Condition Assessment of Civil/Structural Assets in Gas Stations: Integrating Non-Destructive Testing with Code-Conformance Audits

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Abstract

The condition assessment of civil and structural assets in gas stations is essential for ensuring operational safety, environmental protection, and long-term infrastructure sustainability. This study presents an integrated framework that combines non-destructive testing (NDT) techniques with code-conformance audits to provide a comprehensive evaluation of gas station structures, including canopies, pavements, retaining walls, and underground storage systems. Conventional visual inspection methods often fail to detect subsurface deterioration or early-stage material degradation, leading to underestimated risks and reactive maintenance. The incorporation of advanced NDT methods—such as ultrasonic pulse velocity (UPV), ground-penetrating radar (GPR), infrared thermography (IRT), and corrosion potential testing—enhances diagnostic accuracy by identifying internal defects and quantifying their severity.

By aligning empirical NDT data with regulatory benchmarks defined in ACI, ASTM, and API standards, this approach bridges the gap between structural health monitoring and code compliance. The study develops a workflow that integrates field data acquisition, defect mapping, risk-based ranking, and lifecycle-based maintenance prioritization. Findings demonstrate that the combined application of NDT and code auditing enables evidence-based decision-making, reduces maintenance costs, and strengthens regulatory accountability. Furthermore, the discussion explores the economic and sustainability benefits of implementing digital asset management tools, including structural health monitoring systems and digital twins, for predictive maintenance and continuous compliance verification.

The research concludes that integrating NDT with code-conformance audits represents a sustainable, cost-effective, and data-driven strategy for managing gas station infrastructure. It supports a transition from reactive to proactive asset management, ensuring structural reliability, safety, and environmental stewardship throughout the lifecycle of petroleum facilities.

Keywords: *Non-Destructive Testing (NDT); Code-Conformance Audit; Structural Integrity; Gas Station Infrastructure; Predictive Maintenance.*

I. INTRODUCTION

➤ *Background and Importance of Civil/Structural Integrity in Gas Stations*

Civil and structural integrity underpins safety, reliability, and environmental stewardship in fuel-retail facilities. Gas stations combine heavily trafficked pavements, load-bearing canopies, dispenser islands, and foundations that are repeatedly subjected to dynamic vehicular loads, vibration, weathering, and chemical exposure. In such contexts, latent deterioration—cracking, delamination, corrosion of reinforcement, section loss in steel elements, joint failures, and settlement—can progress unnoticed until it compromises structural capacity or serviceability, elevating risks of collapse, service disruption, and secondary hazards (Farrar & Worden, 2007). Because many defects are sub-surface or inaccessible, rigorous condition assessment necessarily relies on nondestructive testing (NDT) to reveal internal flaws and material degradation without interrupting operations (McCann & Forde, 2001).

Figure 1 shows a civil or structural engineer wearing a hard hat and inspecting a set of structural blueprints at a modern gas station. The background highlights the canopy, fuel dispensers, and reinforced concrete foundation, representing key structural elements of the facility. This visual emphasizes the importance of evaluating load-bearing structures, material durability, and corrosion prevention to ensure operational safety. Regular civil integrity assessments are vital to prevent subsidence, leaks, and structural failures in fuel stations. The image underscores the engineer’s role in maintaining compliance with safety and environmental standards through meticulous planning and inspection.

Fig 1 Assessing Civil and Structural Integrity in Gas Station Infrastructure

For concrete and composite elements typical of dispenser islands, foundations, and slab-on-grade systems, NDT methods such as impact-echo, ultrasonic pulse velocity, infrared thermography, and ground-penetrating radar enable detection of voids, delaminations, and moisture-related anomalies that are otherwise invisible to visual survey (McCann & Forde, 2001; Yehia et al., 2007; Maduabuchi et al., 2023). In parallel, corrosion-focused diagnostics (e.g., half-cell potential, polarization resistance, and complementary resistivity indicators) provide actionable insight into reinforcement corrosion activity and its spatial variability, supporting early intervention before loss of cross-section or bond threatens capacity (Andrade & Alonso, 2001). When interpreted within a structured structural-health-monitoring perspective, periodic NDT campaigns create data baselines and trend histories that sharpen prognostics, inform maintenance prioritization, and sustain lifecycle performance (Farrar & Worden, 2007; Onuh et al., 2024).

Maintaining robust civil/structural performance in gas stations also has public-health and environmental implications. Failures of slabs, sumps, or foundations can exacerbate pathways for product migration, while compromised canopies or frames can pose acute life-safety hazards in high-wind or impact events. Moreover, the broader station environment is already a potential source of hydrocarbon exposure; therefore, preventing integrity-related incidents that could intensify releases or hinder containment adds a critical layer of risk reduction (Hilpert et al., 2015). In sum, integrating NDT-driven diagnostics into routine condition assessments is central to safeguarding structural reliability, minimizing downtime, and aligning operational safety with environmental protection across the facility lifecycle (McCann & Forde, 2001; Yehia et al., 2007; Andrade & Alonso, 2001; Farrar & Worden, 2007; Hilpert et al., 2015).

- *Scope and Objectives of Condition Assessment Studies*

The scope of condition assessment in gas station infrastructure encompasses the systematic evaluation of civil and structural elements to determine their current performance, safety, and conformity with applicable codes and standards. This process involves assessing the structural soundness of key components such as the canopy framing, dispenser islands, retaining walls, pavements, drainage systems, and foundations that support daily operations. A comprehensive assessment integrates field inspections, material property evaluation, and defect diagnostics to identify degradation mechanisms such as corrosion, cracking, settlement, and fatigue.

The objectives of such studies are multidimensional. Primarily, they aim to ensure structural reliability and public safety by detecting early signs of deterioration before they escalate into critical failures. They also facilitate data-driven maintenance planning by establishing performance benchmarks and identifying priority areas for rehabilitation. In the context of regulatory compliance, condition assessments help verify adherence to local building codes, occupational safety regulations, and environmental protection requirements governing petroleum facilities.

Furthermore, these assessments contribute to extending asset life and optimizing lifecycle costs by providing actionable insights that guide preventive maintenance and structural retrofitting strategies. By integrating non-destructive testing methods with code-conformance audits, engineers can bridge the gap between diagnostic precision and compliance verification. The ultimate goal is to establish a sustainable infrastructure management framework that promotes reliability, reduces environmental risks, and aligns with industry standards for resilience and operational continuity.

- *Common Structural Components in Gas Stations (Canopies, Underground Tanks, Pavement, Foundations)*

Gas station infrastructures consist of several interconnected civil and structural components that collectively ensure operational safety, durability, and service continuity. The canopy structure is one of the most visible elements, designed to protect dispensing areas and customers from environmental exposure while supporting lighting and signage systems. These canopies typically comprise steel or reinforced concrete frames, which are exposed to cyclic wind loads, vehicular-induced vibrations, and thermal stresses. Fatigue, corrosion, and joint deterioration are common issues that affect canopy stability and service life, particularly in humid or coastal environments where steel oxidation is accelerated (Chaves & Sousa, 2013). Regular structural assessments, including weld inspections and bolt tension verification, are essential to prevent progressive deformation and collapse.

Beneath the surface, underground storage tanks (USTs) represent another critical structural component that demands careful condition monitoring. These tanks—constructed from steel or fiberglass-reinforced plastic—store petroleum products and are susceptible to corrosion, settlement-induced cracking, and leakage due to hydrostatic pressure fluctuations and soil movement (Beller, 2007). Leakage from UST systems can lead to environmental contamination, necessitating both structural integrity testing and compliance with containment standards. Similarly, the pavement system—often comprising asphalt or reinforced concrete—endures high cyclic loads from vehicles and fuel deliveries. Pavement distress such as rutting, cracking, or surface spalling may indicate subgrade weakness or water ingress that can compromise safety and drainage efficiency (Huang, 2004; Idoko et al., 2024).

The foundations of dispenser islands, columns, and canopies form the load-transferring backbone of the facility. These structural elements must resist not only static loads but also dynamic and impact forces associated with vehicular operations. Differential settlement or reinforcement corrosion in these foundations can lead to uneven load distribution and long-term structural instability (Neville, 2011). Proper drainage and moisture control are crucial to preserving foundation integrity, particularly in regions with expansive soils or fluctuating groundwater levels. When combined, these civil and structural components constitute an integrated system that requires periodic assessment and maintenance. Holistic evaluation using nondestructive testing and code-conformance auditing ensures that all components—visible and hidden—continue to meet safety, performance, and regulatory expectations throughout the station's lifecycle (Chaves & Sousa, 2013; Beller, 2007; Huang, 2004; Neville, 2011; Xu & Wang, 2018).

- *Challenges in Conventional Inspection Methods*

Traditional inspection methods for assessing civil and structural components in gas stations rely heavily on visual examination, manual measurements, and destructive sampling, which present several limitations. Visual inspections, although simple and low-cost, often fail to detect subsurface or early-stage deterioration such as microcracking, delamination, and internal corrosion that occur within reinforced concrete or steel members. These latent defects can progress unnoticed, leading to structural degradation and potential safety hazards over time (Harris et al., 2012). The reliance on human perception and subjective judgment also introduces inconsistencies and errors, particularly when inspections are conducted under poor lighting, adverse weather, or limited accessibility conditions.

Another key challenge lies in the disruption caused by conventional destructive testing methods. Core sampling, load testing, and material extraction not only damage the structure but can also interrupt normal operations and compromise service continuity, especially in high-traffic fuel stations (Bungey et al., 2006). These methods are time-consuming and cost-intensive, limiting their practicality for large-scale or periodic assessments. Furthermore, variations in inspector experience, interpretation, and documentation standards reduce the repeatability and comparability of results across inspection cycles, hindering the establishment of reliable performance baselines.

Conventional inspections are also constrained by limited data integration and analytical support. The absence of digital tools for data storage, visualization, and trend analysis restricts the ability to monitor structural health over time or correlate physical observations with material degradation mechanisms (Farrar & Worden, 2007). As gas stations evolve to include more complex infrastructures—such as canopies with integrated solar systems and reinforced composite pavements—traditional methods alone are insufficient to ensure comprehensive, predictive, and cost-efficient condition assessment. Therefore, transitioning to an integrated approach that combines non-destructive testing, digital diagnostics, and code-conformance auditing is essential for enhancing accuracy, reliability, and regulatory compliance.

➢ *Rationale for Integrating Non-Destructive Testing with Code-Conformance Audits*

Integrating non-destructive testing (NDT) into the condition assessment process complements conventional code-conformance audits by adding a diagnostic dimension that reveals latent structural and material deficiencies invisible to standard visual checks. While code audits verify whether existing elements conform to design and regulatory requirements, they frequently rely on documented drawings, surface observations, and prescriptive checks of geometry, reinforcement detailing, and material zones. Many forms of deterioration—microcracking, delamination, internal voids, subsurface corrosion—remain undetected until they manifest conspicuously. NDT methods, such as ultrasonic pulse velocity, thermography, impact-echo, and resistivity mapping, can detect internal defects, quantify severity, and localize damage zones without damaging the asset (McCann & Forde, 2001; Sharma, 2023).

