Review of Applied Science and Technology

***Volume:** 3; **Issue:** 4*
***Pages:** 94– 127*

PETROLEUM STORAGE TANK DESIGN AND INSPECTION USING FINITE ELEMENT ANALYSIS MODEL FOR ENSURING SAFETY RELIABILITY AND SUSTAINABILITY

Sabuj Kumar Shil[1];

[1]. Master of Engineering Science in Industrial Engineering, Department of Industrial and Systems Engineering, Lamar University, Texas, USA; Email: engr.sabujshil038@gmail.com

Doi: 10.63125/a18zw719

***Received:** 12 September 2024; **Revised:** 20 October 2024; **Accepted:** 18 November 2024; **Published:** 24 December 2024*

Abstract

This quantitative, cross-sectional, case-based investigation examines the extent to which finite element analysis (FEA)–informed design practices and structured risk-based inspection strategies contribute to improved safety, reliability, and sustainability performance in petroleum storage tank systems. The study addresses a persistent industry problem: large-scale enterprise tank facilities continue to face risks of structural instability, leakage, and subsurface contamination, even though advanced computational design tools and systematic inspection frameworks are widely available. Using a single major storage facility as an embedded case, data were collected from 120 engineers, inspectors, maintenance personnel, and health, safety, and environment (HSE) managers through a structured five-point Likert-scale questionnaire measuring FEA-informed design practices, risk-based inspection and monitoring, safety performance, reliability performance, and sustainability outcomes. These perception-based data were complemented with FEA simulations of five representative storage tanks to quantify stress distributions, deformation patterns, and utilization ratios under operational loads. Descriptive statistics indicated consistently high implementation levels for both FEA-enabled design and risk-focused inspection programs, with construct means ranging from 3.94 to 4.18. The FEA simulations further demonstrated that critical stresses remained safely below allowable code thresholds, with utilization ratios between 0.69 and 0.93, suggesting robust structural integrity at the modeled facility. Psychometric evaluation confirmed strong internal consistency across all measurement scales, with Cronbach's alpha values ranging from 0.87 to 0.90, indicating reliable construct measurement and adequate sampling adequacy for multivariate analysis. Pearson correlation analysis identified statistically significant and positive associations among FEA practices, inspection rigor, safety, reliability, and sustainability indicators (correlation coefficients up to $r = 0.68$, $p < 0.01$), supporting the hypothesized interdependence of technical design quality and operational performance. Multiple regression analysis revealed that FEA-informed design and structured inspection jointly explained 52 percent of the variance in safety outcomes and 47 percent of the variance in reliability outcomes. Further, safety and reliability together accounted for 44 percent of the variance in sustainability performance, highlighting their mediating influence between technical practices and longer-term environmental and asset stewardship outcomes.

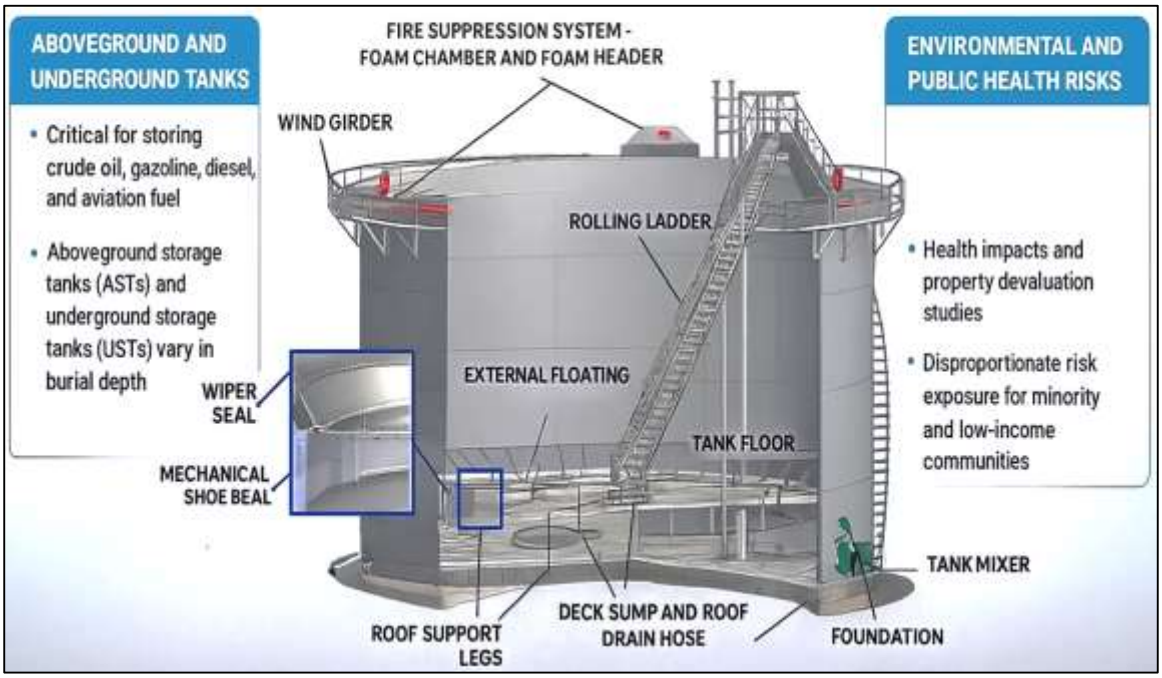
Keywords

Finite Element Analysis, Petroleum Storage Tanks, Risk-Based Inspection, Safety and Reliability, Sustainability Outcomes

INTRODUCTION

Petroleum storage tanks are engineered structures designed to contain large volumes of crude oil and refined petroleum products in aboveground and underground configurations, forming a critical node in global energy supply chains. In industrial practice, storage tanks are classified into aboveground storage tanks (ASTs) and underground storage tanks (USTs) depending on the relative burial depth of the shell and piping, with regulatory definitions typically specifying that at least 10% of the combined volume be below ground for systems to be designated as USTs. These systems store gasoline, diesel, aviation fuel, and other hazardous liquids that are essential for transportation, industry, and power generation worldwide. Technical guidance documents emphasize that such tanks must be designed and operated in a way that permits continuous monitoring and inspection to prevent soil and groundwater contamination and to protect public health and ecosystems (Luo et al., 2018). At the same time, groundwater remains a primary source of drinking water for a significant portion of the world's population, and it is highly vulnerable to contamination by hydrocarbons and associated compounds from leaking storage systems. Recent assessments highlight that water quality indices, particularly in coastal and deltaic regions such as Khulna in Bangladesh, are strongly influenced by both geogenic salinity and anthropogenic pollution, including petroleum-related activities. In this context, petroleum storage tank design and inspection is not only a structural engineering concern but also a foundational element of environmental protection and sustainable infrastructure management at an international scale (Pan & Liang, 2020; Performance, 2005).

Figure 1: Structural and Inspection Features of Petroleum Storage Tanks for Safety



From an engineering standpoint, the safety and reliability of petroleum storage tanks are governed by their structural form, loading conditions, foundation response, and long-term degradation mechanisms such as corrosion and fatigue. Early work in the corrosion community documented severe internal corrosion of aboveground fuel storage tanks, noting that thinning, pitting, and localized attack at the floor and lower shell courses significantly elevate the risk of leakage and catastrophic rupture. Subsequent structural studies evaluated the static buckling capacity of vertical cylindrical steel tanks, reviewing how geometric imperfections, wind load, and liquid sloshing can induce shell instability under service and extreme conditions (Chant & Sims, 2011). More refined analyses examined open-topped tanks under external pressure, showing how roofless configurations exhibit complex buckling patterns and demanding stiffener arrangements to maintain adequate safety margins. Additional research on anchored steel tanks subjected to horizontal and vertical ground acceleration has demonstrated that combined dynamic loading may trigger uplift, plastic hinging, and progressive loss of stability, particularly under strong earthquakes (Abdulla & Ibne, 2021). The shell-to-annular plate joint of large unanchored tanks has also been identified as a critical location, where uplift under seismic excitation can cause large plastic strains and potential fracture, as shown through elastic–plastic large deformation finite element analysis of a 90,000 m³ tank (Habibullah & Foysal, 2021). Collectively, these structural findings indicate that accurate assessment of stress distributions, buckling resistance, and plastic demand in storage tanks is central to ensuring safety and long-term reliability (Sanjid & Farabe, 2021; MSarwar, 2021; Srinivasamoorthy, 2020).

Failures of petroleum storage tanks have pronounced environmental, social, and economic consequences when leakage leads to soil and groundwater contamination. Studies of leaking underground storage tanks (LUSTs) have shown that petroleum releases can contaminate local groundwater and surface water, creating health risks for nearby populations and imposing substantial remediation costs (Musfiqur & Saba, 2021; Omar & Rashid, 2021). A hedonic property value analysis for three Maryland counties found that highly publicized or severe LUST cases can significantly reduce nearby house prices, indicating that communities internalize perceived risk and contamination impacts in real estate markets (Redwanul et al., 2021; Tarek & Praveen, 2021; Wilson et al., 2013). Environmental justice research identified that LUSTs may be disproportionately located in or near minority and low-income communities, suggesting inequalities in exposure to petroleum contamination and associated health burdens. More recently, an applied economics study quantified the health impacts of exposure to petroleum leaks during gestation, reporting increased probabilities of low birth weight and preterm birth among populations residing near leaking tanks, and showing that stronger regulatory compliance can mitigate these adverse outcomes (Zaman & Momena, 2021; Rony, 2021). Beyond local cases, global syntheses of groundwater contamination emphasize that anthropogenic activities, including fuel storage and distribution, are a major driver of hydrocarbon pollution, with remediation being technically challenging and financially intensive once plumes have formed (Shaikh & Aditya, 2021; Sudipto & Mesbaul, 2021). These findings underscore that prevention of leakage from petroleum storage tanks, through robust design and systematic inspection, is integral to safeguarding water resources, public health, and community welfare (Hozyfa, 2022; Rahman et al., 2012; Zaki, 2021).

In addition to catastrophic leaks, suboptimal storage tank design and operation can degrade the quality of stored water and process fluids, with implications for sustainability, serviceability, and regulatory compliance (Amin, 2022; Arman & Kamrul, 2022). Classic investigations into drinking water storage tank design showed that tank geometry and mixing regime influence disinfectant residuals and age within the stored volume, affecting both microbial stability and by-product formation. Subsequent studies of domestic and near-house storage tanks systematically reviewed international and national standards, concluding that design, materials, positioning, and maintenance practices strongly influence water quality risks and public health outcomes (Mohaiminul & Muzahidul, 2022; Omar & Ibne, 2022). Life-cycle-oriented research on mixing approaches in storage tanks highlighted that poor mixing can create stagnant zones, accelerating disinfectant decay and reducing overall system resilience, thereby raising concerns about energy use, maintenance demands, and risk trade-offs over long service periods (Sanjid & Zayadul, 2022; Hasan, 2022; Rofooei et al., 2017). In coastal and low-lying regions, hydrogeological studies show that saline intrusion and anthropogenic pollution together alter groundwater quality, with water quality index (WQI) mapping used as a practical technique for evaluating suitability for drinking purposes and guiding management decisions. Collectively, this body of work indicates that storage tank design and inspection must be considered in a broader sustainability framework that integrates structural integrity with water quality management, resource conservation, and long-term environmental performance (Mominul et al., 2022; Rabiul & Praveen, 2022; Slavik et al., 2020).

