, and Grid Design for NDT

This chapter provides an integrated approach to planning and executing nondestructive evaluation (NDE) in concrete structures, including bridges, with emphasis on core sampling, test location selection, and grid mapping strategies. Referencing ACI 228.1R-19, ACI 228.2R-13, EN 13791:2019, ASTM C823, and ASTM E122, it outlines methodologies for determining the number, size, and placement of cores, as well as the spatial distribution and density of test locations based on structural characteristics, material variability, and inspection objectives. It explores the use of preliminary NDT surveys to define test regions, the statistical rationale behind sampling plans, and criteria for establishing lots and sublots. The chapter also highlights practical and technical considerations for grid spacing in various NDT methods such as RH, UPV, GPR, and others, balancing resolution, efficiency, and project constraints to ensure reliable and cost-effective condition assessment and strength estimation.

C.1 CORE SAMPLING SIZE AND LOCATION

Considering ACI 228.1R (ACI Committee 228, 2019) and EN 13791 (EN, 2019), Table 1 summarizes and compares the core sampling size and locations. It compares ACI 228.1R-19 and EN 13791:2019 guidelines for selecting, sizing, and locating cores in new and existing concrete to estimate compressive strength, including core dimensions, sample quantities, and location strategies.

Table 1 Core sampling strategy for concrete strength estimation

Source	New Construction (age ≤ 28 days)	Existing Construction (age > 28 days)	Number of Cores	Location Strategy
ACI 228.1R-19	Lab-cast or cast-in-place cylinders (e.g., ASTM C873)	Cores drilled in situ 100 mm (4 in.) diameter, L/D ≥1.0, preferably 2.0 per ASTM C42	Minimum of two cores per test location; 6–9 test locations recommended for correlation	Select locations of structural importance, cover a range of expected strength, and avoid rebar when possible
EN 13791:2019	Not applicable (standard focuses on existing structures)	Core diameter ≥75 mm (3 in.) preferred; 50–74 mm (2–2.9 in.) allowed with increased sample count. L/D = 2:1 preferred; 1:1 acceptable. Strength standardized to 2:1, ≥75 mm (3 in.) cores	≥8 (≥75 mm (3 in.)) cores or ≥12 (50 mm (2 in.)) cores for standalone strength estimation; ≥3 (≥75 mm (3 in.)) cores if used with NDT (e.g., RH, UPV)	Select representative test regions; avoid reinforcement, prestressing ducts, cracks, and highly stressed zones. Use GPR or covermeters to locate clear core zones

The 6–9 test locations recommended in ACI 228.1R-19 are for building a strength correlation across the structure. ACI 228.1R-19 states that in selecting the core locations, it is desirable to include the widest range of concrete strengths in the structure that is possible. Therefore, these test locations should capture low-, mid-, and high-strength regions. This is achieved by primarily

inspecting the structure by NDT tests such as the RH and UPV. According to ACI 228.2R, a grid of 3 to 5 ft (practical test density) is practically used for selecting test locations for the RH and UPV. Once the correlation is established, it can be applied to different lots or zones, provided the strength level is within the calibrated range.

EN 13791 (Section 8.3) states: "Take at least three ≥75 mm (3 in.) diameter cores, or an equivalent number of smaller diameter cores, from the area around the location(s) with the lowest indirect test result." This means that when using NDT methods (such as RH or UPV) to estimate concrete strength, EN 13791 allows for a limited number of cores to be used for verification, rather than taking many cores over the entire structure. In this case, you are required to take at least three cores from the area around the lowest NDT readings. The requirement in EN 13791 to take cores around the lowest NDT readings is based on a conservative engineering principle, which is to verify the weakest part of the structure because that's where failure is most likely to occur or where the concrete may not meet strength requirements.

ACI 228.1R-19 recommends avoiding reinforcement when selecting core locations, but does not specify particular tools or methods for detecting rebar. EN 13791:2019 explicitly recommends using tools like covermeters or GPR to avoid reinforcement during core location selection. If a core contains significant reinforcement, the strength result may not be valid, and such cores may need to be discarded or supplemented with additional samples.