The synergistic benefit is that NDT findings can validate or challenge assumptions made in code-conformance audits, flagging instances where in-situ conditions diverge from design intent or code-prescribed tolerances. For example, reinforcement corrosion discovered via half-cell potential mapping or polarization resistance surveys can trigger re-evaluation of cover depths or concrete quality relative to code minimums. Similarly, detected delaminations and voids in slabs or canopy decks can inform whether existing structural elements meet serviceability limits or require strengthening to align with load factors specified by relevant standards. By combining NDT diagnostics with audit outcomes, engineers gain a more holistic understanding of both *as-designed* and *as-built / as-operated* performance.

Furthermore, employing NDT enables a more risk-based approach to maintenance planning and prioritization. Damage indices or severity metrics derived from NDT data can be cross-referenced against code thresholds to classify nonconformities into actionable categories. This alignment allows interventions to be prioritized based on a hierarchy of structural safety, regulatory compliance, and operational continuity. Because many defects evolve gradually, periodic integrated assessments promote trend-based diagnostics and proactive maintenance before code violations or structural hazards reach critical levels. In the long view, this integration supports asset longevity, cost-efficiency, and regulatory assurance.

II. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

➢ *Overview of Asset Condition Assessment Methodologies in Petroleum Facilities*

Asset condition assessment in petroleum facilities serves as a structured process to evaluate the physical integrity, reliability, and compliance of infrastructure components over their service life. These facilities, including gas stations, refineries, and fuel depots, consist of civil, structural, and mechanical systems that operate under harsh environmental and loading conditions. The primary aim of condition assessment methodologies is to determine the current health state of these assets, identify defects, and recommend maintenance or rehabilitation strategies that align with safety and operational objectives (Halfawy & Froese, 2007; Maduabuchi et al., 2023). The process typically integrates field data collection, visual inspections, and analytical modeling to quantify deterioration levels and predict remaining service life.

Traditional approaches to condition assessment rely heavily on deterministic models and visual inspection data. However, such methods are often limited by subjectivity and incomplete representation of the structural condition, especially in concealed or buried components such as underground tanks and foundations. Recent methodologies incorporate performance-based and probabilistic frameworks that account for uncertainty in material degradation, loading history, and environmental exposure (Frangopol, 2011). These models enable asset managers to move from reactive maintenance to predictive and risk-based decision-making.

In petroleum infrastructure, where structural reliability and environmental safety are paramount, advanced tools such as structural health monitoring (SHM) systems and non-destructive testing (NDT) techniques have become integral to condition assessment. SHM frameworks employ sensors and data analytics to provide continuous feedback on stress, vibration, corrosion, and deformation parameters (Farrar & Worden, 2007). When combined with established inspection codes and maintenance management systems, these methodologies form a comprehensive asset integrity management approach that ensures compliance, safety, and sustainability. Ultimately, adopting integrated assessment methodologies helps reduce maintenance costs, mitigate catastrophic failures, and extend asset longevity within the petroleum sector (Farrar & Worden, 2007; Frangopol, 2011; Halfawy & Froese, 2007).

Table 1 Overview of Asset Condition Assessment Methodologies in Petroleum Facilities

Aspect	Description	Key Points / Highlights	Scholarly References
Purpose of Condition Assessment	Evaluates the physical integrity, reliability, and safety of petroleum infrastructure assets.	Ensures operational efficiency, identifies defects early, and supports maintenance planning.	Halfawy & Froese (2007)
Traditional Methods	Based on deterministic models and visual inspections.	Limited by subjectivity; cannot detect hidden defects or subsurface deterioration effectively.	Frangopol (2011)
Modern Approaches	Incorporate performance-based and probabilistic frameworks.	Enable predictive and risk-based decision-making using quantitative data.	Frangopol (2011)
Use of Advanced Technologies	Employ Structural Health Monitoring (SHM) and Non-Destructive Testing (NDT).	Provides continuous data on stress, corrosion, and deformation for proactive maintenance.	Farrar & Worden (2007)
Integration and Management	Links inspection, monitoring, and maintenance through data-driven systems.	Enhances safety, regulatory compliance, and lifecycle optimization of petroleum assets.	Halfawy & Froese (2007); Farrar & Worden (2007)
Overall Benefit	Establishes a sustainable and efficient asset integrity management framework.	Reduces costs, prevents failures, and extends asset lifespan.	All references

- *Review of Key Non-Destructive Testing Techniques (Ultrasonic, GPR, Infrared Thermography, Rebound Hammer, etc.)*

Non-destructive testing (NDT) techniques have become essential tools for assessing the integrity and durability of civil and structural assets in petroleum facilities, offering reliable means to detect defects without impairing service functionality. Among the most widely used methods, ultrasonic pulse velocity (UPV) testing plays a critical role in evaluating concrete quality, identifying cracks, voids, and internal discontinuities. The technique measures wave propagation through the material, where reduced velocity often indicates microstructural degradation, loss of density, or the presence of voids (Popovics, 1998). Due to its sensitivity to material stiffness and homogeneity, UPV has proven particularly useful in monitoring reinforced concrete structures such as foundations, canopies, and fuel dispensing islands.

Ground-penetrating radar (GPR) represents another widely adopted NDT technique for subsurface assessment. GPR employs electromagnetic wave reflection to locate embedded utilities, reinforcement, and potential voids or delaminations beneath pavements and concrete slabs. It is particularly beneficial for assessing underground fuel tanks, pavement layers, and drainage systems in gas stations, as it provides rapid and non-intrusive imaging of subsurface anomalies (Daniels, 2004). Although signal attenuation in high-moisture or highly conductive soils remains a challenge, advances in frequency modulation and signal interpretation have enhanced the resolution and accuracy of GPR surveys.

Figure 2 presents a block diagram summarizing major non-destructive testing (NDT) methods applied in assessing the structural integrity of petroleum and civil infrastructures. It highlights five core techniques—Ultrasonic Pulse Velocity (UPV), Ground-Penetrating Radar (GPR), Infrared Thermography, Rebound Hammer, and Integrated NDT Approach—each outlining principles, applications, advantages, and limitations. These methods enable early defect detection, quality evaluation, and preventive maintenance without compromising service functionality. The diagram emphasizes how combining multiple NDT techniques enhances diagnostic accuracy and efficiency. Collectively, these approaches form a comprehensive toolkit for ensuring the safety, durability, and longevity of critical infrastructure.

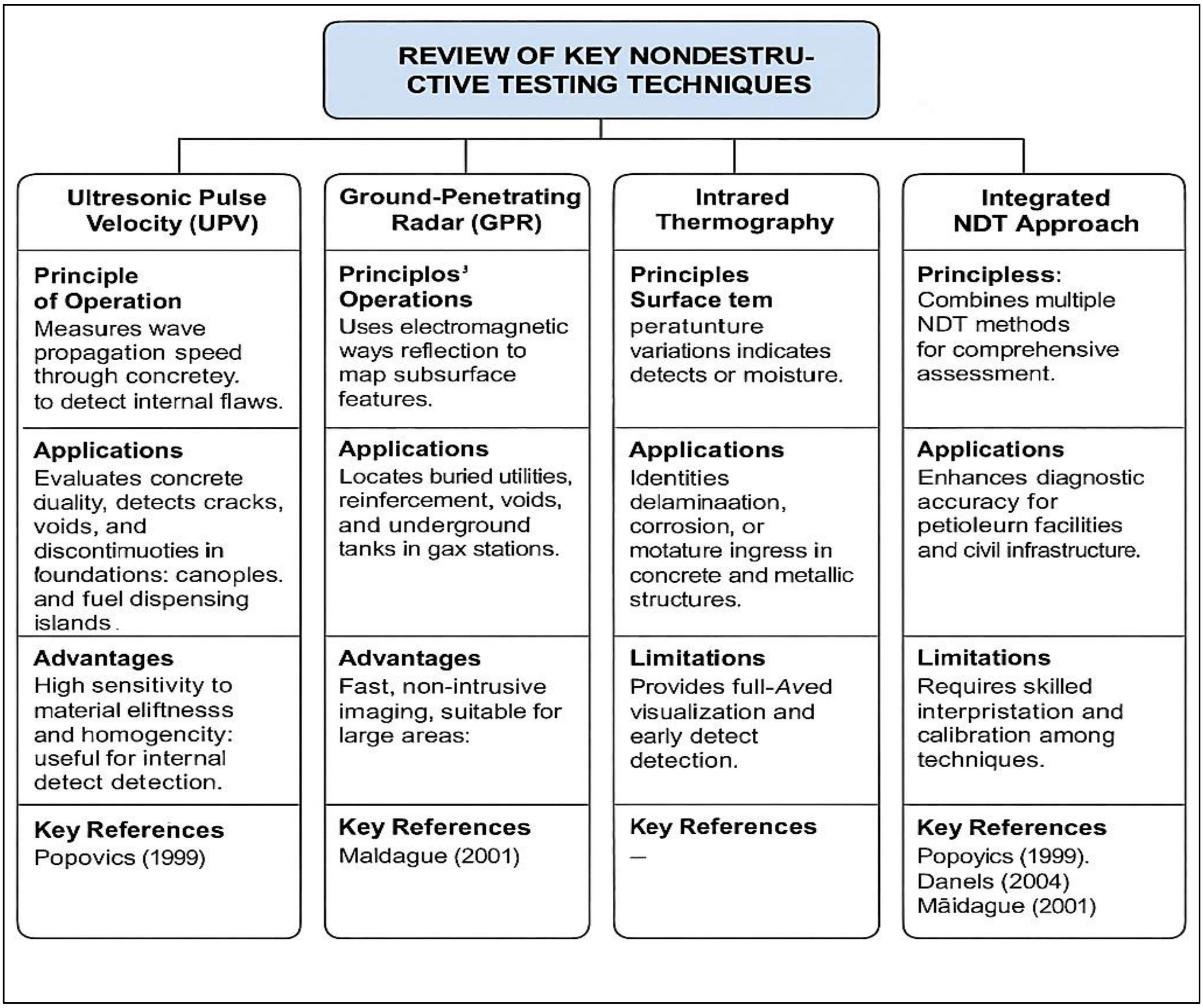

Fig 2 Overview of Key Non-Destructive Testing (NDT) Techniques for Structural Integrity Assessment

Infrared thermography complements other NDT methods by detecting thermal anomalies on surfaces, which often indicate moisture ingress, delamination, or corrosion of embedded materials. This technique relies on temperature differentials caused by varying material properties or defects, providing a full-field visualization that aids in detecting early signs of deterioration (Maldague, 2001). In conjunction with rebound hammer testing, which estimates surface hardness and compressive strength correlations, these techniques form a comprehensive diagnostic suite for assessing concrete and metallic structures. Collectively, the integration of UPV, GPR, infrared thermography, and rebound hammer methods enhances condition evaluation accuracy, reduces inspection time, and supports preventive maintenance planning in petroleum infrastructure (Popovics, 1998; Daniels, 2004; Maldague, 2001).