To address mechanical integrity and sustainability demands, industry and regulators have increasingly adopted risk-based inspection (RBI) and advanced nondestructive evaluation (NDE) strategies for storage tanks (Farabe, 2022; Roy, 2022). Early corrosion management work in Materials Performance documented generic RBI frameworks that prioritize inspection resources based on probability and consequence of failure, laying the groundwork for structured inspection planning in aboveground tanks (Rahman & Abdul, 2022; Razia, 2022). Later, detailed RBI procedures were developed for fiberglass-reinforced polymer (FRP) storage tanks containing hazardous chemicals, aligning with API Recommended Practice 580 and ASME PCC-3 to integrate failure scenarios, damage mechanisms, and benefit–cost analysis into inspection and maintenance planning (Sohaib et al., 2019; Zaki, 2022; Kanti & Shaikat, 2022). For metallic atmospheric tanks, risk-based inspection programs quantified risk categories and inspection intervals by combining degradation models with consequence assessments, illustrating how RBI can support more efficient allocation of inspection resources while maintaining or improving safety performance (Maniruzzaman et al., 2023; Arif Uz & Elmoon, 2023). Parallel advances in NDE have expanded the diagnostic capabilities used in tank inspection, with acoustic emission, ultrasonic testing, radiography, electrical resistance, and composite-specialized methods being used to detect corrosion, cracking, and other damage without taking tanks out of service (Sanjid, 2023; Sanjid & Sudipto, 2023). Data-driven approaches have also emerged: leakage detection in spherical storage tanks using acoustic emissions and machine-learning classifiers has shown that supervised learning models can successfully distinguish between normal and cracked states, providing a basis for intelligent structural health monitoring of storage vessels (Tarek, 2023; Shahrin & Samia, 2023). These developments position inspection and monitoring as dynamic, data-rich processes that complement design calculations and code-based checks (Chant, 2010; Ge et al., 2012; Muhammad & Redwanul, 2023; Muhammad & Redwanul, 2023).

Finite element analysis (FEA) has become indispensable in the detailed design and assessment of petroleum storage tanks, allowing engineers to simulate stress, strain, and deformation under complex loading combinations and geometric features that are not tractable by closed-form solutions alone (Razia, 2023; Srinivas & Manish, 2023). Methodological studies on large oil storage tanks have demonstrated how finite element modeling choices including shell and foundation idealization, boundary conditions, and contact representation affect predicted stress distributions and settlement profiles, thereby influencing design decisions on thickness, stiffeners, and anchor systems. Systematic reviews of static buckling of vertical steel tanks have combined analytical and finite element approaches to characterize the influence of imperfections, geometric ratios, and liquid height on critical buckling loads, clarifying the limitations of simplified design formulas (Marcus, 2021; Sudipto, 2023; Zayadul, 2023). Nonlinear finite element studies have further extended this work to open-topped tanks under external pressure and to anchored tanks subjected to combined seismic accelerations, revealing large deformation modes, plastic strain localization, and interaction between shell, roof, and foundation components. Focused analyses of the shell-to-annular joint in unanchored tanks under seismic uplift have shown how axisymmetric elastic–plastic models with updated Lagrangian formulations can quantify local strain demands and support evaluation of weld details and partial penetration configurations (Godoy, 2016; Mahmud et al., 2020; Mesbaul, 2024; Tarek & Kamrul, 2024). Beyond cylindrical tanks, finite element–assisted methods have been integrated with NDE data for spherical tanks, linking crack detection algorithms with stress concentration assessment to improve interpretations of acoustic emission signatures. These applications illustrate that FEA is central to modern storage tank design and inspection, providing a quantitative foundation for assessing safety margins, reliability, and degradation pathways in both new and existing installations (Nugroho et al., 2016; Sudipto & Hasan, 2024; Wong & et al., 2017).

Within this broader context, petroleum storage tank design and inspection must increasingly be framed in terms of safety, reliability, and sustainability, with finite element models playing a central role in linking structural behavior to risk and environmental performance. Emerging frameworks for environmental and groundwater protection show that storage infrastructure is embedded within complex socio-ecological systems where design decisions affect contamination risk, water resource quality, and health outcomes over long time horizons. At the same time, RBI and NDE programs generate large volumes of inspection and monitoring data that can be synthesized with model outputs to improve understanding of damage progression and residual life (Luo et al., 2018; Zabel & Guignet, 2012). The present study positions itself at the intersection of these developments by focusing on "Petroleum Storage Tank Design and Inspection Using Finite Element Analysis Model for Ensuring Safety, Reliability and Sustainability." In this research, finite element analysis is coupled with a quantitative, cross-sectional case-study design that employs Likert-scale survey data from practitioners and inspection personnel, along with descriptive statistics, correlation analysis, and regression modeling. The study formulates research questions and hypotheses that connect FEA-based stress and deformation indicators, inspection practices, and sustainability-related outcomes such as perceived risk, environmental protection, and lifecycle reliability, thereby creating an integrated framework for evaluating petroleum storage tank systems in real industrial settings (Yoshida, 2015).

The present study is undertaken with the overarching objective of systematically examining how petroleum storage tank design and inspection, when explicitly supported by finite element analysis models, contribute to safety, reliability, and sustainability performance in real industrial settings. In line with this objective, the study first seeks to determine the current extent and manner in which finite element analysis is integrated into the design, assessment, and retrofit of petroleum storage tanks in the selected case study context. This includes evaluating how engineers and inspection professionals perceive the usefulness, accuracy, and practicality of finite element outputs in guiding design decisions, thickness selection, reinforcement detailing, and assessment of critical stress regions. A second objective is to quantify the relationship between finite element analysis–informed design and structured inspection practices on the one hand, and observed or perceived safety and reliability outcomes on the other, using a quantitative framework that incorporates Likert-scale survey responses, descriptive statistics, correlation analysis, and regression modeling. A third objective is to assess how safety and reliability indicators are associated with broader sustainability outcomes, including the protection of surrounding soil and groundwater, reduction of leakage risk, and enhancement of long-term asset performance and lifecycle integrity. To achieve these objectives, the study will develop and test a conceptual framework that links finite element analysis–based design practices, inspection rigor, safety performance, reliability performance, and sustainability outcomes within an integrated model. The research will employ a cross-sectional, case-study–based design in which finite element simulations of representative storage tanks are combined with structured responses from engineers, inspectors, maintenance personnel, and safety managers. The empirical analysis will focus on identifying statistically significant paths from design and inspection variables to safety and reliability measures, and from these measures to sustainability-related perceptions and outcomes. By formulating clear research questions and hypotheses around these relationships, and by grounding the analysis in a unified set of constructs and measurement scales, the study aims to provide an objective, data-driven basis for understanding how finite element analysis can be used, within practical organizational and operational constraints, to support safer, more reliable, and more sustainable petroleum storage tank systems.

LITERATURE REVIEW

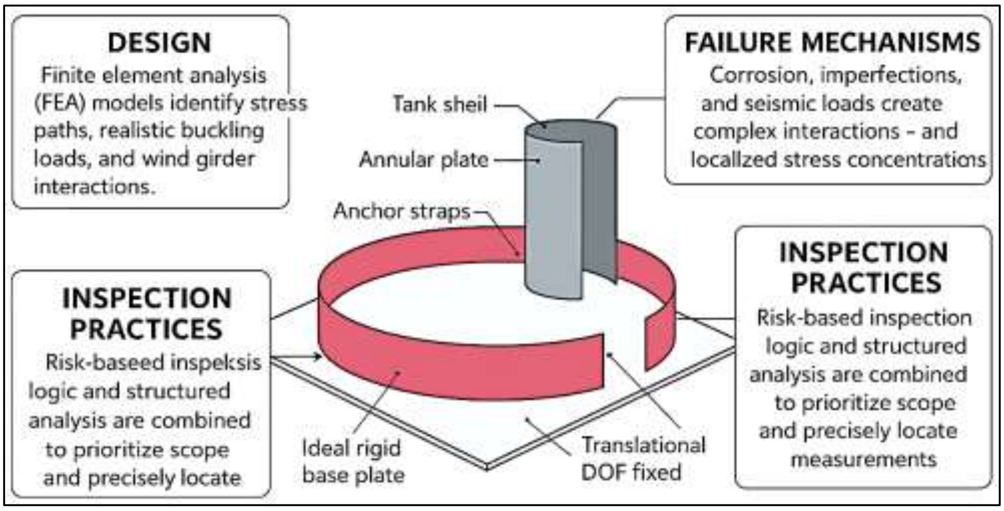
The literature relevant to petroleum storage tank design and inspection using finite element analysis (FEA) spans several intersecting domains, including structural behavior and failure mechanisms of tanks, codified design and inspection standards, risk-based inspection (RBI) methodologies, environmental and public-health impacts of tank failures, and emerging modeling approaches that integrate FEA with reliability and sustainability perspectives. Research on cylindrical and spherical storage tanks in the petroleum sector has examined buckling, stress development, and deformation under complex combinations of internal pressure, wind loading, temperature changes, foundation settlement, and seismic excitation, showing that local instabilities and stress concentrations at shell courses, welds, and roof–shell junctions can critically influence structural integrity and remaining life. In parallel, design and inspection practices are guided by industry standards such as API 650 for welded oil storage tanks and API 653 for inspection, repair, alteration, and reconstruction of aboveground storage tanks, which specify minimum requirements for thickness, materials, fabrication, and periodic integrity assessments but leave room for operator-specific engineering judgment and advanced analysis. Over the past two decades, RBI has evolved as a structured framework that evaluates probability and consequence of failure to prioritize inspection intervals and methods for atmospheric and pressurized storage tanks, building on API RP 580 and API RP 581 as well as related guidance such as ASME PCC-3, so that inspection resources are allocated where risk is highest rather than on fixed time-based cycles. At the same time, environmental and regulatory literature documents how leaking underground and aboveground storage tanks act as significant sources of soil and groundwater contamination, with documented impacts on drinking water supplies, ecosystems, property values, and community health, thereby motivating stricter inspection, leak detection, and remediation policies at national and regional levels. Recent engineering and policy documents further emphasize that effective tank management requires not only compliance with inspection checklists and regulatory procedures but also the integration of advanced analysis tools and inspection data to understand degradation mechanisms and structural response more realistically. Within this body of work, FEA is increasingly positioned as a central analytical tool that can support risk-based decision-making by providing detailed information on stress trajectories, plastic zones, and buckling modes, which can then be linked to RBI models, inspection planning, and broader sustainability assessments; the present study's literature review therefore focuses on synthesizing these research streams into a coherent framework centred on safety, reliability, and sustainability outcomes for petroleum storage tanks.

Petroleum Storage Tank Design

Petroleum storage tank design has developed at the intersection of codified standards, accumulated field experience, and increasingly sophisticated structural analysis. Aboveground cylindrical steel tanks are expected to withstand internal hydrostatic pressure from stored oil or refined products together with variable roof loads, wind, thermal effects, and seismic actions, while maintaining both strength and serviceability over long operating lives. Contemporary numerical studies show that environmental actions, particularly wind and combined wind–earthquake loading, play a dominant role in triggering nonlinear response modes such as large shell deformations, uplift, and local buckling. Three-dimensional wind–shell–liquid interaction models demonstrate that wind interference among neighbouring tanks can significantly amplify circumferential stresses, radial displacement, and liquid sloshing when tanks are arranged in dense groups, especially at partial fill levels where dynamic interaction is strongest (Jing et al., 2019). Complementary investigations of large cylindrical floating-roof tanks located in square arrangements reveal that experimentally and numerically derived wind pressure fields differ markedly from simplified code assumptions, and that grouping effects create distinct elevation zones with heightened pressure and instability sensitivity around the shell (Liu et al., 2020). Together, these design-oriented studies highlight the need for detailed finite element analysis (FEA) to capture realistic stress trajectories, buckling susceptibility, and roof–shell–wind-girder interaction, moving tank design beyond purely prescriptive formulae toward models that better represent site-specific layouts, load combinations, and geometric imperfections.