EN 13791 appears to be more economical but less robust than ACI 228.1R-19 in terms of accuracy, due to the fewer required cores and simpler correlation approaches. Both ACI 228.1R-19 and EN 13791:2019 refer broadly to concrete in the structure and do not prescribe sample collection based on defined 'lots' as in production quality control. EN 13791 introduces the concept of a 'test region,' but leaves its definition to engineering judgment rather than rigid statistical zoning.

C.2 NUMBER OF CORES AND CONFIDENCE LEVEL

The more cores you extract from a zone, the more confident you can be that your estimate of the true average strength is accurate.

Let's say there are 3 cores with strengths of 3000, 3200, and 3400 psi. Calculate "margin of errors" at 95% confidence level.

With core strengths of 3000, 3200, and 3400 psi, the results are:

- Number of cores: n=3
- Mean strength: 3200 psi
- Standard deviation: s=200 psi
- Degree of freedom: df=n-1=3-1=2
- t-value for 95% confidence and 2 degrees of freedom: $t_{0.025,2}=4.303$
- Margin of error (95% confidence):

$$Margin\ of\ Error = t \times \frac{s}{\sqrt{n}} = \pm 496.8\ psi$$

Interpretation:

We can say with 95% confidence the true average compressive strength of the concrete lies between 2703 psi and 3697 psi.

C.3 LOT, TEST LOCATIONS, GRID MAPPING, AND GRID SPACING (ACI COMMITTEE 228, 2013, 2019; EN, 2019)

A lot is a defined area or volume of concrete selected for evaluation, which is assumed to be statistically uniform and influenced by a single source of variability in material properties or construction conditions. It can be a full structural component (like an entire pier, beam, or abutment) or a subdivision of one, depending on observed or suspected variability. It is the basic unit used in planning and executing a sampling strategy, especially for statistical analysis.

If test results (e.g., NDT or core strengths) reveal that the concrete within a lot is not statistically uniform, then the lot should be subdivided into multiple lots for separate analysis. The lot is primarily identified using Table 2.

Table 2 The process to identify a lot

Step	Action	Purpose
1. Review Construction Records	Examine drawings, pour schedules, mix designs, and repair logs	Identify areas cast or repaired under similar conditions
2. Visual Inspection	Look for signs of differences in texture, cracking, staining, repair patches, surface finishes, or construction joints	Spot obvious zones of potential variability
3. Evaluate Exposure Conditions	Check whether parts of the structure are exposed to different environments (e.g., wet vs dry, sun vs shade)	Different exposure = potential strength or condition difference
4. Consider Structural Function and Geometry	Divide by logical segments (e.g., midspan vs. beam-end, pier base vs top)	Geometry or loading may affect quality or durability
5. Preliminary NDT Survey (Optional)	Use RH, UPV, or GPR to scan selected points	Detect hidden inconsistencies in material uniformity
6. Define Lot Boundaries	Based on above steps, group regions into zones expected to behave uniformly	Each lot is now ready for formal NDT/core sampling
7. Reevaluate After Testing	If test results show large variability, split lot into multiple strength levels or smaller sub-lots	Ensure statistical reliability and valid interpretations

A test location is a region where an in-place test is performed. The number of test locations is the minimum number required to ensure statistical validity. Test locations are distributed throughout a lot to provide representative data. Table 3 shows examples of a test location.

Table 3 Examples of test locations

Method Type	Test Location Format
Point-based (e.g., RH, UPV)	A small area where multiple readings are taken and averaged
Line-based (e.g., GPR, SASW)	A scan line or path where the device collects continuous data
Area-based (e.g., IRT)	A thermal or visual image of a defined surface zone

Grid Mapping (Lines + Area Survey) is commonly used for methods like GPR and Covermeter surveys, where measurements are taken continuously along lines or densely at intersections. The grid allows you to reference the position (X, Y coordinates) of the measurements across the surface.

Grid Spacing or Test Density (Point-by-Point Measurements) is typically used for RH, UPV, and HCP, where measurements are taken point-by-point at discrete locations. The emphasis is on how far apart the points are, not scanning along continuous lines. The grid paper shown in Figure 8.1 is used to guide GPR scanning paths. If the grid paper is thin, non-coated (plain paper), and placed flatly on the surface, it usually does not affect results. Some inspectors use chalk lines, masking tape, or thin plastic sheets as alternatives.