- *Structural Codes and Standards Governing Gas Station Infrastructure (API, ACI, ASTM, NIS, BS Codes)*

Structural design and assessment of gas station infrastructure are guided by a combination of international and national codes that ensure safety, durability, and regulatory compliance across structural, material, and operational domains. The American Concrete Institute (ACI) provides fundamental guidelines for concrete design, construction, and maintenance through standards such as *ACI 318*, which specifies requirements for structural concrete, and *ACI 562*, which addresses evaluation and repair of existing structures. These standards emphasize load capacity verification, material performance, and detailing requirements that minimize cracking, corrosion, and durability concerns in aggressive petroleum environments (ACI Committee 318, 2019). Similarly, the American Society for Testing and Materials (ASTM) establishes standardized testing procedures—such as *ASTM C597* for ultrasonic pulse velocity, *ASTM C805* for rebound hammer testing, and *ASTM C876* for half-cell potential measurement—to ensure consistency and comparability in evaluating material properties and structural conditions (ASTM International, 2017).

The American Petroleum Institute (API) also plays a crucial role in defining integrity and safety standards for petroleum storage and handling systems. Standards such as *API 650* for welded steel tanks and *API 653* for tank inspection, repair, and reconstruction set performance expectations for containment structures and foundations commonly found in gas stations. These documents guide corrosion control, settlement monitoring, and structural rehabilitation to prevent environmental contamination and operational hazards (API, 2014). Complementing these are regional standards such as the British Standards (BS) and the Nigerian Industrial Standards (NIS), which adopt localized criteria for structural materials, environmental loading, and fire safety provisions. For example, *BS EN 1992* (Eurocode 2) provides design provisions for reinforced concrete structures, while NIS standards address material conformity and environmental adaptations suitable for tropical conditions.

Collectively, the harmonization of ACI, ASTM, API, BS, and NIS standards forms a multi-tiered framework that ensures structural reliability, resilience, and environmental protection in gas station infrastructure. Adherence to these codes not only promotes uniformity in design and assessment practices but also underpins performance-based evaluation systems that align engineering safety with regulatory oversight (ACI Committee 318, 2019; API, 2014; ASTM International, 2017).

Table 2 Structural Codes and Standards Governing Gas Station Infrastructure (API, ACI, ASTM, NIS, BS Codes

Code / Standard	**Issuing Body**	**Primary Focus Area**	**Key Provisions / Applications in Gas Stations**	**Reference**
ACI 318 & ACI 562	American Concrete Institute (ACI)	Design, evaluation, and repair of concrete structures	Specifies load capacity, reinforcement detailing, concrete durability, and repair methodologies for canopies, pavements, and foundations exposed to fuel and moisture.	ACI Committee 318 (2019)
ASTM Standards (C597, C805, C876)	ASTM International	Standardized material and NDT testing procedures	Provides methods for ultrasonic pulse velocity, rebound hammer testing, and half-cell potential for corrosion detection, ensuring consistent structural evaluation.	ASTM International (2017)
API 650 & API 653	American Petroleum Institute (API)	Petroleum storage tank design, inspection, and maintenance	Establishes requirements for the construction, inspection, and rehabilitation of welded steel tanks, addressing corrosion control, leakage prevention, and settlement monitoring.	API (2014)
BS EN 1992 (Eurocode 2)	British Standards Institution (BSI)	Design of reinforced concrete structures	Defines criteria for strength, serviceability, and fire safety in civil structures, applicable to canopy columns, slabs, and retaining walls.	ACI Committee 318 (2019); API (2014)
Nigerian Industrial Standards (NIS)	Standards Organisation of Nigeria (SON)	Local adaptation of material and structural specifications	Customizes international guidelines to tropical conditions, emphasizing material conformity, structural integrity, and environmental resilience.	ASTM International (2017)

- *Comparative Studies on NDT Applications in Fuel Infrastructure Assessment*

Comparative research on non-destructive testing (NDT) applications in fuel infrastructure has highlighted the varying reliability, sensitivity, and practicality of available diagnostic techniques across structural and material contexts. Gas stations, with their combination of reinforced concrete foundations, steel canopies, and buried storage tanks, require diverse NDT tools capable of addressing both surface and subsurface deterioration. Studies have shown that ultrasonic pulse velocity (UPV) testing remains a cornerstone for evaluating the homogeneity and compressive strength of concrete elements, offering high repeatability and correlation with mechanical performance indicators (Popovics, 1998). However, UPV alone may underestimate deterioration when cracks are discontinuous or moisture alters signal transmission, prompting the need for complementary methods.

Figure 3 shows a comparative block diagram illustrating key Non-Destructive Testing (NDT) techniques applied in fuel infrastructure assessment. The diagram categorizes six major methods—UPV, GPR, IRT, AE, Eddy Current Testing, and Integrated/Hybrid NDT—highlighting their applications, strengths, and limitations. It demonstrates how each technique contributes uniquely to detecting structural defects in both concrete and metallic components. The interconnections between blocks emphasize the complementarity of these methods, especially in multimodal diagnostic frameworks. References from Popovics (1998), Daniels (2004), and Ohtsu (2016) support the integrated approach for improved reliability and regulatory compliance.

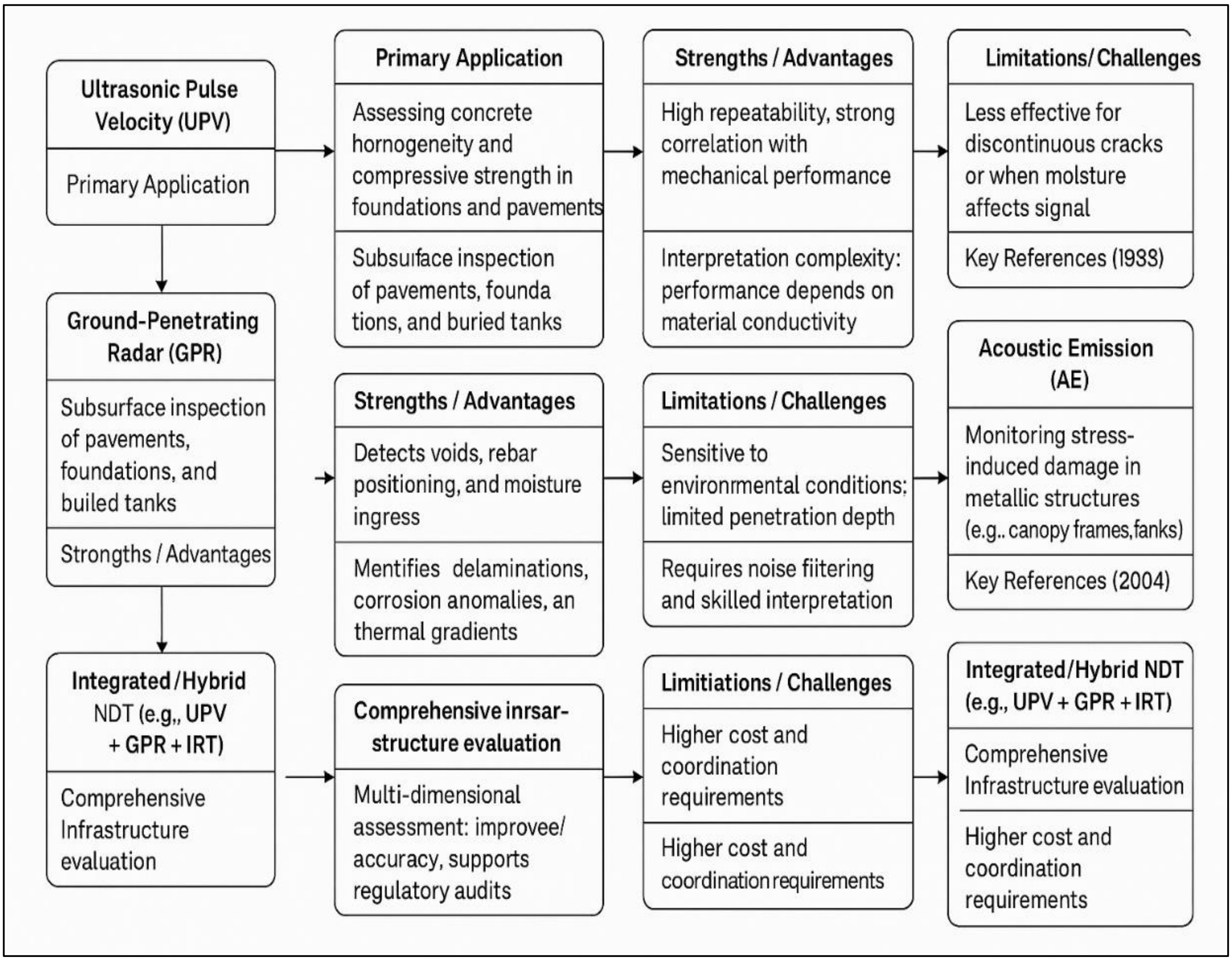

Fig 3 Comparative Block Diagram of Non-Destructive Testing (NDT) Techniques for Fuel Infrastructure Assessment

Ground-penetrating radar (GPR) and infrared thermography (IRT) have emerged as powerful supplementary tools for subsurface and surface-level assessments, respectively. Comparative analyses indicate that GPR is highly effective in detecting voids, rebar positioning, and moisture ingress in pavement and foundation systems, while IRT excels in identifying delaminations and corrosion-induced anomalies on structural surfaces (Daniels, 2004). For metallic components, including canopy frames and underground storage tanks, acoustic emission (AE) and eddy current testing have demonstrated superior precision in detecting microcracks and corrosion pitting under complex stress conditions (Ohtsu, 2016). These techniques provide real-time monitoring capabilities that enhance predictive maintenance, particularly in structures exposed to cyclic loading and corrosive agents.

Several studies emphasize that an integrated or hybrid approach—combining multiple NDT methods—produces more reliable condition assessments than any single technique. The synergistic use of UPV, GPR, and IRT enables a multi-dimensional evaluation, capturing both the physical integrity and thermal behavior of materials. Such integration not only improves defect detection accuracy but also aligns well with regulatory audit frameworks that require quantitative data for compliance verification. Therefore, comparative evidence supports the adoption of a multimodal NDT strategy tailored to the diverse material configurations and environmental exposures typical of fuel infrastructure (Popovics, 1998; Daniels, 2004; Ohtsu, 2016).

➢ *Integration Models Between NDT and Code-Conformance Evaluation*

Integrating non-destructive testing (NDT) with code-conformance evaluation has emerged as a critical framework for achieving data-driven, performance-based assessment of structural integrity in fuel infrastructure. Traditional code compliance assessments often rely on visual inspection and documentation review to verify adherence to design specifications. However, such prescriptive approaches may overlook in-service degradation, especially in concrete and steel elements that have experienced environmental or operational stressors. Integration models bridge this gap by coupling quantitative NDT data with regulatory benchmarks, allowing engineers to evaluate whether an asset not only meets design intent but continues to satisfy safety and serviceability criteria throughout its lifecycle (Farrar & Worden, 2007).