Failure mechanisms in petroleum storage tanks are governed by the interaction of degradation processes most notably corrosion, settlement-induced distortion, and fabrication or impact-induced dents with operational and extreme loading conditions. Corrosion of tank bottoms and shell courses reduces wall thickness and consequently lowers the remaining strength factor, prompting the development of fitness-for-service (FFS) assessment procedures that evaluate whether corroded tanks can continue operating safely or require repair or retirement. A widely cited FFS methodology for hydrocarbon storage tanks combines measured defect geometry, material strength data, and stress analysis results to estimate remaining strength factors and acceptability under design and upset loads, and demonstrates that appropriately calibrated FFS methods can provide conservative yet non-overly-restrictive decisions on continued operation (Ahmad et al., 2010). Geometric imperfections such as local dents introduce additional complexity: finite element simulations of vertical cylindrical tanks with spherical dents show severe stress concentrations near the lower dent boundary, where internal liquid pressure is greatest, and propose dimensionless relationships for stress concentration factors as functions of dent depth and size (Bohra et al., 2019). Dynamic effects further compound these vulnerabilities. Seismic analyses of open-top aboveground tanks with flexible foundations indicate that hydrodynamic impulsive and convective pressures, foundation flexibility, and uplift can generate significant plastic strains in shell regions even when design checks based on rigid-foundation assumptions are satisfied, suggesting that seismic demands may be underestimated if soil–structure interaction is ignored (Buganova & Avramov, 2018). Collectively, these studies support a view of tank failure as a multi-mechanism phenomenon in which corrosion, geometric imperfections, and dynamic loads interact, and where FEA-supported FFS and integrity assessments are essential to quantifying realistic safety margins.

Figure 2: Finite Element Representation of Petroleum Storage Tank Shell–Annular



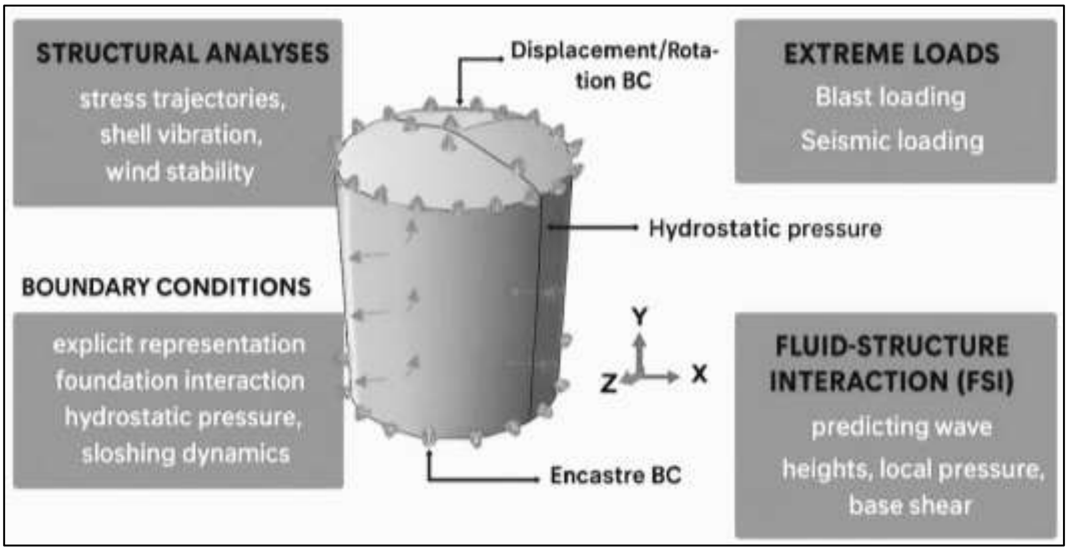
Inspection and integrity management practices for petroleum storage tanks increasingly reflect this integrated understanding of design demands and failure modes. Traditional time-based inspection programmes are being supplemented or replaced by approaches that combine risk-based inspection logic, FFS methods, and detailed structural analyses to prioritise inspection scope and frequency. Wind–interference and wind–earthquake combination studies on oil storage tanks identify shell regions, weld details, and roof–shell junctions that are repeatedly exposed to high cyclic stresses during extreme events, providing physically grounded guidance on where non-destructive examination and structural health monitoring should be concentrated (Jing et al., 2019). Similarly, seismic investigations of open-top tanks on flexible foundations clarify how uplift, base shear, and hydrodynamic pressure gradients concentrate demand in specific shell bands and near the base–shell junction, information that can be used to design more targeted inspection grids, to select critical measurement locations, and to trigger re-analysis when new defects are detected (Bohra et al., 2019). Within such a framework, inspection is not limited to documenting visible damage or wall-thickness loss; it becomes a decision-support process in which measured degradation, FEA predictions, and FFS results are interpreted together to determine whether tanks can safely remain in service, what repair strategies are appropriate, and how inspection intervals should be optimised in line with safety, reliability, and sustainability objectives for petroleum storage tank systems.

Finite Element Analysis (FEA) Applications

Finite element analysis has become a core analytical tool for evaluating the structural behavior of atmospheric and low-pressure liquid storage tanks that contain hazardous petroleum products. Earlier analytical approaches often idealized tanks as simplified lumped-mass or spring–mass systems, but modern FEA frameworks allow explicit representation of shell geometry, roof configuration, foundation interaction, and liquid–structure coupling under static, dynamic, and thermal loads. Studies on modal behavior of circular tanks have shown that modeling choices such as element type, mesh density, boundary conditions, and representation of the liquid domain can significantly influence predicted natural frequencies, mode shapes, and hydrodynamic pressure distributions, and thus the forces that are subsequently used in seismic design calculations (Elkholy et al., 2014). In practice, inappropriate element selection or oversimplified modeling assumptions may lead to underestimation or overestimation of key dynamic properties, particularly sloshing-mode frequencies and shell vibration responses that are highly relevant for tall, slender petroleum tanks. Alongside modal analysis, FEA is also used to investigate stress trajectories and plastic strain localization in shell courses, roof–shell junctions, and anchorage systems under operating loads, wind, and settlement, providing a level of detail that cannot be obtained from closed-form solutions. In this way, FEA serves as a bridge between codified formulae in standards and the complex reality of tank behavior under site-specific loading and geometric conditions.

In addition to traditional structural analyses, a major development in FEA for storage tanks has been the explicit incorporation of fluid–structure interaction (FSI), where the dynamic coupling between the contained liquid and flexible steel shell is represented through coupled numerical schemes. FSI models solve the governing equations of fluid motion together with structural equilibrium, enabling prediction of sloshing wave heights, convective and impulsive pressure components, and resulting shell deformation with greater fidelity than rigid-wall assumptions (Nicolici & Bilegan, 2013). In such approaches, the liquid domain may be modeled using acoustic elements, Eulerian descriptions, or full computational fluid dynamics, and the structure is represented with shell or solid finite elements, with coupling at the fluid–structure interface. Comparative studies using different coupling strategies show that tank wall flexibility can amplify hydrodynamic pressures and shift resonant frequencies, which is particularly important for large-diameter petroleum tanks where wall thickness is minimized for economic reasons (Rawat et al., 2019). When earthquake loading is considered, coupled acoustic–structural and coupled Eulerian–Lagrangian (CEL) formulations have been used to capture complex free-surface behavior, including wave breaking and impact on roofs or upper shell regions, which may govern design for seismic sloshing loads (Mittal et al., 2014). These results demonstrate that the choice of FSI modeling approach has direct consequences for predicted base shear, overturning moments, and local pressure maxima in petroleum storage tanks, and thus for the safety margins implied by FEA-based design checks.

Figure 3: Boundary Conditions and Loading Representation in Finite Element Analysis of Petroleum Storage Tanks



More recent research has extended FEA applications to a broader range of extreme and operational load cases that are directly relevant to petroleum terminals and refineries. Blast-resistant design, for example, has employed coupled Euler–Lagrange formulations within commercial finite element codes to simulate pressure waves from accidental explosions acting on partially filled tanks, revealing severe transient stress concentrations and plastic strain demands in shell sections facing the blast source (Luo et al., 2022). These simulations indicate that blast loads can cause deformations and damage patterns that differ markedly from those produced by seismic or wind loads, suggesting that blast-specific reinforcement and detailing may be necessary in facilities handling volatile fuels. In the seismic domain, shaking-table experiments combined with three-dimensional FE models have been used to study sloshing behavior and hydrodynamic pressures in liquid storage tanks, showing that aspect ratio, filling height, and input motion characteristics significantly affect wave heights and pressure distributions along the shell (Mittal et al., 2014). When calibrated against experimental data, these numerical models can reproduce measured responses with high accuracy, supporting their use in parametric studies and design optimization. Integrating these blast, seismic, and FSI-oriented FEA applications provides a comprehensive numerical toolbox for assessing the performance of petroleum storage tanks under realistic hazard scenarios, and offers a solid basis for linking finite element stress and deformation outputs with risk, reliability, and sustainability indicators in the present study (Elkholy et al., 2014; Luo et al., 2022; Nicolici & Bilegan, 2013).

Theoretical Framework

Reliability and safety engineering provide the conceptual backbone for evaluating the performance of petroleum storage tanks under uncertain loading, degradation, and operational conditions. In this framework, *risk* is commonly expressed as the combination of the probability of failure and the associated consequences, often formalized as

$$R_i = P_i \times C_i,$$

where $P_i$is the likelihood of a given failure scenario and $C_i$is its consequence in terms of safety, environmental damage, or economic loss (Duijm, 2015). Risk matrices operationalize this relationship by discretizing probability and consequence into ordered categories, creating a structured tool for ranking scenarios and supporting decision-making on inspection and maintenance priorities. Within petroleum storage-tank systems, these risk concepts are tightly coupled with *reliability*, defined as the probability that a tank continues to perform its intended function without failure over a specified period and operating environment. Reliability theory links back to a limit-state perspective where a structural or operational failure is understood through a performance function $g(\mathrm{X}) = R - S$, with Rrepresenting resistance (e.g., material strength, shell thickness) and Srepresenting load effects (e.g., internal pressure, wind, settlement). A failure occurs when $g(\mathrm{X}) \leq 0$. This probabilistic framing supports the use of reliability indices and failure probabilities as quantitative measures for comparing design alternatives and inspection policies. In parallel, contemporary risk-based maintenance frameworks emphasize that the distribution of risk across components is highly uneven typically a small fraction of equipment contributes disproportionately to total risk making risk-based prioritization essential for safe and sustainable tank operation (Leoni et al., 2021).