Figure 1 Grid paper for GPR mapping and data collection

C.3.1 Number of Test Locations

According to Section 4.2.1 in ACI 228.2R-13, "Because of the variety of situations that may be encountered, it is difficult to define a sampling scheme that would be applicable to all NDT methods and all investigations. Global techniques, such as infrared thermography (IRT), can be used to inspect the entire exposed surface of a structure. Other scanning techniques, such as GPR, can provide complete inspection along each scan line. Point-by-point tests, such as impact-echo (IE), provide information at the test point. Other methods, such as impulse-response (IR), can provide information about an entire structural element. ASTM C823 can be adapted to provide some guidance on planning the sampling program. Sampling situations can be assigned to two categories:

1. Where preliminary investigation and other information indicate that conditions are similar throughout the structure. Sampling locations should be distributed randomly or systematically over the region of interest.

2. Where preliminary investigation and other information indicate that conditions are not similar throughout the structure, the structure is divided into portions within which conditions are similar. Each portion that appears to be of similar condition should be sampled independently and treated as a different category, unless and until test results reveal no significant differences.

ACI 228.2R-13 refers to ASTM E122 for two-stage sampling as follows.

- First Stage (Pilot Sampling):
  - Perform an initial sampling with 50–70% (based on engineering practice) of the full planned sample size.
  - If no prior information is available (like defect rate or variability), use at least 30 locations as a rough minimum.
  - Purpose: Quickly estimate variability (like standard deviation or defect proportion) in the real structure.
- Second Stage (Adjust Final Sample Size):
  - Based on the pilot sample results (how variable or defective the concrete is), recalculate the final required number of test points using statistical formulas (like the one from ASTM E122).
  - Then either increase or reduce the total number of locations depending on actual measured variability.

The following example clarifies the above two stages.

<u>Step 1:</u> Assume "worst case" variability.

- Assume 50% defective ($p_o = 0.5$) because this gives the largest required sample size (most conservative). The maximum of $P_0(1\text{-}P_0)$ is mathematically obtained by P_0=0.5. Fraction Defective (p_0) is the estimated proportion of defective units (nonconforming areas) in the lot you are inspecting. For instance, if you think about 30% of the tested areas may have defects, then p_0= 0.30
- Assume acceptable error (E) you are willing to tolerate, for example:
  - ±5% error → E = 0.05
  - ±10% error → E = 0.10
- Choose risk level (confidence):
  - 90% confidence → k ≈ 1.645
  - 95% confidence → k ≈ 1.960

<u>Step 2:</u> Use the formula below from ASTM E122:

$$n = \frac{k^2 \times p_0(1 - p_0)}{E^2}$$

where:

- n = estimated total sample size
- k = statistical factor (from confidence)
- p_0 = assumed fraction defective (usually 0.5 worst case)
- E = acceptable margin of error

Example Calculation:

Suppose you want:

- 95% confidence (k = 1.960)
- ±10% margin of error (E = 0.10)
- Assume worst-case defect rate (p_0 = 0.5)

Then:

$$n = \frac{(1.960)^2 \times 0.5 \times (1 - 0.5)}{(0.10)^2} = \frac{3.8416 \times 0.25}{0.01} = \frac{0.9604}{0.01} = 96\ locations$$

Full estimated sample size = 96 locations.

Step 3: Do a Pilot Test using ~50–70% of that size.

- 50% of 96 ≈ 48 locations
- 70% of 96 ≈ 67 locations

So, you would initially test about 48–67 locations, then use the real results to adjust if needed.

Step 4: Analyze the Pilot Test Results

After testing 50–70% of the initially estimated locations:

- Calculate actual field data:
  - Observed defect rate (for p_0 update).
  - Standard deviation if measuring a continuous property (like pulse velocity, resistivity, etc.).
- See if the field variability is better or worse than you assumed in Step 1

Step 5: Recalculate Final Required Sample Size

Now, use the actual field values to re-apply the ASTM E122 formula:

$$n = \frac{k^2 \times p_0(1 - p_0)}{E^2}$$

But this time:

- Use the *observed* p_0 instead of assuming 0.5.
- Keep the same k (confidence level) and E (error margin) unless you decide to adjust.