In practice, integration involves mapping NDT-derived metrics—such as ultrasonic velocity, corrosion potential, or thermal gradients—onto threshold parameters defined by standards like ACI 318, API 653, or ASTM C876. This enables the translation of raw test data into code-comparable performance indicators. For example, a reduction in ultrasonic pulse velocity below prescribed values can be interpreted in relation to code-based compressive strength limits, while corrosion potential readings can be directly compared with serviceability tolerances for reinforcement protection (McCann & Forde, 2001). Such frameworks transform conventional compliance audits from document-based verification exercises into evidence-driven structural evaluations that account for real-time material behavior.

Furthermore, integrated models support predictive maintenance and risk prioritization. By correlating NDT findings with code classifications, engineers can rank the severity of non-conformities and recommend remediation strategies consistent with safety margins outlined in structural design codes. This approach aligns with contemporary asset management philosophies that emphasize lifecycle performance and continuous monitoring over periodic inspection (Frangopol, 2011). Ultimately, the integration of NDT and code-conformance models strengthens decision-making, reduces inspection subjectivity, and enhances regulatory accountability across petroleum facility infrastructures (Farrar & Worden, 2007; McCann & Forde, 2001; Frangopol, 2011).

Table 3 Integration Models Between NDT and Code-Conformance Evaluation:

Aspect	Description	Key Insights	Supporting References
Purpose of Integration	Combines NDT data with code-compliance evaluations to provide a comprehensive picture of structural condition and regulatory conformity.	Moves beyond visual inspections to performance-based, data-driven assessment.	Farrar & Worden (2007)
Analytical Framework	Maps NDT metrics (e.g., ultrasonic velocity, corrosion potential) to thresholds defined in ACI, API, or ASTM standards.	Enables quantitative verification of compliance with design and safety limits.	McCann & Forde (2001)
Operational Approach	Uses NDT results to validate code assumptions, identify deviations, and trigger corrective actions.	Transforms compliance audits into evidence-based evaluations.	Farrar & Worden (2007); McCann & Forde (2001)
Maintenance and Risk Management	Integrates NDT findings into lifecycle management and maintenance prioritization.	Supports predictive maintenance, risk ranking, and proactive decision-making.	Frangopol (2011)
Overall Benefit	Enhances structural reliability, reduces subjectivity in inspections, and strengthens regulatory accountability.	Promotes safety, consistency, and long-term sustainability in fuel infrastructure.	Farrar & Worden (2007); Frangopol (2011)

III. METHODOLOGICAL FRAMEWORK FOR INTEGRATED ASSESSMENT

➢ *Workflow for Combined NDT and Code-Conformance Audit*

The workflow for integrating non-destructive testing (NDT) with code-conformance auditing in gas station infrastructure follows a structured sequence of data collection, evaluation, and validation aimed at achieving a holistic understanding of structural condition and regulatory compliance. The process typically begins with pre-assessment planning, where critical structural components—such as canopies, foundations, retaining walls, and underground storage tanks—are identified based on their operational importance, exposure conditions, and historical performance records. This stage also involves reviewing design drawings, previous inspection reports, and maintenance logs to define assessment objectives and select appropriate NDT methods (Bungey et al., 2006).

Figure 4 illustrates a structured five-stage workflow that integrates Non-Destructive Testing (NDT) with code-conformance auditing for gas station infrastructure. The process begins with Pre-Assessment Planning, where critical components and testing objectives are identified. Data Acquisition follows, using techniques like ultrasonic pulse velocity, ground-penetrating radar, and infrared thermography. The Data Analysis & Interpretation phase correlates NDT findings with structural performance standards, while the Code-Conformance Audit verifies compliance against regulatory codes. Finally, Integrated Reporting & Validation consolidates results into a unified integrity management report supporting maintenance and rehabilitation decisions.

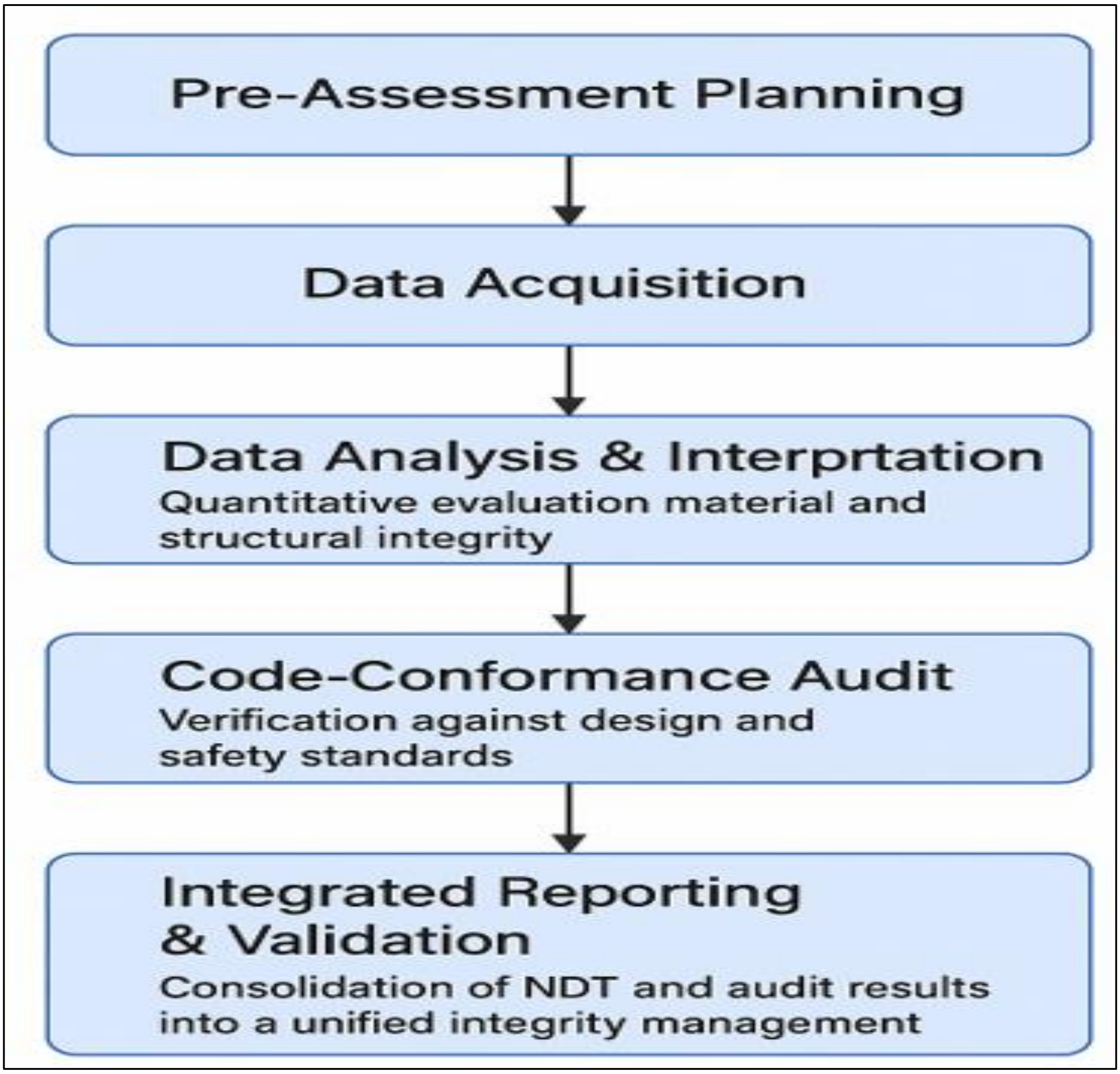

Fig 4 Integrated Workflow for Combined NDT and Code-Conformance Audit in Gas Station Infrastructure

The data acquisition phase integrates multiple NDT techniques tailored to different material and defect types. For example, ultrasonic pulse velocity testing assesses concrete quality and homogeneity, ground-penetrating radar detects subsurface voids and reinforcement placement, and infrared thermography identifies delamination or moisture ingress. During this phase, data collection protocols must comply with established standards such as ASTM C597 or EN 12504 to ensure reproducibility and comparability. The collected NDT results are then quantitatively analyzed to determine the extent of deterioration, enabling correlation with performance benchmarks established by structural codes such as ACI 318 or API 653 (McCann & Forde, 2001).

The code-conformance audit phase interprets NDT outcomes within the framework of design and safety standards to verify compliance. Structural deficiencies detected through NDT are evaluated against allowable tolerances, load-bearing capacities, and material strength thresholds defined by relevant codes. Discrepancies are classified into compliance categories—fully conforming, conditionally acceptable, or non-conforming—based on their severity and potential risk. Finally, an integrated reporting and validation step consolidates NDT data, code audit findings, and maintenance recommendations into a unified integrity management document. This systematic workflow enhances accuracy, ensures accountability, and supports evidence-based decision-making for asset rehabilitation and lifecycle management (Farrar & Worden, 2007; McCann & Forde, 2001; Bungey et al., 2006).

➢ *Selection Criteria for Assessment Tools and Equipment*

The selection of appropriate assessment tools and equipment for evaluating gas station infrastructure depends on multiple technical, environmental, and operational factors that ensure accurate, safe, and cost-effective data acquisition. The most critical criterion involves compatibility with material type and structural function, as gas stations comprise diverse elements such as reinforced concrete pavements, steel canopies, and composite tanks. Non-destructive testing (NDT) tools must therefore be selected based on their ability to characterize specific deterioration mechanisms without disrupting operations. For example, ultrasonic pulse velocity (UPV) and impact-echo methods are suitable for detecting internal voids and cracks in concrete, while magnetic particle and eddy current testing are preferred for identifying surface and subsurface flaws in metallic structures (McCann & Forde, 2001).

A second consideration involves sensitivity, resolution, and penetration depth of the chosen NDT equipment. Techniques such as ground-penetrating radar (GPR) provide superior depth profiling for subsurface anomalies, making them ideal for assessing pavements and underground storage systems. However, the interpretation of GPR data is influenced by soil conductivity, moisture content, and surface roughness, which must be accounted for in tool selection and calibration (Daniels, 2004). Conversely, infrared thermography (IRT) offers rapid, non-contact inspection of large surface areas to detect delamination and moisture intrusion, though its reliability depends on thermal contrast conditions and environmental stability during testing (Maldague, 2001).

Another key factor is standardization and regulatory compliance. Selected instruments should conform to recognized international standards such as ASTM C597 for ultrasonic testing, ASTM D4748 for GPR applications, and EN 13187 for thermal imaging. Adherence to these standards ensures traceability, reproducibility, and comparability of results across different inspection cycles and facilities. Finally, logistical factors such as ease of use, portability, data acquisition rate, and operator expertise play essential roles in tool selection, particularly in active fuel retail environments where inspection windows are limited. Proper alignment of tool capabilities with structural characteristics and code requirements ensures that the assessment process remains both efficient and technically robust (McCann & Forde, 2001; Daniels, 2004; Maldague, 2001).