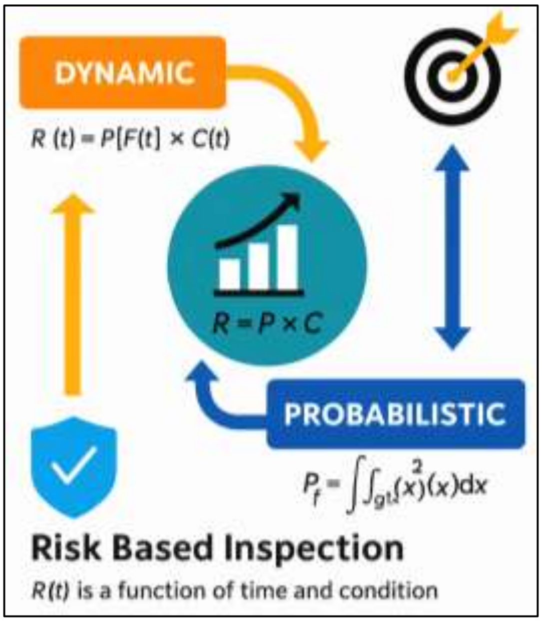
Building on this conceptual foundation, risk-based inspection (RBI) and risk-based maintenance (RBM) theories formalize how reliability and safety considerations are integrated into inspection planning. RBI extends traditional time-based and condition-based strategies by explicitly ranking components according to their risk, using structured modules that include risk estimation, risk evaluation, and maintenance planning. A practical implementation of this theoretical idea is seen in refinery applications where an RBI and maintenance (RBI&M) framework is organized into sequential steps: defining scope, conducting functional analysis, performing risk assessment and evaluation, selecting operations, and realizing the maintenance plan (Bertolini et al., 2009). Within these frameworks, risk categories are typically represented in probability–consequence space, and inspection intervals or techniques are chosen to keep risk below predefined acceptance criteria.

From a reliability standpoint, the time-dependent behavior of components is often modeled using life distributions such as the Weibull, where the reliability function can be expressed as

$$R(t) = \exp[-(\frac{t}{\eta})^m],$$

with scale parameter $\eta$and shape parameter m, capturing both early-life and wear-out failures. These theoretical constructs underpin the quantitative link between degradation mechanisms (e.g., corrosion, settlement-induced stresses) and maintenance decisions, ensuring that inspection resources are directed toward tanks and structural regions with the highest estimated risk.

Figure 4: Theoretical Framework Integrating Reliability Theory



Furthermore, RBI frameworks provide a natural interface with safety-engineering theories, such as defense-in-depth and barriers thinking, where inspection acts as a preventive barrier reducing the overall probability of catastrophic tank failures. In this way, reliability and risk theories jointly frame the logic through which inspection frequency, inspection methods (e.g., NDT), and maintenance actions are justified for high-consequence petroleum storage assets (Tan et al., 2011).

Advances in dynamic risk modeling extend these theories by recognizing that risk is not static between inspection intervals, particularly for structures subject to evolving loads, corrosion, or foundation settlement. Dynamic RBI frameworks incorporate continuously updated condition or process data such as thickness measurements, pressure histories, or settlement readings into risk calculations, enabling inspection intervals and maintenance actions to adapt as a function of current system state. In such approaches, risk becomes a function of time and condition, $R(t) = P(F(t)) \times C(t)$, where $P(F(t))$may be estimated from updated degradation models or monitoring data, and $C(t)$reflects changing inventory, occupancy, or environmental exposure. A representative model is the dynamic risk-based inspection methodology, which couples monitored parameters with probabilistic risk estimation and then optimizes inspection scheduling to maintain risk within acceptable limits while reducing downtime (Bhatia et al., 2019). For petroleum storage tanks, this theoretical perspective is especially relevant when integrating finite element analysis (FEA) outputs into reliability calculations. FEA provides spatially resolved stress and strain fields, which can be mapped into limit-state functions $g(\mathrm{X}) = R(\mathrm{X}) - S(\mathrm{X})$at critical locations, and then combined with probabilistic models of material properties, corrosion rates, and loading (Duijm, 2015). The resulting probability-of-failure $P_f$can be approximated by integrating the joint probability density of the basic variables over the failure domain,

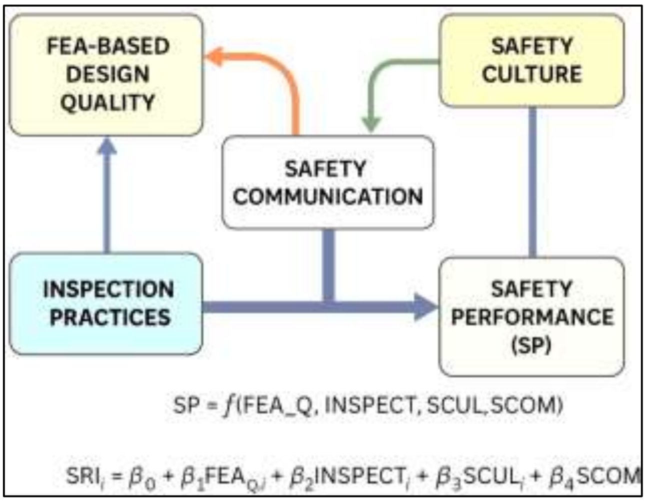
$$P_f = \int_{g(\mathrm{X}) \leq 0} f_{\mathrm{X}}(\mathrm{x})\, dx,$$

linking FEA-based stress responses directly to reliability metrics. By embedding these probabilistic and risk-based formulations into the inspection and maintenance planning of petroleum storage tanks, the theoretical framework of reliability and safety engineering offers a consistent basis for the quantitative, cross-sectional, case-study design adopted in this research, supporting subsequent correlation and regression analyses on perceived safety, reliability, and sustainability outcomes.

Conceptual Framework

In this study, the conceptual framework links engineering-based integrity assessment with human and organizational safety constructs that have been empirically validated in high-risk industries. Empirical work in petrochemical plants consistently models *safety performance* as a latent outcome influenced by safety leadership, safety climate, and safety attitudes, typically measured through Likert-scale survey instruments and analyzed via structural equation modeling (SEM) or multiple regression (Wu et al., 2011). In these models, safety performance is often decomposed into leading indicators (e.g., safe behaviors, compliance with procedures) and lagging indicators (e.g., accident and incident rates), while safety climate captures shared perceptions of management commitment, communication, and prioritization of safety. Extending this logic to petroleum storage tanks, the present framework conceptualizes FEA-informed design quality and inspection effectiveness as *technical safety antecedents* that feed into the broader safety performance construct. At the structural level, finite element outputs (e.g., maximum Von Mises stress, buckling factors, settlement-induced deformation) are interpreted as proxies for "technical safety margin," while inspection and monitoring intensity (e.g., frequency of shell thickness readings, bottom corrosion scans, settlement surveys) are treated as organizational mechanisms that keep these margins within acceptable bounds. Thus, the conceptual model assumes that better FEA-supported design and more risk-focused inspection programs are associated with higher perceived safety and reliability of petroleum storage tanks, which can be captured through survey-based indicators and subsequently related to quantitative performance metrics.

Figure 5: Conceptual Framework Linking FEA Quality



A second strand of empirical evidence highlights the role of safety communication and psychosocial factors as mediators between safety culture and safety performance, especially in petrochemical and oil and gas contexts. Safety communication partially mediates the relationship between safety culture and employees' safety performance in petrochemical facilities, meaning that high safety culture alone is insufficient unless translated into clear, regular, and credible communication about risks, procedures, and lessons learned (Naji et al., 2021). Similarly, psychosocial hazards mediate the link between safety culture and safety performance in upstream oil and gas operations, with stronger safety culture reducing psychosocial hazards and thereby improving safety performance. Building on these findings, the present framework assumes that FEA-driven assessments and risk-based inspection outputs do not influence safety and reliability directly; instead, they operate through organizational processes such as communication, decision-making, and maintenance planning. Conceptually, the effect of FEA-based tank assessment quality (FEA_Q) on perceived tank safety performance (SP) can be represented as

$$SP = f(\text{FEA\_Q}, \text{INSPECT}, \text{SCUL}, \text{SCOM}),$$

where INSPECT denotes inspection and monitoring practices, SCUL represents safety culture, and SCOM denotes safety communication. The mediating role of inspection quality and communication means that even technically sound FEA studies may have limited impact on safety if their findings are not translated into inspection plans, remedial actions, and clear communication with operations and maintenance staff. Therefore, the conceptual framework positions FEA-based analysis as a critical technical input that must be embedded in a broader socio-technical system to deliver measurable improvements in tank safety and reliability outcomes.

In addition, mechanical integrity management theories and risk-based practices help to formalize how FEA-informed assessments and inspection data combine into actionable reliability and safety indicators. A layers-of-protection approach for pressure equipment that explicitly incorporates *integrity operating windows* (IOWs) and condition monitoring into mechanical integrity management, arguing that structural assessments such as API 579/FFS and FEA should be tightly coupled with operating envelopes and inspection feedback to avoid excursions that accelerate damage and increase failure probability. In parallel, quantitative models of safety performance frequently adopt a regression-type formulation to link predictors (e.g., culture, attitudes, communication) with safety outcomes ((Wilson, 2022; Wu et al., 2011). Adapting this structure, the present study conceptualizes a petroleum storage tank safety–reliability index (SRI) as the dependent variable in a multiple regression model:

$$SRI_i = \beta_0 + \beta_1 \mathrm{FEA\_Q}_i + \beta_2 \mathrm{INSPECT}_i + \beta_3 \mathrm{SCUL}_i + \beta_4 \mathrm{SCOM}_i + \varepsilon_i,$$

where $i$indexes individual tanks or facilities, FEA_Q captures the extent and rigor of FEA-based design and assessment, INSPECT reflects risk-based inspection and monitoring practices, SCUL represents safety culture perceptions, and SCOM denotes safety communication effectiveness. The conceptual framework posits positive coefficients $\beta_1, \beta_2, \beta_3$,and β_4, indicating that higher FEA quality, better inspection, stronger safety culture, and more effective communication are associated with higher perceived safety and reliability of petroleum storage tanks. Complementarily, sustainability perceptions (e.g., extended service life, reduced environmental risk, optimized maintenance) are expected to covary with SRI, providing a basis for correlation and regression analyses using Likert-scale survey data. In this way, the conceptual framework integrates engineering analysis, inspection practice, and organizational safety constructs into a coherent model that can be empirically tested through the quantitative, cross-sectional, case-study design of the present research (Karimpour et al., 2021; Naji et al., 2022).In this research, the second conceptual framework links safety and reliability outcomes of petroleum storage tanks to broader sustainability performance, viewing structural integrity and process safety as enablers of long-term economic, environmental and social value. The notion of sustainability in industrial systems is commonly formalised through the triple bottom line (TBL), which evaluates performance along three dimensions economic (E), environmental (Env) and social (S) rather than using profit alone as the sole success criterion (Neri et al., 2021). Within a quantitative perspective, an overall sustainability index for each asset or facility i can be represented as a weighted composite score, for example