Example:

Suppose pilot testing showed only 20% defective (p_0 = 0.2). Then:

$$n = \frac{(1.960)^2 \times 0.2 \times 0.8}{(0.10)^2} = \frac{3.8416 \times 0.16}{0.01} = \frac{0.614656}{0.01} = 61\ locations$$

New total sample size = 61 locations, not 96 anymore.

<u>Step 6:</u> Decide: Stop, Continue, or Expand Testing

- If the pilot sample size already covers the new required sample size, stop sampling.
- If not, continue testing more locations to reach the new required sample size.
- If variability is high ($p_0 > 0.5$), you might even need to expand testing, such as zone-by-zone sampling.

According to Table 3 in EN 1379-19 (EN, 2019):

> "A regularly spaced RH survey will show variations in concrete surface hardness over the structure and identify parts of the test region where cores should be taken or further investigations undertaken."
>
> "A regularly spaced UPV survey will show variations in concrete density over the structure and identify parts of the test region where cores should be taken or further investigations undertaken."

Therefore, there is no fixed grid spacing (like 1 m × 1 m) recommended anywhere in EN 13791. Grid mapping is recommended for RH and UPV surveys, but specific spacing must be decided by the investigator based on project needs.

C.3.2 Grid Mapping and Spacing

If there is no obvious zoning (damage, construction change, etc.), then ACI 228.2R-13 (ACI Committee 228, 2013) recommends using a uniform grid. Two main methods are recommended by ACI 228.2R-13 as summarized in Table 4.

Table 4 The main methods recommended by ACI 228.2R-13

Method	Description
Systematic Grid Sampling	Lay a uniform grid over the lot or structure and pick evenly spaced locations (example: every 2 ft, 3 ft, etc.). Particularly recommended when the concrete condition is relatively uniform.
Zoning and Stratified Sampling	Divide the structure into zones (based on visible differences like damage, exposure, casting sequences) and sample separately in each zone to ensure each area's behavior is captured.

ACI 228.1R-19 provides some recommendations for existing construction (above 28 days age) using RH and UPV. When evaluating existing structures, the sampling strategy depends first on whether the concrete is uniform or non-uniform (through construction records, age, repairs, and visual inspection):

- If the concrete is believed to be uniform, random sampling should be spread across the entire structure and results analyzed together.
- If different compositions or qualities of concrete are suspected, separate sections should be tested and evaluated independently *(Section 6.2.2, p. 31)*.

For in-place NDT testing using RH or UPV, ACI 228.1R-19 specifies the minimum number of replicate measurements needed at each test location to obtain a representative average:

- Rebound number: 10 readings per location
- UPV: 5 readings per location
- Penetration resistance: 3 to 6 readings per location
- Pullout tests: 3 readings per location *(Section 6.2.3, p. 31–32)*

The number of total test locations is not fixed but depends on three statistical factors:

- The variability of the concrete strength,
- The acceptable error between the sample average and the true average,
- The acceptable risk that the error will be exceeded *(Section 6.2.3, p. 32)*

Additional specific geometric requirements are also provided for RH testing:

- Minimum thickness of member: 100 mm (4 in.)
- Minimum test area diameter: 300 mm (12 in.)
- Minimum distance between adjacent test points: 25 mm (1 in.) *(Table for Rebound Number Requirements, based on ACI 228.1R-19 guidance.)*

Table 4.2.2.2 in ACI 228.2R-13 provides "Ideal test density" and "practical Test density" for some NDT methods. The test density is the spacing or grid interval between individual test points.

Ideal test density is applied when very high resolution is required. This involves a smaller grid size, resulting in more data points, which enhances the ability to detect and accurately localize defects.

Practical test density, on the other hand, recognizes that not every minor anomaly needs to be detected. It uses a larger grid size, which reduces the number of data points collected. While this approach provides only a general overview of the structure's condition, it offers significant advantages regarding reduced time and cost. Table 5 presents the testing frequency for selected representative NDT methods, as specified in ACI 228.2R-13 (original Table 4.2.2.2).