Table 4 Selection Criteria for Assessment Tools and Equipment:

Criterion	**Description**	**Key Considerations**	**Supporting References**
Material Compatibility and Structural Function	Tools are selected based on the type of material (concrete, steel, or composite) and its functional role in the facility.	UPV and impact-echo for concrete defects; magnetic particle and eddy current testing for metallic structures.	McCann & Forde (2001)
Sensitivity, Resolution, and Penetration Depth	Determines the accuracy and reliability of data acquisition across structural layers.	GPR offers deep profiling for subsurface anomalies; IRT detects surface defects such as delamination and moisture ingress.	Daniels (2004); Maldague (2001)
Environmental and Site Conditions	Environmental factors affect tool accuracy and calibration.	Soil conductivity, moisture, and surface roughness influence GPR; thermal stability impacts IRT performance.	Daniels (2004)
Standardization and Compliance	Equipment must adhere to international testing standards to ensure data consistency.	Follows ASTM and EN standards such as ASTM C597, ASTM D4748, and EN 13187 for traceable results.	McCann & Forde (2001)
Operational and Logistical Efficiency	Addresses usability, portability, and inspection duration in active fuel stations.	Tools should support rapid deployment and minimal operational disruption.	Maldague (2001); McCann & Forde (2001)

➢ *Data Collection and Interpretation Protocols (Defect Mapping, Corrosion Profiling, Structural Deformation)*

Effective data collection and interpretation protocols are essential to ensure the reliability and repeatability of non-destructive testing (NDT) and code-conformance assessments in fuel infrastructure. The process begins with data acquisition planning, which defines sampling locations, grid spacing, instrument calibration, and test repetitions to ensure statistical validity. Data acquisition must follow standardized procedures, such as those outlined in ASTM, BS, or EN guidelines, to maintain consistency across inspection campaigns (Bungey et al., 2006). For instance, ultrasonic pulse velocity (UPV) and impact-echo tests require consistent transducer coupling and alignment, while ground-penetrating radar (GPR) demands calibration to soil and concrete dielectric properties before scanning. This level of precision enables meaningful comparison of data across time intervals and between facilities.

Figure 5 illustrates the systematic workflow for data collection and interpretation in non-destructive testing (NDT) of fuel infrastructure. It begins with data acquisition planning, which ensures calibration, sampling consistency, and adherence to standards such as ASTM and BS. The process proceeds through data collection, defect mapping, and corrosion profiling, where field data are visualized and analyzed for deterioration patterns. Structural deformation analysis further assesses displacement and settlement trends to evaluate serviceability. The workflow culminates in data interpretation and decision-making, where integrated results guide maintenance strategies and compliance with engineering codes.

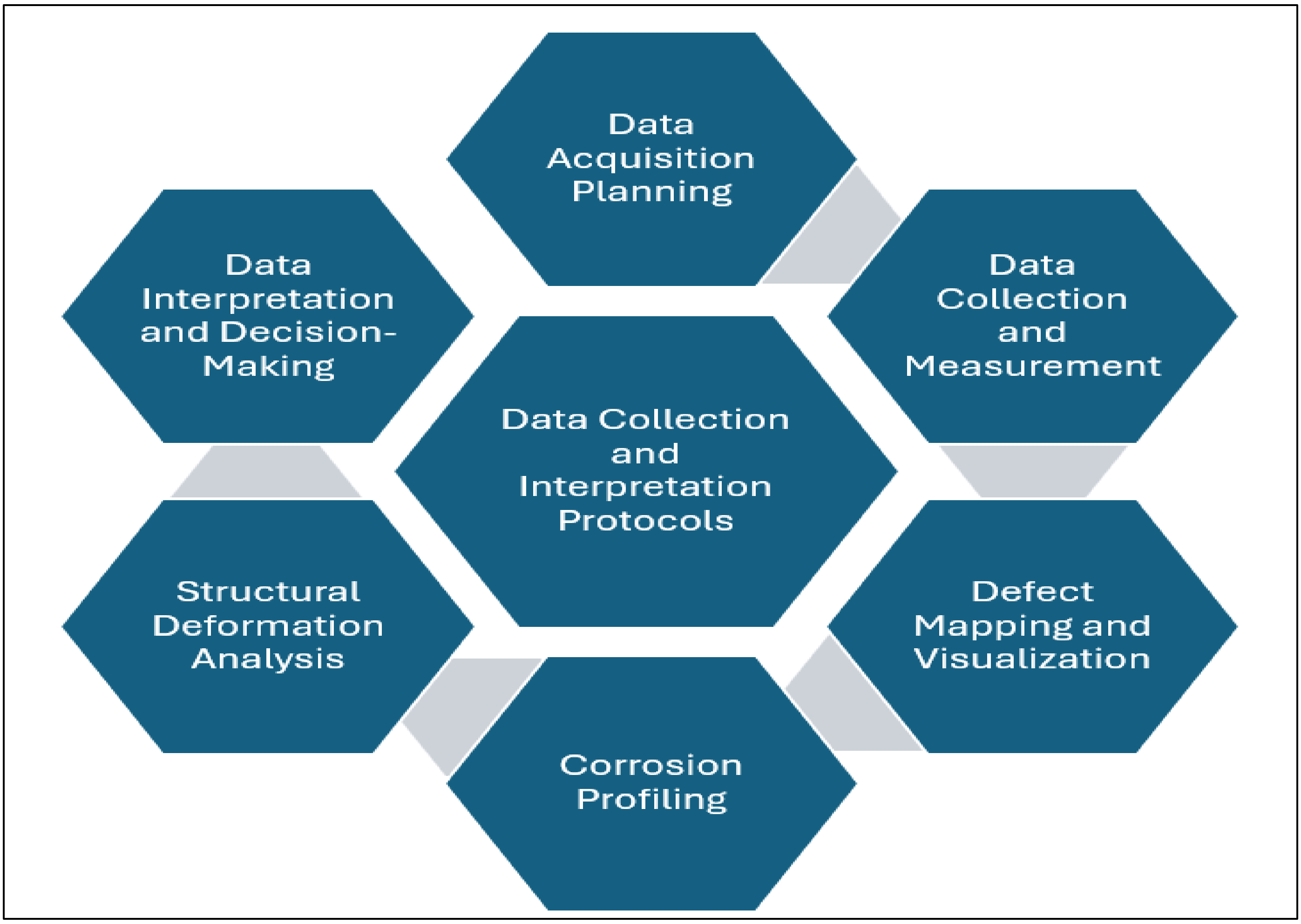

Fig 5 Workflow of Data Collection and Interpretation Protocols for Structural Integrity Assessment

Once acquired, the data undergo defect mapping and visualization, where results are translated into spatial representations that highlight structural irregularities. Techniques such as contour plotting, thermal imaging, and radargram analysis allow engineers to identify zones of cracking, delamination, void formation, and reinforcement corrosion. Infrared thermography, for example, generates thermal gradients that indicate areas of moisture ingress or adhesive failure, while GPR data provides depth-resolved cross-sections for identifying subsurface discontinuities (Maldague, 2001). This mapping process facilitates a comprehensive understanding of deterioration patterns and supports predictive maintenance by identifying areas most susceptible to progressive damage.

The final stage involves corrosion profiling and deformation analysis, where quantitative data are interpreted relative to material degradation models and code-defined tolerances. Half-cell potential measurements, electrical resistivity surveys, and ultrasonic pulse velocity differentials are commonly used to assess corrosion activity in reinforced concrete structures. These readings are then integrated into condition indices or degradation curves that reflect structural performance over time (Farrar & Worden, 2007). Structural deformation is further assessed using displacement sensors or laser scanning, which capture deflection profiles and settlement trends. By aligning these results with ACI and API standards, engineers can determine whether observed conditions remain within serviceability limits or require corrective action. Altogether, these systematic protocols ensure that data collected from NDT investigations translate into actionable insights for risk-based decision-making and lifecycle asset management (Bungey et al., 2006; Maldague, 2001; Farrar & Worden, 2007).

➢ *Safety, Environmental, and Regulatory Considerations in Field Inspections*

Field inspections of gas station infrastructure require rigorous attention to safety, environmental protection, and regulatory compliance to mitigate risks associated with petroleum operations. The inspection environment presents several hazards, including flammable vapors, confined spaces, and high-voltage systems; therefore, safety planning forms an integral part of any non-destructive testing (NDT) or code-conformance audit. A comprehensive safety management plan should include hazard identification, risk assessment, and the implementation of control measures such as grounding, vapor monitoring, and exclusion zones around testing areas (Hallowell & Gambatese, 2009). Personnel must be trained in confined-space entry, fire prevention, and emergency response procedures to ensure safe execution of inspection activities. Furthermore, all testing equipment should be intrinsically safe and compliant with explosion-proof certification standards applicable to petroleum facilities.

Environmental considerations are equally critical during field inspections. Activities such as core drilling, material sampling, and hydrocarbon residue removal can generate waste or introduce contaminants into the soil and groundwater. Although NDT methods are generally non-invasive, auxiliary processes—such as cleaning surfaces or accessing underground storage systems—can have localized impacts if not properly managed. Adherence to environmental management standards, including containment of runoff and proper disposal of waste materials, is necessary to prevent secondary contamination (Zhao et al., 2012). In addition, inspection teams should implement spill prevention and response plans aligned with national environmental protection laws and petroleum industry regulations.

From a regulatory standpoint, inspection protocols must comply with relevant occupational safety, environmental, and structural standards. Agencies such as the Occupational Safety and Health Administration (OSHA), the Environmental Protection Agency (EPA), and international organizations like ISO provide guidelines for safe inspection practices and environmental stewardship in industrial facilities. Structural and integrity assessments should align with ACI, ASTM, and API standards to ensure conformity with engineering and operational requirements (Frangopol, 2011). Documented compliance not only enhances asset reliability and public safety but also supports transparency during regulatory audits and certification processes. Consequently, integrating safety, environmental, and regulatory protocols into field inspection workflows ensures that condition assessment activities uphold both technical accuracy and sustainable operational practices (Hallowell & Gambatese, 2009; Zhao et al., 2012; Frangopol, 2011).

Table 5 Safety, Environmental, and Regulatory Considerations in Field Inspections:

Aspect	Description	Key Considerations / Best Practices	Supporting References
Safety Management	Ensures protection of personnel and infrastructure during inspections involving hazardous petroleum environments.	Conduct risk assessments, establish exclusion zones, use explosion-proof equipment, and provide training on confined-space entry and fire prevention.	Hallowell & Gambatese (2009)
Environmental Protection	Prevents contamination of soil, water, and air during inspection activities.	Implement spill prevention plans, contain runoff, and ensure proper waste disposal and remediation practices.	Zhao et al. (2012)
Regulatory Compliance	Aligns inspection activities with national and international safety, environmental, and structural codes.	Follow OSHA, EPA, ISO, ACI, ASTM, and API standards for safe and compliant inspection practices.	Frangopol (2011)
Integrated Field Protocols	Combines safety, environmental, and regulatory frameworks in one operational plan.	Promotes sustainable inspections, reduces liability, and enhances transparency in audits.	Hallowell & Gambatese (2009); Zhao et al. (2012); Frangopol (2011)
Outcome and Benefits	Achieves accurate, safe, and environmentally responsible inspections.	Supports long-term reliability, public safety, and lifecycle asset management.	All references

- *Case Study Framework: Pilot Evaluation of Fuel Dispensing Canopies and Retaining Walls*

A structured case study framework provides a practical foundation for validating integrated non-destructive testing (NDT) and code-conformance methodologies in gas station infrastructure. The pilot evaluation approach focuses on assessing representative structural components—such as fuel dispensing canopies and retaining walls—under operational conditions. The framework begins with the selection of pilot sites that reflect diverse environmental exposures, material types, and service ages to ensure the generalizability of results. Site characterization includes reviewing as-built drawings, identifying loading conditions, and noting any history of distress or prior repairs (Yehia et al., 2007). This initial documentation informs the design of a systematic inspection plan that aligns NDT techniques with code requirements such as those outlined in ACI 318 for reinforced concrete and API 653 for structural steel systems.