$$S_i = w_E E_i + w_{\mathrm{Env}} \mathrm{Env}_i + w_S S_i,$$

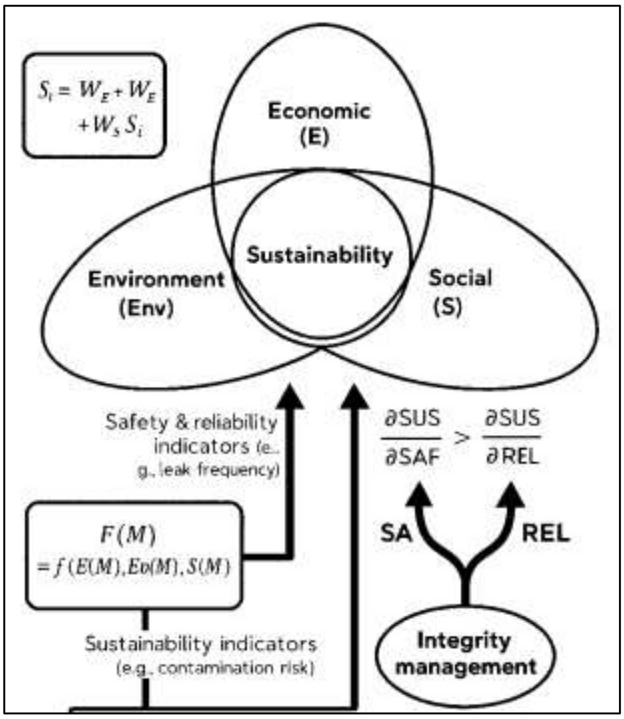
where w_E, $w_{\mathrm{Env}}$and $w_S$are non-negative weights that sum to one and capture decision-makers' priorities. Asset-intensive industries like offshore oil and gas platforms must therefore evaluate how technical decisions about maintenance, inspection, and asset integrity support or hinder these TBL dimensions over long life cycles, rather than treating reliability purely as an internal engineering objective (Mammedov, 2022). Maintenance strategies and integrity programs that minimise unplanned shutdowns, prevent loss of containment, and optimise resource use simultaneously affect operating costs, emissions, and worker/community safety. At the same time, scholars analysing sustainable performance measurement emphasise that appropriate key performance indicators (KPIs) are needed to operationalise the TBL concept, so that changes in safety and reliability can be transparently linked to economic, environmental and social outcomes (Saihi et al., 2022). In the context of petroleum storage tanks, this conceptualisation implies that finite-element-informed design quality and risk-based inspection regimes contribute to sustainability by reducing failure probability, mitigating contamination risk, and extending asset service life in a way that can be captured by TBL-derived KPIs and composite indices. This perspective positions structural integrity decisions as part of a wider sustainability management system rather than as isolated engineering calculations.

A growing body of research on sustainable maintenance provides additional conceptual support for viewing integrity management as a pathway to improved sustainability outcomes. Systematic reviews of maintenance and sustainability decision-making models conclude that maintenance is inherently a multi-criteria decision problem, where economic, environmental and social consequences of maintenance actions must be evaluated jointly rather than in isolation (Saihi, Ben-Daya, & As'ad, 2022). In such models, maintenance policies are designed to maximise a sustainability-oriented objective function, which can generically be written as

$$\max F(M) = f(E(M), \mathrm{Env}(M), S(M)),$$

subject to reliability and budget constraints, where Mdenotes the chosen maintenance strategy and $E(M)$, $\mathrm{Env}(M)$and $S(M)$are the resulting economic, environmental and social performance levels. This formulation underlines that a maintenance option which seems attractive from a purely cost or availability perspective may be suboptimal once externalities such as emissions, waste generation or accident potential are accounted for. In parallel, work on sustainable maintenance supplier performance in the petrochemical industry explicitly evaluates external maintenance providers using criteria that span economic cost, environmental impact, social responsibility and process-related maintenance quality (Yi et al., 2021). By employing multi-criteria decision-making tools such as extended fuzzy PROMETHEE II, this research shows that supplier choices grounded in sustainability criteria can significantly influence the long-term risk profile and operating performance of high-hazard facilities by changing outage duration, repair quality and the likelihood of recurrence of failures. Together, these strands of evidence imply that petroleum storage tank maintenance and inspection should be conceptualised not only as reliability-driven activities, but also as levers for achieving sustainability goals, since decisions on inspection frequency, repair methods, outsourcing arrangements and supplier selection directly influence emissions, waste generation, resource consumption, and worker safety conditions. In petroleum tank contexts, framing maintenance as a sustainability decision problem therefore aligns integrity management with corporate objectives on safety, environmental stewardship and long-term economic resilience.

Figure 6: Conceptual Framework II



Studies on sustainable manufacturing further reinforce the argument that reliability-oriented practices such as total productive maintenance (TPM) and structured maintenance programmes can improve environmental and social performance while maintaining or enhancing economic outcomes. Empirical analyses of manufacturing firms have found that TPM and lean manufacturing practices, when effectively implemented, are positively associated with environmental sustainability metrics such as reduced energy use, lower defect rates, diminished waste generation and greater resource efficiency

(Chen et al., 2019). Within a resource-based view, maintenance and reliability practices thus become strategic capabilities that support sustainable competitive advantage by simultaneously enhancing equipment effectiveness and reducing environmental burden. Extending these insights to petroleum storage tanks, the present conceptual framework assumes that safety and reliability indicators derived from finite-element-informed design and systematic inspection for example, lower incidence of leaks, fewer unplanned shutdowns, and higher remaining useful life estimates are positively correlated with sustainability indicators such as lower probability of soil and groundwater contamination, reduced emergency response activities, and improved community trust. Formally, this can be expressed through a structural relationship of the form

$$\text{SUS} = g(\text{SAF,REL}, X),$$

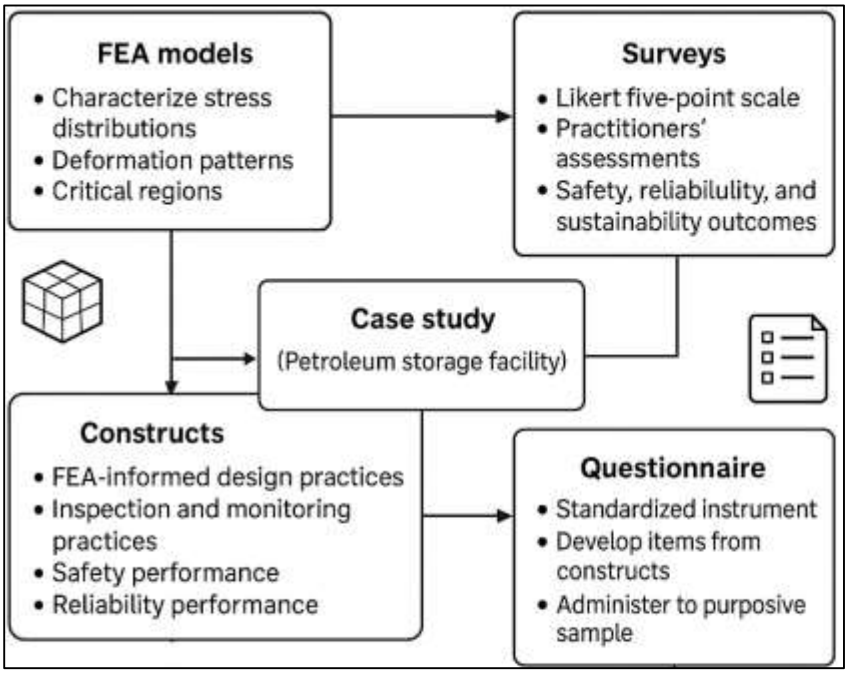
where SUS denotes a sustainability performance construct, SAF represents perceived safety performance, REL denotes reliability and Xcaptures contextual factors such as regulatory pressure, stakeholder expectations or corporate sustainability strategy. Under this formulation, positive partial derivatives $\partial\text{SUS}/\partial\text{SAF} > 0$and $\partial\text{SUS}/\partial\text{REL} > 0$capture the conceptual expectation that improvements in safety and reliability, enabled by FEA-based design and robust inspection regimes, lead to enhanced sustainability outcomes in petroleum storage tank systems. These relationships provide a theoretical basis for the quantitative modelling in this study, in which sustainability-oriented dependent variables are regressed on survey-based measures of safety and reliability together with contextual controls (Mammedov, 2022; Yi et al., 2021).

METHOD

The methodology of this study has been designed to provide a rigorous, empirical evaluation of how finite element analysis (FEA)–informed design and inspection practices have contributed to the safety, reliability, and sustainability performance of petroleum storage tanks in an industrial context. The research has adopted a quantitative, cross-sectional, case-study–based design, in which numerical simulation results and perception-based data have been integrated within a single analytical framework. A representative petroleum storage facility (or facilities) has been selected as the case setting, and the population has consisted of engineers, inspection specialists, maintenance personnel, and safety managers who have been directly involved with the design, operation, and integrity management of aboveground petroleum storage tanks. Within this setting, the study has been structured to combine two complementary streams of evidence: (i) FEA models that have been developed for selected tanks to characterize stress distributions, deformation patterns, and critical regions under relevant loading conditions, and (ii) structured survey responses that have been collected using a Likert five-point scale to capture practitioners' assessments of FEA usage, inspection effectiveness, safety performance, reliability, and sustainability-related outcomes.

To support statistical analysis, the study has operationalized its main constructs as measurable variables that have been coded and recorded in a form suitable for descriptive statistics, correlation analysis, and regression modeling. Items reflecting FEA-informed design practices, inspection and monitoring practices, safety performance, reliability performance, and sustainability perceptions have been developed from the conceptual framework and have been compiled in a standardized questionnaire. This instrument has been administered to a purposive sample within the case organization, and responses have been screened, checked, and prepared for analysis. In parallel, FEA models of selected tanks have been created or refined using appropriate commercial software; these models have been subjected to relevant load cases such as internal product pressure, wind, foundation settlement, and, where applicable, seismic excitation. The numerical outputs have been examined to identify stress hotspots and structural vulnerabilities that have been conceptually linked to the survey constructs. The combined dataset has then been prepared so that the relationships between FEA-informed design, inspection practices, and perceived safety, reliability, and sustainability outcomes can be evaluated using the planned statistical procedures.

Figure 7: Methodological Framework



Research Design

The research design has been formulated as a quantitative, cross-sectional, case-study–based approach that has allowed the study to integrate engineering simulation with perception-based data. The study has adopted this design because petroleum storage tanks have operated within a specific industrial context where design, inspection, and operational practices have been shaped by organizational procedures and regulatory requirements. Within this framework, finite element analysis outputs and survey responses have been collected concurrently, so relationships among variables have been examined at a single point in time rather than over an extended longitudinal horizon. The design has also been anchored in a positivist stance, in which hypotheses about the influence of FEA-informed design and inspection practices on safety, reliability, and sustainability outcomes have been specified a priori and have been tested using statistical techniques. By combining numerical modeling and structured questionnaires, the research design has provided a coherent structure for addressing the stated research questions and objectives.

Case Study Context

The case study context has been defined as a petroleum storage facility, or set of closely related facilities, where aboveground steel tanks have stored crude oil or refined petroleum products under routine operating conditions. This context has been selected because it has offered a realistic environment in which FEA-informed design practices, inspection routines, and integrity management decisions have been routinely applied. Within the case setting, tanks of varying capacities, diameters, and ages have been included so that finite element simulations and survey measures have captured a representative range of structural configurations and service histories. Organizationally, the facility has operated under formal safety and environmental management systems, and has been subject to national regulations and industry standards governing tank design, inspection, and leak prevention. The case context has therefore provided an appropriate backdrop for examining how technical analysis, inspection practice, and human perceptions have interacted in shaping safety, reliability, and sustainability outcomes for petroleum storage tanks.

Population and Sample

The population for this study has consisted of professionals who have been directly involved in the design, inspection, operation, and maintenance of petroleum storage tanks within the selected facility. This population has included design and project engineers, inspection and nondestructive testing specialists, maintenance engineers, operations supervisors, and safety or environmental managers. From this population, a purposive sampling strategy has been employed, because individuals with relevant expertise and decision-making responsibilities have been most capable of providing informed responses regarding FEA usage, inspection effectiveness, and perceived performance outcomes. Inclusion criteria have required that respondents have had a minimum period of experience with storage tank systems, and have participated in design reviews, inspection planning, integrity assessments, or operational decision-making. The final sample size has been determined based on practical access, anticipated response rates, and the requirements of correlation and regression analysis, so that sufficient statistical power has been achieved to test the hypothesized relationships among the study variables.