Table 5 Frequency of testing for some representative NDT methods (ACI Committee 228, 2013)

Test method	Ideal test density	Practical test density	Remarks
Through-transmission pulse velocity	1 to 2 ft (0.3 to 0.6 m) grid	3 to 5 ft (1 to 1.5 m) grid	Typical spacing to check for concrete density and honeycombing
Rebound hammer (one side of wall or slab)	1 to 2 ft (0.3 to 0.6 m) grid	3 to 5 ft (1 to 1.5 m) grid	Spacing used to assess fire-damaged walls
Impulse-response	1 to 2 ft (0.3 to 0.6 m) grid	3 to 10 ft (1 to 3 m) grid	Typical spacing used in assessment of chimney stacks, cooling towers, and silos

C.3.3 Key Parameters Influencing Grid Spacing in NDT Mapping of Concrete Structures

When planning nondestructive testing (NDT) surveys for concrete structures, the selection of an appropriate grid spacing is critical to balancing detection accuracy, inspection efficiency, and practicality. Grid spacing directly affects the resolution of defect detection, data interpretation reliability, and cost-effectiveness of the inspection process. Table 6 summarizes the key factors influencing grid spacing decisions in typical NDT applications.

Table 6 Key parameters affecting grid spacing in NDT mapping

Category	Parameter	Effect on Grid Spacing
1. Inspection Objective	• Type of defect (e.g., voids, corrosion) • Resolution needed (detailed vs. broad scan)	Tighter spacing (e.g., 0.2–0.3 m) is recommended for detecting small or localized defects. Coarser spacing (e.g., 0.5–1.0 m) may be suitable for identifying general trends or homogeneous conditions.
2. NDT Method Used	• Spatial resolution capability • Penetration depth • Imaging approach (2D vs. 3D)	High-resolution techniques such as GPR, MIRA, and IE require denser grids for accuracy. Methods with lower spatial sensitivity, such as HCP and surface resistivity, can tolerate wider spacing.
3. Structure Type & Size	• Geometry and dimensions of the component (e.g., pier, beam end, deck, wall) • Surface accessibility	Smaller or more complex elements often demand finer grids to ensure adequate coverage. Larger, more uniform areas may permit increased grid spacing.
4. Defect Severity / Risk	• Known or suspected problem zones • Visual indicators of distress (e.g., cracks, rust staining)	Grid spacing should be reduced in areas of known or suspected distress to enhance defect resolution and ensure reliable data.
5. Access and Surface Conditions	• Surface roughness and uniformity • Presence of obstacles (rebar, grout, coatings)	Irregular, obstructed, or heavily reinforced surfaces may necessitate non-uniform or tighter spacing to avoid data gaps.
6. Statistical Requirements	• Required number of data points • Variability of measured data and confidence level needed	Statistical principles (e.g., per ASTM E122, EN 13791) may dictate minimum test counts, thereby influencing grid density and spacing.
7. Equipment Capabilities	• Sensor footprint or array width • Scanning mode (manual, robotic, continuous)	Large sensor arrays and robotic systems may enable wider spacing while maintaining adequate coverage and data density.
8. Time and Budget Constraints	• Fieldwork duration and personnel availability • Project budget limitations	Practical constraints may require a balance between ideal test spacing and feasible grid sizes, typically leading to adoption of "practical" grid spacing guidelines.

Manufacturers often provide recommended grid spacing in their manuals or technical notes to guide users in selecting an appropriate balance between:

- Resolution / Accuracy (defect detection sensitivity)
- Testing speed and efficiency (time and cost)

This recommendation ensures that the NDT instrument is used optimally, providing reliable results while being practical for field use. It is concluded that grid spacing in NDT is not fixed because it must be adapted to various factors, including the type and size of defects targeted, the resolution capabilities of the instrument, the geometry and accessibility of the structure, and practical field considerations such as time and budget. While manufacturers and standards provide recommended ranges or guidelines, inspectors must adjust grid spacing based on the inspection objectives and site conditions to ensure adequate defect detection without unnecessary effort or cost.

Appendices References

ACI Committee 228. (2013). *Report on nondestructive test methods for evaluation of concrete in structures* (ACI-228.2R-13). American Concrete Institute.

ACI Committee 228. (2019). *Report on methods for estimating in-place concrete strength* (ACI-228.1R-19). American Concrete Institute.

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About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at docs.lib.purdue.edu/jtrp/.

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