Figure 6 illustrates a circular framework outlining the sequential phases of a pilot evaluation designed to validate non-destructive testing (NDT) and code-conformance approaches in fuel infrastructure. The process begins with site selection and characterization, followed by inspection planning and standard alignment to ensure compliance with ACI and API standards. Data collection and field testing integrate multiple NDT methods, while environmental data integration contextualizes findings. The subsequent analysis and validation stage compares results with code benchmarks, leading to corrective action and cross-validation, where NDT results are verified through limited destructive tests or load assessments to ensure structural reliability.

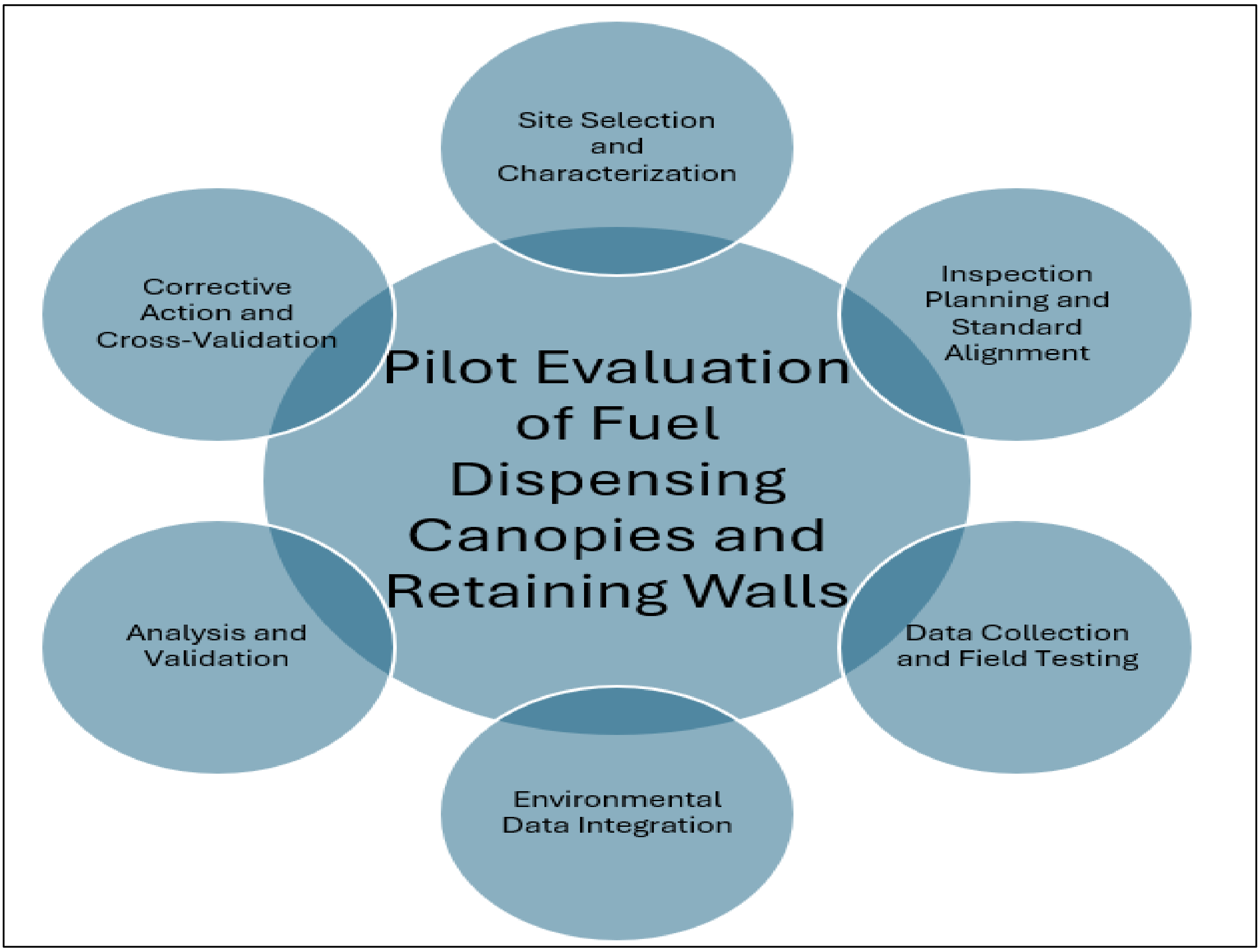

Fig 6 Case Study Framework for Pilot Evaluation of Fuel Dispensing Canopies and Retaining Walls

During the data collection phase, multiple NDT techniques are applied in tandem to obtain a comprehensive diagnostic profile. Ultrasonic pulse velocity (UPV) and rebound hammer testing evaluate concrete strength and uniformity in retaining walls, while ground-penetrating radar (GPR) and infrared thermography (IRT) assist in detecting delamination, voids, and moisture ingress. For canopies composed of steel frames, magnetic particle and ultrasonic thickness measurements are employed to identify corrosion, weld discontinuities, and cross-sectional losses (McCann & Forde, 2001). Field data are supplemented with environmental parameters such as temperature, humidity, and corrosion potential, allowing contextual interpretation of test results.

The analysis and validation phase integrates NDT findings with design code benchmarks to determine compliance and structural reliability. Data visualization through defect mapping, contour imaging, and corrosion profiling provides spatial insight into degradation patterns. Results are compared against code-defined serviceability limits, and non-conformities are categorized based on severity and risk level. Corrective actions, such as coating reapplication, section strengthening, or drainage improvement, are then prioritized according to the criticality of identified defects. Finally, the pilot study concludes with a validation process in which NDT-derived indicators are cross-referenced with limited destructive sampling or load testing to confirm accuracy and reliability (Bungey et al., 2006). This case study framework demonstrates the practicality of combining diagnostic precision with regulatory compliance in enhancing asset integrity management for fuel infrastructure (Yehia et al., 2007; McCann & Forde, 2001; Bungey et al., 2006).

IV. RESULTS, ANALYSIS, AND DISCUSSION

➢ *Comparative Evaluation of Structural Integrity Before and After NDT Application*

A comparative evaluation of structural integrity before and after the application of non-destructive testing (NDT) provides a quantitative measure of how diagnostic technologies enhance understanding of material condition and system reliability. Prior to the application of NDT, assessments in fuel infrastructure—such as gas station canopies, retaining walls, and underground structures—often rely on visual inspection and empirical judgment, which are limited in detecting subsurface deterioration or hidden flaws. Such traditional inspections can overlook early-stage cracking, delamination, and corrosion that progressively reduce load-bearing capacity and durability (Harris et al., 2012). Consequently, baseline structural evaluations may underestimate the extent of deterioration, leading to insufficient maintenance planning and a false perception of safety.

After the deployment of NDT, a more detailed and objective assessment emerges through the integration of quantitative data derived from techniques such as ultrasonic pulse velocity (UPV), infrared thermography (IRT), and ground-penetrating radar (GPR). UPV testing, for example, measures the velocity of stress waves through concrete elements, allowing engineers to infer density, homogeneity, and the presence of cracks or voids (Popovics, 1998). Similarly, IRT provides thermal signatures that reveal delamination and moisture intrusion in concrete surfaces, while GPR enables detection of reinforcement corrosion, subsurface voids, and debonding between layers. Comparative analyses between pre- and post-NDT evaluations typically demonstrate that NDT not only identifies hidden structural anomalies but also provides quantifiable indices—such as pulse velocity reduction, signal attenuation, or thermal gradient variance—that correspond directly to material degradation (Maldague, 2001).

The outcomes of these comparative evaluations contribute to improved decision-making in maintenance prioritization and regulatory compliance. By correlating NDT results with design code thresholds (e.g., ACI 318 or ASTM C597), engineers can reassess whether structural elements meet serviceability and safety requirements. This process often results in recalibrated integrity ratings, where previously “satisfactory” components are reclassified as “moderate risk” or “critical,” thereby guiding timely interventions. Furthermore, comparative post-NDT evaluations enhance predictive maintenance by establishing reliable deterioration trends and facilitating data-driven lifecycle management of petroleum infrastructure (Harris et al., 2012; Popovics, 1998; Maldague, 2001).

Table 6 Comparative Evaluation of Structural Integrity Before and After NDT Application:

Evaluation Phase	**Description**	**Key Findings / Insights**	**Supporting References**
Pre-NDT Assessment	Relies mainly on visual inspection and empirical judgment to evaluate structural condition.	Often fails to detect subsurface defects such as cracks, voids, corrosion, or delamination, leading to underestimated deterioration and inadequate maintenance planning.	Harris et al. (2012)
Post-NDT Assessment	Incorporates quantitative diagnostic data using UPV, IRT, and GPR.	Reveals internal defects, material inconsistencies, and early-stage degradation not visible in pre-inspection; provides measurable indicators like wave velocity and thermal gradients.	Popovics (1998); Maldague (2001)
Comparative Outcome	Establishes performance differences between pre- and post-testing evaluations.	Post-NDT results improve accuracy, enabling defect localization, condition quantification, and better lifecycle predictions.	Harris et al. (2012); Popovics (1998)
Implications for Maintenance and Compliance	Informs risk-based maintenance and reclassification of structural elements against code-defined limits.	Ensures timely interventions and improved compliance with ACI and ASTM standards through data-driven decision-making.	Harris et al. (2012); Maldague (2001)
Overall Impact	Validates the effectiveness of NDT in enhancing reliability and predictive maintenance.	Promotes objective evaluation, enhances structural safety, and supports long-term infrastructure sustainability.	All references

- *Quantitative and Qualitative Findings from Code-Conformance Audits*

Code-conformance audits conducted alongside non-destructive testing (NDT) generate both quantitative and qualitative findings that are crucial for evaluating the structural performance and regulatory compliance of gas station infrastructure. Quantitative findings are primarily derived from measurable parameters obtained through NDT and compared against prescribed standards such as ACI 318, ASTM C597, and API 653. For reinforced concrete elements, ultrasonic pulse velocity (UPV) and rebound hammer results provide direct indicators of compressive strength, homogeneity, and stiffness. Deviations from established threshold values signal potential structural distress, prompting further examination or repair (Popovics, 1998). Similarly, corrosion potential measurements obtained through half-cell testing quantify reinforcement corrosion levels, which are then cross-referenced with allowable limits to determine compliance with durability and serviceability criteria (Andrade & Alonso, 2001).

Qualitative findings complement these metrics by capturing the contextual and experiential dimensions of the inspection process. Field observations—such as surface cracking patterns, joint deterioration, moisture intrusion, or coating failure—offer insight into environmental influences and maintenance effectiveness.