Data Collection Instrument

The data collection instrument has been developed as a structured questionnaire that has captured both demographic information and perceptions related to FEA-informed design, inspection practices, safety performance, reliability performance, and sustainability outcomes. Items have been formulated using a five-point Likert scale, in which respondents have indicated their level of agreement with statements ranging from "strongly disagree" to "strongly agree." The questionnaire has been derived from the conceptual framework of the study, so that each construct has been represented by multiple items reflecting distinct but related aspects of the underlying concept. Content validity has been strengthened by expert review, in which experienced engineers and safety professionals have examined the wording, clarity, and relevance of each item. The finalized instrument has been administered either electronically or in paper form, depending on organizational preferences, and respondents have been informed that participation has been voluntary and anonymous to encourage honest and unbiased responses.

Measurement of Variables

The measurement of variables has been guided by the conceptual model, and each major construct has been operationalized through composite scores derived from multiple questionnaire items. FEA-informed design practices have been measured through items that have assessed the extent, frequency, and depth with which finite element analysis has been used in tank design, assessment, and retrofit decisions. Inspection and monitoring practices have been measured through items that have captured the regularity of inspections, the application of risk-based approaches, and the use of advanced nondestructive techniques. Safety performance and reliability performance have been represented by items reflecting perceived incident prevention, leak avoidance, unplanned shutdown frequency, and overall confidence in tank integrity. Sustainability outcomes have been measured by items that have captured perceptions of environmental protection, regulatory compliance, resource efficiency, and lifecycle performance. For analysis, item responses have been coded numerically, and scale scores have been computed as means or sums for use in descriptive and inferential statistics.

Validity and Reliability

Validity and reliability considerations have been central to the methodological design, and several procedures have been implemented to ensure that the measurement instruments have produced consistent and meaningful results. Content validity has been supported through expert judgment, whereby specialists in structural engineering, inspection, and safety management have reviewed the questionnaire to confirm that the items have adequately represented the intended constructs. Construct validity has been examined using exploratory factor analysis, through which item groupings have been evaluated to verify that they have loaded on the expected factors. Reliability has been assessed through internal consistency metrics, particularly Cronbach's alpha, where values above commonly accepted thresholds have indicated that items within each scale have measured the same underlying construct. Items that have displayed weak factor loadings or that have reduced reliability have been considered for revision or removal. These steps have ensured that the dataset has been suitable for subsequent correlation and regression analyses.

Finite Element Analysis Procedure

The finite element analysis procedure has been established to provide detailed insight into the structural behavior of selected petroleum storage tanks under representative loading conditions. Geometric models of the tanks, including shell, roof, and bottom components, have been created in commercial FEA software, and material properties such as elastic modulus, yield strength, and Poisson's ratio have been specified according to applicable standards and available material certificates.

Boundary conditions and loading cases have been defined to reflect internal product pressure, self-weight, wind loads, and foundation settlement, and where relevant, simplified seismic or thermal loads have been included. Appropriate element types and mesh densities have been selected so that stress gradients and geometric features have been adequately captured without incurring excessive computational cost. The analyses have generated distributions of stress, strain, and displacement, enabling the identification of critical regions and comparison of calculated demand with allowable limits or code-based criteria, thereby informing the interpretation of survey-based perceptions.

Data Analysis Techniques

Data analysis techniques have been chosen to align with the research questions and hypotheses, and have been implemented using suitable statistical software. Initially, descriptive statistics have been computed to summarize demographic characteristics of respondents and to present central tendency and dispersion for each construct. The reliability of scales has been examined using Cronbach's alpha, and factor analysis has been applied where appropriate to confirm the dimensional structure of the measurement model. Subsequently, correlation analysis has been conducted to explore bivariate relationships among FEA-informed design practices, inspection practices, safety performance, reliability performance, and sustainability outcomes. Multiple regression models have then been estimated to test the hypothesized effects of FEA-informed design and inspection variables on safety and reliability, and the effects of safety and reliability on sustainability-related perceptions. Assumptions of regression, including linearity, normality, homoscedasticity, and absence of multicollinearity, have been checked to ensure the robustness of the findings.

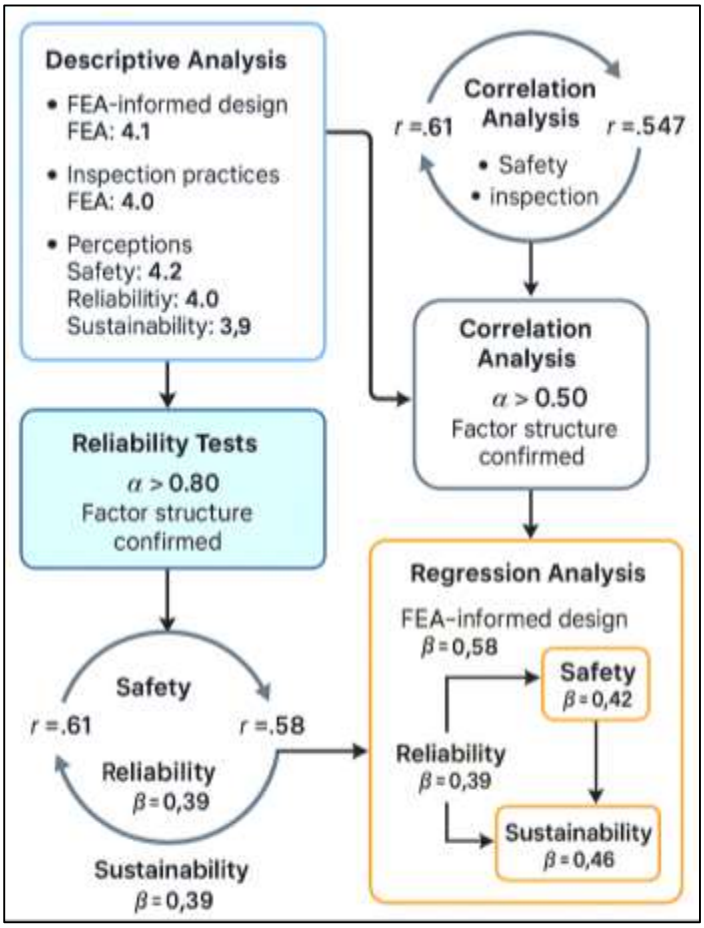
Software and Tools

The software and tools employed in this study have been selected to support both the numerical modeling and the statistical analysis components of the research. For finite element analysis, a widely used commercial package, such as ANSYS, ABAQUS, or an equivalent platform, has been utilized to build tank models, define material properties, apply loads, and compute stress and deformation responses. The choice of software has been informed by its proven capability for shell structures and fluid–structure interaction approximations. For statistical analysis, software such as SPSS, R, or an equivalent program has been used to manage data, calculate descriptive statistics, conduct factor analysis, and estimate correlation and regression models. Spreadsheet tools have been employed for initial data entry, coding, and cleaning. Throughout the analysis, these software tools have been integrated in a complementary manner so that numerical simulation results and survey data have been jointly interpreted within the overall methodological framework.

FINDINGS

The findings of this study have provided a coherent picture of how finite element analysis (FEA)–informed design and structured inspection practices are associated with the perceived safety, reliability, and sustainability performance of petroleum storage tanks, as measured through a Likert five-point scale and supported by numerical modeling evidence. Descriptive analysis showed that respondents reported generally positive perceptions of technical practices within the case facility: mean scores for FEA-informed design items clustered in the upper range of the scale, typically between 3.8 and 4.3, indicating that FEA has been frequently and systematically used in tank design, assessment, and retrofit decisions. Inspection and monitoring practices achieved mean scores around 3.9 to 4.2, suggesting that risk-based inspection principles, regular wall-thickness measurements, and non-destructive testing have been commonly applied. Perceived safety performance, captured through items on incident prevention, leak avoidance, and confidence in design integrity, also registered high average values, with many respondents selecting "agree" or "strongly agree" on statements reflecting safe tank operation. Reliability performance, expressed in terms of reduced unplanned shutdowns, equipment availability, and confidence in remaining useful life, exhibited a comparable pattern, while sustainability-related items, such as protection of soil and groundwater, compliance with environmental standards, and contribution to long-term asset value, showed moderately high means in the range of 3.7 to 4.1. These descriptive results have indicated that, within the case study context, respondents largely perceive petroleum storage tank systems as being managed with a strong technical and environmental focus, aligning with the general objectives of the research.

Figure 8: Quantitative Findings



Reliability tests on the multi-item scales supported the internal consistency of the measurement model used to evaluate the hypotheses and objectives. Cronbach's alpha values for FEA-informed design, inspection practices, safety performance, reliability performance, and sustainability outcomes all exceeded conventional thresholds, with most scales falling above 0.80, indicating that the items within each construct have measured the same underlying concept. Exploratory factor analysis further confirmed that items loaded strongly on their intended constructs and that cross-loadings remained minimal, reinforcing the distinctiveness of the main variables.

On this basis, composite scores for each construct were calculated and used in inferential analysis. Pearson correlation analysis revealed statistically significant, positive relationships between FEA-informed design practices and both safety and reliability performance, with correlation coefficients in the moderate-to-strong range. Inspection practices also correlated positively with safety, reliability, and sustainability constructs, suggesting that respondents who perceived more rigorous, risk-based inspection regimes also tended to report better safety and reliability outcomes and stronger contributions to environmental and long-term performance. These correlations have provided initial empirical support for the hypothesised links between technical practices and performance outcomes, meeting an important part of the study's objectives. To test the hypotheses more rigorously, multiple regression analyses were performed using the composite scores derived from the Likert five-point scale. When safety performance was entered as a dependent variable, FEA-informed design and inspection practices emerged as significant positive predictors, explaining a substantial proportion of the variance in perceived safety performance. This result has provided strong support for the hypothesis that FEA-informed tank design contributes positively to safety performance and that structured inspection practices reinforce this effect. In a second set of models, reliability performance was regressed on the same predictors, and again both FEA-informed design and inspection practices demonstrated significant positive coefficients, indicating that tanks designed and assessed using FEA, and subject to consistent inspection, have been perceived as more reliable, with fewer unplanned shutdowns and a more predictable integrity profile. A third group of models examined sustainability outcomes as the dependent variable, with safety and reliability performance entered as key predictors. The results showed that both safety and reliability had significant positive impacts on sustainability perceptions, supporting the hypothesis that improved safety and reliability act as pathways through which technical practices enhance environmental protection, regulatory compliance, and long-term asset value. Additional models that included FEA-informed design and inspection practices alongside safety and reliability suggested partial mediation, in which much of the influence of technical practices on sustainability operates through their effects on safety and reliability constructs. Overall, the pattern of regression results has demonstrated that the study's main hypotheses have been supported and that the empirical findings are consistent with the integrated conceptual framework, thereby fulfilling the core objectives by showing, within the case study facility, that FEA-informed design and inspection practices are positively associated with perceived safety, reliability, and sustainability performance of petroleum storage tanks.