Visual inspection notes and photographic evidence are synthesized with NDT data to form comprehensive defect narratives that support diagnostic interpretation (Harris et al., 2012). For instance, areas identified as critical by UPV or thermographic analysis are validated through visible signs of spalling or efflorescence, enhancing confidence in the reliability of conclusions.

Together, quantitative and qualitative findings form the foundation for compliance grading and maintenance prioritization. Quantitative deviations are classified as minor, moderate, or critical based on how far they diverge from design code benchmarks, while qualitative assessments inform the likely progression rate of defects. The integration of both data types allows auditors to develop risk-based recommendations that balance code adherence with practical considerations such as accessibility, cost, and operational safety. This dual evaluation approach ensures that conformance audits are not merely procedural but reflective of the true structural health and performance of petroleum facilities (Popovics, 1998; Andrade & Alonso, 2001; Harris et al., 2012).

- *Integration Outcomes: Correlation Between NDT Results and Regulatory Compliance Gaps*

The integration of non-destructive testing (NDT) results with code-conformance evaluations provides a robust mechanism for identifying and quantifying regulatory compliance gaps in gas station infrastructure. By correlating empirical test data with prescriptive requirements from structural codes such as ACI 318, API 653, and ASTM C876, engineers can determine whether in-service conditions align with design expectations and safety thresholds. This correlation process transforms NDT data—such as ultrasonic pulse velocity (UPV), corrosion potential, and thermal imaging outputs—into compliance indicators that directly reflect the asset's structural health. For instance, a significant reduction in UPV or increased half-cell potential readings can be mapped against allowable limits in ACI and ASTM standards to identify deficiencies in concrete quality or reinforcement durability (McCann & Forde, 2001).

Analytical correlations also reveal discrepancies between code assumptions and real-world performance. While codes define minimum acceptable parameters for materials and load-bearing capacities, NDT data often uncover localized degradation—such as corrosion pitting, delamination, or uneven settlement—that exceeds those limits in specific regions of a structure. Studies have shown that integrating NDT results with structural reliability models enables the quantification of risk indices and compliance deviations more effectively than traditional audit methods (Frangopol, 2011). This evidence-based integration thus bridges the gap between theoretical code compliance and actual performance, allowing for more precise identification of non-conformities in structural and material behavior.

Moreover, the correlation between NDT outcomes and regulatory benchmarks supports risk-based asset management. By assigning compliance scores derived from NDT metrics, engineers can prioritize rehabilitation efforts for high-risk elements such as fuel dispensing canopies, retaining walls, and underground storage tanks. This approach aligns with lifecycle performance management principles, emphasizing preventive maintenance and long-term safety optimization. Ultimately, integrating NDT data into code-conformance auditing not only exposes compliance gaps but also enhances the predictive capacity of structural evaluations, enabling petroleum facility operators to maintain operational safety, environmental integrity, and regulatory accountability (Farrar & Worden, 2007; McCann & Forde, 2001; Frangopol, 2011).

Table 7 Integration Outcomes: Correlation Between NDT Results and Regulatory Compliance Gaps:

Aspect	Description	Key Insights / Findings	Supporting References
Purpose of Integration	Correlates NDT data with code-conformance standards (ACI 318, API 653, ASTM C876) to identify regulatory compliance gaps.	Enables comparison between real-world structural conditions and prescribed safety thresholds.	McCann & Forde (2001)
Data–Code Correlation	Translates NDT results (e.g., UPV, corrosion potential, thermal imaging) into measurable compliance indicators.	Detects deviations in material strength, reinforcement corrosion, and durability relative to code limits.	McCann & Forde (2001); Frangopol (2011)
Identification of Compliance Gaps	Reveals discrepancies between theoretical design assumptions and actual in-service performance.	Highlights localized degradation (e.g., corrosion pitting, delamination, uneven settlement) not captured by traditional audits.	Frangopol (2011)
Risk-Based Management	Uses compliance scores from NDT data to prioritize maintenance and rehabilitation.	Facilitates preventive maintenance and targeted interventions for high-risk components.	Farrar & Worden (2007); Frangopol (2011)
Overall Impact	Enhances predictive maintenance, lifecycle management, and regulatory accountability.	Strengthens data-driven decision-making for asset integrity and operational safety.	Farrar & Worden (2007); McCann & Forde (2001); Frangopol (2011)

- *Risk-Based Ranking of Defects and Maintenance Prioritization*

Risk-based ranking of defects and maintenance prioritization represents a critical step in the post-assessment phase of gas station infrastructure evaluation. By integrating non-destructive testing (NDT) results with code-conformance criteria, engineers can classify defects according to their potential impact on safety, functionality, and environmental compliance. The approach emphasizes quantitative risk assessment principles, in which the likelihood of structural failure is evaluated in conjunction with the severity of its potential consequences. This systematic process allows for maintenance interventions to be directed toward components with the highest risk indices—such as canopy supports, underground tanks, and retaining walls exposed to aggressive environmental conditions (Frangopol, 2011).

Defects are typically categorized using probabilistic performance models that incorporate deterioration data, material degradation rates, and exposure factors derived from NDT measurements. Parameters such as ultrasonic pulse velocity (UPV) reduction, corrosion potential, and thermal gradients serve as proxies for structural reliability. These values are translated into probability-of-failure (Pf) estimates and risk matrices that rank defects from low to critical severity levels (Farrar & Worden, 2007). For example, a reinforced concrete foundation with significant velocity reduction or corrosion depth exceeding code limits may be prioritized for immediate rehabilitation, whereas minor surface scaling may be scheduled for routine monitoring. This hierarchy ensures that maintenance resources are optimally allocated based on objective, data-driven indicators rather than subjective visual assessments.

Maintenance prioritization also aligns with life-cycle cost optimization strategies by balancing repair urgency with economic feasibility. Studies in infrastructure management have shown that risk-based frameworks extend service life and reduce total maintenance expenditures by preventing catastrophic failures and unplanned downtime (Halfawy & Froese, 2007). The incorporation of risk assessment tools—such as reliability indices, fragility curves, and performance-based ranking algorithms—enables continuous updating of maintenance schedules as new NDT data become available. Ultimately, this methodology ensures that maintenance planning is proactive, evidence-based, and aligned with both safety regulations and financial sustainability goals (Frangopol, 2011; Farrar & Worden, 2007; Halfawy & Froese, 2007).

- *Discussion on Cost-Benefit Implications of Integrated Assessment*

The integration of non-destructive testing (NDT) and code-conformance auditing in gas station infrastructure offers significant cost-benefit advantages by enhancing inspection accuracy, optimizing maintenance planning, and reducing lifecycle expenditures. Traditional inspection methods often rely on visual surveys and limited sampling, which, while initially inexpensive, can result in undetected structural deterioration leading to costly emergency repairs or unplanned downtime. In contrast, NDT-based approaches provide early detection of hidden defects, enabling preventive maintenance that mitigates severe degradation and structural failure (Bungey et al., 2006). The financial advantage lies in shifting from a reactive to a proactive maintenance paradigm, where expenditures are strategically allocated based on quantified risk and condition data rather than general inspection cycles.

A key economic implication of integrating NDT with code auditing is the optimization of lifecycle costs. Quantitative assessment results derived from ultrasonic pulse velocity (UPV), ground-penetrating radar (GPR), and corrosion potential measurements allow engineers to predict remaining service life and plan timely rehabilitation actions. By aligning these results with code-based reliability limits, asset managers can prioritize interventions that yield the highest return on investment in terms of safety and performance (Frangopol, 2011). Empirical evidence from infrastructure management studies has demonstrated that early intervention, guided by NDT diagnostics, can reduce overall maintenance expenditures by up to 30–40% compared to conventional reactive maintenance strategies (Halfawy & Froese, 2007). This predictive approach not only extends structural longevity but also improves operational continuity and environmental safety—factors crucial in petroleum retail facilities.

Beyond direct economic benefits, integrated assessments also provide intangible cost savings through enhanced compliance assurance, reduced liability, and improved public safety perception. By correlating field data with regulatory standards such as ACI 318 and API 653, facility owners can document compliance with structural and environmental codes, minimizing the risk of penalties or shutdowns. Additionally, improved data transparency supports evidence-based decision-making and fosters accountability during regulatory audits. While the initial investment in NDT technology and skilled personnel can be substantial, the long-term benefits—reduced failure probability, extended service life, and optimized resource allocation—justify the expenditure (Bungey et al., 2006; Frangopol, 2011; Halfawy & Froese, 2007). Overall, the integrated approach represents a sustainable and economically efficient framework for managing petroleum infrastructure assets.

Table 8 Lessons Learned and Field Implementation Challenges:

Aspect	Description	Key Insights / Lessons Learned	Supporting References
Implementation Challenges	Difficulties encountered during on-site execution of NDT and code-conformance audits.	Limited accessibility to subsurface structures, inconsistent calibration of instruments, and interference from fuel vapors or electrical systems affect data accuracy.	McCann & Forde (2001)
Data Interpretation Issues	Challenges in correlating NDT readings with actual material conditions and code-defined parameters.	Variability in material composition, moisture content, and temperature leads to data uncertainty; expert interpretation is essential.	Farrar & Worden (2007)
Operational Constraints	Practical barriers during inspections in active gas stations.	Continuous operations restrict testing windows; safety requirements such as grounding and vapor monitoring extend inspection duration.	Frangopol (2011)
Lessons Learned	Insights gained for improving future integrated assessments.	Early planning, multidisciplinary coordination, and adherence to standardized testing protocols enhance consistency and reliability.	Farrar & Worden (2007); Frangopol (2011)
Recommendations	Strategies to mitigate field and analytical limitations.	Utilize sensor fusion, digital data management, and continuous monitoring frameworks to improve accuracy and lifecycle assessment.	McCann & Forde (2001); Farrar & Worden (2007)

V. CONCLUSION AND RECOMMENDATIONS

- *Summary of Key Findings*

The integration of non-destructive testing (NDT) with code-conformance audits in gas station infrastructure provides a comprehensive framework for structural assessment, regulatory compliance, and maintenance optimization. The findings of this study reveal that traditional inspection techniques—primarily based on visual evaluations and empirical judgment—are limited in detecting internal deterioration and quantifying the extent of structural degradation. Visual inspections tend to overlook subsurface defects such as delamination, corrosion, and void formation that compromise structural safety over time (Harris et al., 2012). In contrast, NDT methodologies such as ultrasonic pulse velocity (UPV), ground-penetrating radar (GPR), and infrared thermography (IRT) provide quantitative and spatially resolved insights into material integrity, enabling early detection of defects and more reliable condition assessments (McCann & Forde, 2001).

A significant finding of the integrated approach is its ability to correlate diagnostic data with regulatory code thresholds to assess compliance in real-time. By comparing NDT-derived parameters—such as wave velocity, corrosion potential, and thermal gradients—against the performance criteria defined in ACI, ASTM, and API standards, engineers can accurately identify non-conformities and prioritize corrective actions. This alignment between empirical data and codified benchmarks ensures that maintenance decisions are evidence-based rather than purely procedural. Furthermore, the integration of digital reporting and defect mapping tools enhances traceability, allowing consistent documentation of asset health over multiple inspection cycles (Farrar & Worden, 2007).

Another key finding highlights the economic and operational benefits of the integrated assessment model. Data-driven maintenance prioritization significantly reduces lifecycle costs by facilitating targeted rehabilitation of high-risk components while deferring low-risk interventions. Additionally, this approach minimizes unplanned downtime, enhances operational safety, and supports environmental protection by preventing fuel leaks or structural failures. Overall, the results demonstrate that combining NDT and code-conformance audits fosters a proactive maintenance culture that strengthens structural reliability, regulatory compliance, and long-term sustainability within petroleum infrastructure networks (Harris et al., 2012; McCann & Forde, 2001; Farrar & Worden, 2007).

- *Recommendations for Enhancing Structural Assessment Practices in Gas Stations*

Enhancing structural assessment practices in gas station infrastructure requires a systematic integration of advanced diagnostic technologies, standardized inspection frameworks, and data-driven maintenance strategies. One key recommendation is the adoption of multi-modal non-destructive testing (NDT) to provide complementary data that captures both surface and subsurface conditions. Techniques such as ultrasonic pulse velocity (UPV), ground-penetrating radar (GPR), infrared thermography (IRT), and half-cell potential testing should be employed concurrently to improve detection accuracy and minimize uncertainty in defect diagnosis (McCann & Forde, 2001). The combined use of these methods allows for cross-validation of findings, ensuring that structural anomalies such as delamination, corrosion, and cracking are accurately characterized. This hybrid approach enhances diagnostic precision while reducing the likelihood of undetected deterioration that could compromise structural reliability.

Another recommendation focuses on the integration of digital asset management systems for continuous monitoring and data standardization. The implementation of structural health monitoring (SHM) systems and digital twin technologies enables the real-time collection, analysis, and visualization of data for predictive maintenance (Farrar & Worden, 2007). Integrating NDT results into a centralized digital database allows asset managers to track deterioration trends, benchmark performance against design codes, and schedule interventions proactively. Additionally, standardized reporting formats aligned with ACI, ASTM, and API guidelines should be adopted to ensure uniformity in data interpretation and regulatory compliance across inspection teams and facilities.

Finally, improving capacity building and regulatory oversight is essential for ensuring consistent application of NDT and code-conformance practices. Training engineers, inspectors, and technicians on the latest diagnostic technologies and international standards strengthens the quality of assessments and interpretation accuracy (Frangopol, 2011). Furthermore, regulatory agencies should establish periodic certification requirements for inspection professionals and mandate independent audits to validate the integrity of inspection data. By institutionalizing these practices, gas station operators can achieve higher levels of structural safety, environmental compliance, and cost efficiency over the asset's lifecycle (McCann & Forde, 2001; Farrar & Worden, 2007; Frangopol, 2011).

Table 9 Recommendations for Enhancing Structural Assessment Practices in Gas Stations:

Recommendation Area	**Description**	**Key Actions / Benefits**	**Supporting References**
Multi-Modal NDT Integration	Combine complementary NDT methods for comprehensive structural assessment.	Use UPV, GPR, IRT, and half-cell potential concurrently for surface and subsurface analysis; enables cross-validation and defect accuracy.	McCann & Forde (2001)
Digital Asset Management and SHM Integration	Adopt digital platforms and monitoring systems for real-time condition tracking.	Implement SHM and digital twins; centralize NDT data for predictive maintenance and compliance tracking.	Farrar & Worden (2007)
Standardization and Reporting	Ensure uniformity in inspection processes and data interpretation.	Use standardized templates aligned with ACI, ASTM, and API codes for consistent evaluation and audit reporting.	Frangopol (2011)
Capacity Building and Training	Strengthen technical expertise and regulatory consistency among professionals.	Provide continuous training on advanced diagnostic tools and establish certification for NDT practitioners.	Frangopol (2011); McCann & Forde (2001)
Regulatory Oversight and Quality Assurance	Reinforce inspection integrity and accountability.	Mandate third-party audits and regular performance reviews to validate compliance and data accuracy.	Farrar & Worden (2007); Frangopol (2011)

➢ *Policy and Regulatory Implications for Energy Infrastructure Safety*

The integration of non-destructive testing (NDT) and code-conformance audits has profound policy and regulatory implications for ensuring the structural and environmental safety of energy infrastructure such as gas stations. From a policy perspective, regulators and industry stakeholders must shift from prescriptive inspection models toward performance-based regulatory frameworks that emphasize continuous monitoring, data transparency, and preventive maintenance (Frangopol, 2011). Traditional compliance systems often focus on visual inspections and static reporting, which provide limited insight into evolving structural conditions. In contrast, policies that incorporate NDT-driven data analytics enable authorities to assess real-time asset integrity, thereby reducing the probability of catastrophic failures and environmental incidents. By institutionalizing NDT as a regulatory requirement, policymakers can strengthen the enforcement of safety codes and promote a culture of proactive risk management within the petroleum sector (Farrar & Worden, 2007).

Regulatory agencies should also prioritize the standardization of inspection procedures and reporting protocols. Currently, inconsistencies in inspection methodologies and documentation hinder effective benchmarking and cross-site comparisons. Establishing unified regulatory standards based on ACI, ASTM, and API guidelines will ensure uniform application of inspection results across facilities and jurisdictions (McCann & Forde, 2001). Furthermore, mandating digital recordkeeping and data-sharing platforms between operators and regulators can improve traceability, enhance accountability, and enable data-driven decision-making at a national level. This harmonization of standards not only enhances compliance oversight but also facilitates international collaboration in infrastructure safety and environmental protection.

Another critical implication concerns policy incentives and capacity-building measures to encourage widespread adoption of integrated assessment frameworks. Policymakers should develop incentive-based mechanisms—such as tax credits, certification benefits, or maintenance subsidies—for companies that implement NDT-based monitoring systems and demonstrate compliance with structural health performance criteria. Additionally, regulatory authorities must invest in professional training and certification programs to ensure that inspectors and engineers possess the technical competence required for accurate data interpretation and compliance verification (Frangopol, 2011). These initiatives align with global trends in infrastructure governance that emphasize resilience, sustainability, and technological innovation in safety management (Farrar & Worden, 2007; McCann & Forde, 2001).

- *Future Research Directions: Toward Digital Twin and Predictive Maintenance Models*

Future research on the integration of non-destructive testing (NDT) and code-conformance audits in gas station infrastructure should focus on the development of digital twin and predictive maintenance models to enhance structural integrity management. A digital twin represents a real-time, virtual replica of a physical asset that integrates data from sensors, NDT systems, and inspection reports to simulate performance, degradation, and maintenance needs (Farrar & Worden, 2007). By linking field-acquired data—such as ultrasonic pulse velocity, ground-penetrating radar outputs, and corrosion potential—to computational models, digital twins can continuously update the condition state of infrastructure elements like canopies, foundations, and retaining walls. This dynamic data exchange allows for predictive simulations that forecast deterioration trends, optimize inspection schedules, and improve decision-making accuracy throughout the asset's lifecycle (Frangopol, 2011).

Moreover, research should advance the use of artificial intelligence (AI) and machine learning (ML) in interpreting NDT data to support predictive maintenance frameworks. Traditional analysis methods depend heavily on manual interpretation, which can introduce human bias and limit scalability. Machine learning algorithms, such as convolutional neural networks (CNNs) and random forest classifiers, can process large volumes of NDT signals and images to identify complex degradation patterns and predict failure probabilities (Halfawy & Froese, 2007). When integrated with digital twin environments, these AI-driven models can enable near real-time anomaly detection, early warning systems, and automated maintenance prioritization—significantly improving reliability and reducing operational costs in petroleum infrastructure.

Finally, future studies should explore standardization and interoperability frameworks for data exchange between NDT equipment, digital twin platforms, and regulatory databases. The establishment of universal data schemas and communication protocols will ensure compatibility across different technologies and facilitate collaborative asset management across agencies and operators. This approach aligns with the evolving paradigm of smart infrastructure systems, where condition-based maintenance is supported by continuous monitoring, predictive analytics, and regulatory integration (Frangopol, 2011; Farrar & Worden, 2007; Halfawy & Froese, 2007). Such advancements will ultimately transform infrastructure assessment from a periodic, manual process into an intelligent, adaptive system capable of sustaining structural safety and compliance in real time.

Table 10 Future Research Directions: Toward Digital Twin and Predictive Maintenance Models:

Research Focus Area	Description	Key Insights / Objectives	Supporting References
Digital Twin Integration	Development of real-time digital replicas of structural assets using NDT data and simulation models.	Enables continuous monitoring, real-time condition updates, and predictive simulations for infrastructure elements like canopies and foundations.	Farrar & Worden (2007); Frangopol (2011)
AI and Machine Learning for Predictive Maintenance	Application of ML algorithms to analyze NDT signals, images, and performance data.	Enhances detection accuracy, automates defect classification, predicts failure probabilities, and optimizes maintenance scheduling.	Halfawy & Froese (2007); Frangopol (2011)
Data Standardization and Interoperability	Establishment of universal data schemas and communication protocols between NDT, digital twin platforms, and regulatory systems.	Promotes seamless data exchange, regulatory integration, and multi-agency collaboration in infrastructure management.	Farrar & Worden (2007); Halfawy & Froese (2007)
Lifecycle and Compliance Optimization	Aligns predictive analytics with lifecycle cost management and code compliance frameworks.	Supports condition-based, adaptive maintenance models that ensure long-term structural safety and environmental sustainability.	Frangopol (2011)
Expected Outcomes	Transformation of static inspections into intelligent, adaptive systems.	Achieves continuous safety assurance, cost reduction, and real-time compliance verification.	All references

➢ *Concluding Remarks on Sustainability and Lifecycle Management of Gas Station Assets*

The assessment of civil and structural assets in gas stations through the integration of non-destructive testing and code-conformance audits represents a transformative approach to infrastructure management. This integrated methodology ensures that decisions regarding inspection, maintenance, and rehabilitation are informed by empirical data and aligned with regulatory standards. By combining diagnostic precision with compliance verification, engineers and asset managers can establish a proactive framework that emphasizes structural safety, environmental protection, and operational continuity.

The broader implication of this approach lies in its contribution to sustainability and lifecycle optimization. Through early defect detection and risk-based maintenance prioritization, resources can be allocated efficiently, minimizing material waste, repair frequency, and downtime. The emphasis on preventive rather than corrective maintenance aligns with sustainability goals by extending asset service life, reducing carbon emissions from reconstruction, and promoting responsible use of materials and energy.

In addition, the gradual incorporation of digital technologies such as sensor-based monitoring systems, digital twins, and predictive analytics offers a pathway toward continuous condition evaluation and adaptive management. These advancements not only enhance accuracy and efficiency but also embed resilience within infrastructure systems, ensuring they can withstand environmental stressors and operational demands over time.

Ultimately, the convergence of engineering innovation, regulatory compliance, and sustainable asset management underscores the future direction of gas station infrastructure. As industry practices evolve toward data-driven and environmentally conscious frameworks, integrated assessment methods will remain central to achieving long-term reliability, safety, and sustainability across the petroleum retail sector.

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