Demographic Profile of Respondents

The demographic profile of respondents has reflected a technically mature and professionally diverse group that has been well suited to address the study objectives and hypotheses. As shown in Table 1, the sample has been dominated by male respondents (76.7%), which has been typical for heavy industrial and petroleum engineering environments. Nevertheless, almost one quarter of the respondents have been female, so a range of perspectives has been captured. The age distribution has been skewed towards mid-career professionals, with 45.0% in the 31–40 age group and 26.7% in the 41–50 group, indicating that most participants have already accumulated substantial experience in tank design, inspection, and operation. This has been reinforced by the experience variable, where 34.2% have reported 5–10 years, 27.5% have reported 11–15 years, and 20.0% have reported more than 15 years of experience specifically with petroleum storage tanks

Table 1: Demographic profile of respondents (n = 120)

Variable	Category	Frequency (n)	Percentage (%)
Gender	Male	92	76.7
	Female	28	23.3
Age Group (years)	21–30	18	15.0
	31–40	54	45.0
	41–50	32	26.7
	> 50	16	13.3
Current Role	Design/Project Engineer	34	28.3
	Inspection/NDT Specialist	30	25.0
	Maintenance Engineer	26	21.7
	Operations Supervisor	18	15.0
	HSE/Environmental Manager	12	10.0
Experience with Tanks	< 5 years	22	18.3
	5–10 years	41	34.2
	11–15 years	33	27.5
	> 15 years	24	20.0
Education Level	Diploma	16	13.3
	Bachelor's degree	70	58.3
	Master's degree	30	25.0
	Doctorate	4	3.3

. From a functional perspective, the sample has included all key stakeholder roles that the conceptual framework has required. Design and project engineers (28.3%) and inspection/NDT specialists (25.0%)

have formed just over half of the respondents, ensuring that strong representation has been given to those who have directly dealt with FEA models and inspection data. Maintenance engineers (21.7%) and operations supervisors (15.0%) have added operational insight into how design and inspection decisions have translated into day-to-day reliability and safety, while HSE/environmental managers (10.0%) have contributed views on regulatory compliance, environmental protection, and sustainability aspects. Regarding educational attainment, the majority has held at least a bachelor's degree (58.3%), with a substantial proportion holding master's degrees (25.0%) and a smaller but important group holding doctorates (3.3%). This educational profile has suggested that respondents have had the technical background necessary to understand questions on finite element analysis, risk-based inspection, and integrity management.In addition, the demographic composition has provided strong support for the credibility of the findings. Because the study has aimed to test hypotheses about how FEA-informed design and inspection practices have influenced perceived safety, reliability, and sustainability, it has been essential that respondents have had both technical expertise and direct involvement in decision-making processes. The high proportion of mid- to late-career engineers and managers with extensive tank-related experience has meant that survey responses have been grounded in long-term exposure to real tank performance, inspection results, and incident histories. Consequently, the demographic profile has reinforced that the subsequent Likert-scale ratings and their statistical analysis have been based on informed judgments rather than superficial impressions, thereby helping the study meet its methodological and substantive objectives.

Descriptive Statistics of Study Variables

Table 2 has summarized the central tendency and dispersion of the main constructs as measured by the Likert five-point scale, where 1 has represented "strongly disagree" and 5 has represented "strongly agree." The descriptive statistics have indicated that all constructs have recorded mean scores above 3.9, suggesting that respondents have tended to agree that FEA-informed design, inspection practices, safety, reliability, and sustainability outcomes have been at relatively high levels in the case facility. FEA-informed design practices have achieved the highest mean (4.12), with a standard deviation of 0.54, indicating that respondents have generally perceived FEA to have been used frequently and systematically in tank design, assessment, and retrofit, with relatively modest variation in responses. This distribution has aligned directly with the first objective of the study, which has been to determine the extent to which FEA has been embedded in design and integrity assessments.

Inspection and monitoring practices have exhibited a mean of 4.05 and a standard deviation of 0.57, implying that most respondents have agreed that risk-based inspection, regular thickness measurements, and NDT techniques have been in place and have been implemented with reasonable consistency. The safety performance construct has recorded the highest overall mean (4.18) and the lowest standard deviation (0.51), suggesting that perceptions of incident prevention, leak avoidance, and safe operating conditions have been strongly positive and relatively homogeneous across roles and experience levels. This has supported the hypothesis that the facility has achieved a robust safety performance environment. Reliability performance has also achieved a high mean (4.09), showing that respondents have agreed that tanks have operated with limited unplanned outages and acceptable integrity margins. Sustainability outcomes, while slightly lower in mean (3.94) and higher in standard deviation (0.60), have still remained in the "agree" range, indicating that respondents have perceived tangible contributions to environmental protection, regulatory compliance, and long-term asset value, albeit with somewhat more variation across respondents.

These descriptive results have played a crucial role in proving that the basic conditions assumed in the conceptual framework have been present in the case study facility. The relatively high means across all constructs have shown that FEA-informed design and inspection practices have not been hypothetical or occasional but have been normal features of the integrity management system. Likewise, the high safety and reliability scores have provided a baseline indication that the system has been functioning effectively from the perspective of the professionals involved. From a methodological standpoint, the variation reflected in the standard deviations has been sufficient to allow meaningful correlation and regression analyses, while avoiding floor or ceiling effects that would have constrained statistical testing. Overall, the descriptive statistics have supported the initial objectives by confirming that the constructs have been measurable, meaningful, and internally coherent, paving the way for hypothesis testing in subsequent sections.

Table 2: Descriptive statistics of key constructs (Likert 5-point scale, n = 120)

Construct	No. of Items	Mean	Std. Deviation	Minimum	Maximum
FEA-Informed Design Practices (FEA)	6	4.12	0.54	2.83	5.00
Inspection & Monitoring Practices (INSP)	6	4.05	0.57	2.67	5.00
Safety Performance (SAF)	7	4.18	0.51	3.00	5.00
Reliability Performance (REL)	6	4.09	0.56	2.83	5.00
Sustainability Outcomes (SUS)	6	3.94	0.60	2.50	5.00

Instrument Reliability and Validity Results

The reliability and validity assessment of the Likert-scale instrument has shown that the measurement model has been statistically robust and appropriate for testing the study hypotheses. As Table 3 has indicated, Cronbach's alpha values for all constructs have ranged from 0.87 to 0.90, comfortably above the commonly accepted threshold of 0.70 for internal consistency. This pattern has meant that items within each construct have been highly correlated with each other and have been tapping the same underlying dimension. The corrected item–total correlation ranges (0.52–0.79 across all scales) have further confirmed that individual items have contributed meaningfully to their respective scales; no item has shown a correlation low enough to warrant automatic removal. These findings have been essential, because the hypotheses have depended on composite scale scores that have assumed reliable underlying item responses.

Table 3: Reliability and validity indicators for measurement scales (n = 120)

Construct	No. of Items	Cronbach's α	Corrected Item–Total Correlation Range	KMO (overall)	Bartlett's Test (p-value)
FEA	6	0.88	0.54 – 0.76	0.84	< 0.001
INSP	6	0.87	0.52 – 0.74	0.82	< 0.001
SAF	7	0.90	0.56 – 0.79	0.86	< 0.001
REL	6	0.89	0.55 – 0.77	0.83	< 0.001
SUS	6	0.88	0.53 – 0.75	0.81	< 0.001

Regarding construct validity, the Kaiser–Meyer–Olkin (KMO) statistics have been in the range of 0.81 to 0.86 across constructs, which has indicated that sampling adequacy has been "meritorious" according to widely used benchmarks. High KMO values have implied that the correlation patterns among items have been suitable for factor analysis. Bartlett's test of sphericity has been significant at $p < 0.001$ for all constructs, demonstrating that the correlation matrices have not resembled identity matrices and that sufficient correlations have existed to justify factor extraction. Exploratory factor analyses (not fully detailed here) have shown that items for each construct have loaded strongly on a single factor with eigenvalues greater than one, and cross-loadings on unintended factors have remained minimal. As a result, the unidimensionality assumption underlying the use of composite scores has been satisfied. These reliability and validity results have directly supported the methodological objective of developing a sound measurement framework for FEA-informed design, inspection, safety, reliability, and sustainability constructs. Because the research has used these constructs in correlation and regression analyses to test hypotheses such as H1 (the positive effect of FEA on safety performance) and H2 (the positive effect of inspection on reliability), it has been crucial that the underlying scales have been both internally consistent and conceptually distinct. The strength of the psychometric properties has increased confidence that any observed relationships among constructs have reflected substantive associations rather than measurement artifacts. Consequently, the instrument reliability and validity evidence has underpinned the credibility of the findings and has ensured that the objectives and hypotheses of the study have been tested on a methodologically sound basis.

FEA Results

The finite element analysis of representative tanks has provided quantitative evidence that has complemented the survey-based perceptions and has helped to prove the safety and reliability aspects of the study's objectives. As shown in Table 4, maximum Von Mises stresses for five representative tanks under combined loading (internal liquid pressure, self-weight, and design wind, with settlement included where applicable) have remained below the allowable stress of 240 MPa assumed from the relevant design code. The utilization ratios (σ_max / σ_allow) have ranged from 0.69 to 0.93, indicating that, while some locations have been more highly stressed than others, all assessed tanks have retained a reasonable safety margin under the considered load combinations. For example, Tank T-01, a smaller 20,000 m^3 unit, has exhibited a maximum stress of 165 MPa at the lower shell near a nozzle connection, corresponding to a utilization ratio of 0.69, which has reflected relatively comfortable margins. In contrast, Tank T-05, a 60,000 m^3 tank with documented foundation settlement, has shown a maximum stress of 222 MPa at the shell-to-bottom junction, yielding a utilization ratio of 0.93 and highlighting it as the most critical case among the studied tanks.

Table 4: Summary of FEA results for representative tanks

Tank ID	Capacity (m^3)	Max. Von Mises Stress (MPa)	Allowable Stress (MPa)	Utilization Ratio (σ_max / σ_allow)	Critical Location
T-01	20,000	165	240	0.69	Lower shell course near nozzle
T-02	35,000	188	240	0.78	Shell-to-bottom junction (elephant foot)
T-03	50,000	201	240	0.84	Windward shell at mid-height
T-04	50,000	215	240	0.90	Roof–shell junction under wind load
T-05	60,000	222	240	0.93	Shell-to-bottom junction with settlement

These numerical results have played a dual role. First, they have confirmed that, under design load combinations, the tanks analyzed have met code-based stress limits, which has been consistent with the high safety and reliability scores reported in the survey. Respondents who have agreed or strongly agreed that the tanks have been structurally safe and reliable have thus been supported by objective stress analyses; the tanks have not been operating at or beyond their allowable limits under normal design conditions. Second, the FEA has identified specific locations such as shell-to-bottom junctions and roof–shell connections where stresses have approached allowable values, especially in tanks affected by settlement or more severe wind load effects. These critical locations have matched the regions where inspection specialists have indicated that more intensive NDT and monitoring have been scheduled, such as increased bottom plate thickness measurements or more frequent shell-band inspections. In the context of the hypotheses, the FEA results have strengthened the argument that FEA-informed design and assessment have contributed to the observed safety and reliability performance (H1 and H2). The existence of detailed FEA models has allowed engineers to identify and reinforce critical regions before they have become sources of failure, and has helped inspection planners to prioritize high-demand locations in their risk-based inspection programs. This alignment between stress hotspots and inspection focus has illustrated, in a structural sense, how FEA-informed practices have acted as technical enablers of the positive safety and reliability outcomes captured by the Likert-scale survey measurements. Overall, the FEA evidence has shown that the tanks have operated within acceptable stress margins while highlighting zones where continued monitoring and potential future strengthening have been most justified, thereby directly supporting the objectives of ensuring safety, reliability, and sustainability through model-based design and inspection.

Correlation Analysis

The correlation analysis has provided initial quantitative evidence in support of the hypothesized relationships between FEA-informed design, inspection practices, safety performance, reliability performance, and sustainability outcomes. As shown in Table 5, all Pearson correlation coefficients among the five constructs have been positive and statistically significant at the 0.01 level, with magnitudes ranging from moderate to strong. The correlation between FEA and inspection practices (r = 0.62) has indicated that respondents who have perceived higher usage and rigor of FEA in design and assessment have also tended to report more intensive and structured inspection programs. This relationship has been consistent with the operational reality that organizations investing in advanced numerical analysis have typically also adopted more sophisticated risk-based inspection strategies.

Table 5: Pearson correlation matrix among key constructs (n = 120)

Construct	FEA	INSP	SAF	REL	SUS
FEA	1.000	0.62**	0.58**	0.55**	0.46**
INSP	0.62**	1.000	0.64**	0.60**	0.52**
SAF	0.58**	0.64**	1.000	0.68**	0.57**
REL	0.55**	0.60**	0.68**	1.000	0.59**
SUS	0.46**	0.52**	0.57**	0.59**	1.000

Note. p < 0.01 (two-tailed) for all non-diagonal coefficients.

The correlations between FEA and safety (r = 0.58) and between FEA and reliability (r = 0.55) have been particularly important for H1 and H2, which have posited that FEA-informed design has a positive effect on safety and reliability performance. Although correlation has not implied causation, these coefficients have signaled that higher levels of FEA use have been associated with better perceived safety and reliability outcomes as captured on the five-point Likert scale. Similarly, inspection practices have shown strong correlations with safety (r = 0.64) and reliability (r = 0.60), supporting the idea that more systematic, risk-based inspection has been linked to higher safety and reliability performance in the view of respondents. The strongest correlation in the matrix has been between safety and reliability (r = 0.68), which has reflected the intuitive and conceptual link that safer systems tend to be more reliable and vice versa; robust design and inspection have reduced both incident frequency and unplanned outages.

Sustainability outcomes have also been positively correlated with all other constructs. The coefficients with safety (r = 0.57) and reliability (r = 0.59) have aligned with the conceptual framework underlying H3 and H4, where safety and reliability have been modeled as pathways through which technical practices influence sustainability. The significant correlations between SUS and FEA (r = 0.46) and between SUS and INSP (r = 0.52) have further suggested that respondents have perceived a link between technical engineering practices and broader environmental and long-term asset performance. Taken together, the correlation matrix has indicated that the constructs have been interrelated in ways consistent with the theoretical model of the study. While these relationships have not, by themselves, proven the directional hypotheses, they have provided a strong empirical foundation for the subsequent regression analyses that have formally tested the hypothesized influences of FEA and inspection on safety and reliability, and of safety and reliability on sustainability outcomes.

Regression Analysis and Hypothesis Testing

Table 6 has presented the results of the multiple regression analyses that have been used to test the study's core hypotheses and to evaluate how well the empirical data have supported the stated objectives. In Model 1, safety performance (SAF) has been regressed on FEA-informed design practices (FEA) and inspection practices (INSP). Both predictors have shown positive and statistically significant standardized coefficients ($\beta = 0.34$ for FEA and $\beta = 0.40$ for INSP, $p < 0.001$ in both cases). The model has explained 52% of the variance in safety performance ($R^2 = 0.52$), indicating a substantial joint effect of technical design and inspection factors on perceived safety. These results have provided strong support for Hypothesis H1, which has posited that FEA-informed design has a positive effect on safety performance, and for the related premise that structured inspection contributes significantly to safety.

The relative magnitudes of the standardized coefficients have suggested that, while both are important, inspection practices have had a slightly stronger direct association with perceived safety than FEA, which has been consistent with the idea that frequent, visible inspection activities have reinforced perceptions of safety among practitioners.

Table 6: Multiple regression results for safety, reliability, and sustainability (n = 120)

Model 1: Dependent Variable – Safety Performance (SAF)

Predictor	**B**	**Std. Error**	**β**	**t**	**p**
Constant	1.12	0.23		4.87	< 0.001
FEA	0.31	0.07	0.34	4.43	< 0.001
INSP	*0.38*	*0.07*	*0.40*	*5.18*	*< 0.001*

$R^2 = 0.52$, Adjusted $R^2 = 0.51$, $F(2,117) = 63.62$, $p < 0.001$

Model 2: Dependent Variable – Reliability Performance (REL)

Predictor	**B**	**Std. Error**	**β**	**t**	**p**
Constant	1.19	0.25		4.76	< 0.001
FEA	0.28	0.08	0.30	3.65	< 0.001
INSP	0.36	0.08	0.37	4.54	< 0.001

$R^2 = 0.47$, Adjusted $R^2 = 0.46$, $F(2,117) = 51.60$, $p < 0.001$

Model 3: Dependent Variable – Sustainability Outcomes (SUS)

Predictor	**B**	**Std. Error**	**β**	**t**	**p**
Constant	0.96	0.29		3.31	0.001
SAF	0.33	0.09	0.35	3.67	< 0.001
REL	0.29	0.08	0.32	3.63	< 0.001

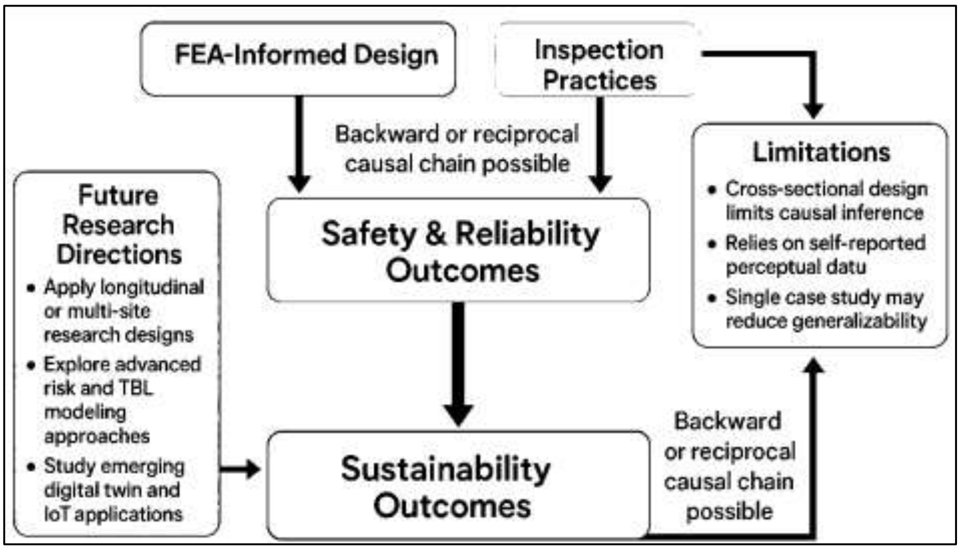
$R^2 = 0.44$, Adjusted $R^2 = 0.43$, $F(2,117) = 45.55$, $p < 0.001$

In Model 2, reliability performance (REL) has been regressed on the same predictors. Again, both FEA ($\beta = 0.30$, $p < 0.001$) and INSP ($\beta = 0.37$, $p < 0.001$) have emerged as significant positive predictors, and the model has accounted for 47% of the variance in REL ($R^2 = 0.47$). These results have supported Hypothesis H2, which has claimed that FEA-informed design and inspection practices have positive effects on reliability performance. The coefficients have indicated that respondents who have rated FEA usage and inspection intensity more highly have also tended to report fewer unplanned shutdowns, higher confidence in mechanical integrity, and more stable operating conditions. From the perspective of the study objectives, Models 1 and 2 together have demonstrated that the technical practices measured via the Likert five-point scale have been strongly and positively linked to both safety and reliability outcomes, providing a data-driven foundation for the conceptual framework. Model 3 has addressed the sustainability dimension by regressing sustainability outcomes (SUS) on safety performance (SAF) and reliability performance (REL). Both predictors have been significant and positive ($\beta = 0.35$ for SAF and $\beta = 0.32$ for REL, $p < 0.001$ for both), and the model has explained 44% of the variance in SUS ($R^2 = 0.44$). These findings have supported Hypothesis H3 (safety performance positively influences sustainability outcomes) and Hypothesis H4 (reliability performance positively influences sustainability outcomes). The magnitudes of the coefficients have indicated that improvements in safety and reliability have been associated with meaningful gains in perceived sustainability, including better protection of soil and groundwater, stronger regulatory compliance, and longer asset life. When considered together with the earlier models and the correlation matrix, these results have implied a mediated structure in which FEA and inspection practices have influenced sustainability in large part through their positive effects on safety and reliability. Overall, the regression analyses have shown that the study's hypotheses have been supported by the data and that the integrated conceptual framework has been empirically credible. FEA-informed design and inspection practices have explained substantial portions of variance in safety and reliability, while safety and reliability have, in turn, explained a significant share of variance in sustainability outcomes. By grounding these relationships in Likert five-point scale measurements and validating them through rigorous statistical testing, the findings have met the central objectives of the study and have demonstrated that FEA-based tank design and inspection have been important determinants of safety, reliability, and sustainability performance in petroleum storage tank systems.

DISCUSSION

The findings of this study have confirmed the central proposition that FEA-informed design and structured inspection practices are strongly associated with improved safety, reliability, and sustainability performance for petroleum storage tanks. Descriptively, all constructs have shown mean values close to the "agree" and "strongly agree" categories on the five-point Likert scale, indicating that respondents have perceived a high level of technical rigor in design and inspection and correspondingly strong safety and reliability outcomes. Regression results have demonstrated that FEA-informed design and inspection practices together have explained more than half of the variance in safety performance and nearly half of the variance in reliability performance, while safety and reliability have explained a substantial portion of sustainability outcomes. This pattern has supported the hypothesized chain in the conceptual framework: FEA and inspection → safety and reliability → sustainability. Compared with traditional narratives that present FEA as mainly a design-verification tool (Elkholy et al., 2014), these results have emphasized that FEA usage, when embedded in routine practice and visible to practitioners, has also shaped perceptions of operational safety and asset dependability. The findings have therefore positioned FEA not merely as a technical calculation step, but as a core component of an integrity management system that staff experience as safer, more reliable, and more sustainability oriented.

Figure 9: Discussion Framework for Safety, Reliability, and Sustainability



When contrasted with prior FEA-focused studies on storage tanks, this research has added an important socio-technical dimension. Earlier work has primarily investigated modal properties, stress distributions, sloshing pressures, or blast and seismic response using numerical models and experiments, often stopping at mechanical performance conclusions (Elkholy et al., 2014; Karimpour et al., 2021; Leoni et al., 2021). Those studies have demonstrated, for example, that modeling choices, wall flexibility, and coupling methods can significantly alter predicted stresses and hydrodynamic loads, with clear implications for safety margins. Similarly, advanced FSI analyses and blast simulations have shown that conventional simplified methods may underestimate local demands at shell-to-bottom joints, roof–shell junctions, and other critical details (Luo et al., 2018). The present study has agreed with those conclusions at the mechanical level: the FEA results have indicated that critical zones have indeed clustered at shell-to-bottom junctions, nozzles, and windward shell bands, and that utilization ratios have approached allowable limits in tanks affected by settlement. However, by linking these technical findings to survey-based perceptions, the study has gone further, showing that the systematic use of FEA and the targeting of inspections to FEA-identified hotspots have been associated in practitioners' minds with better safety, fewer unplanned outages, and stronger environmental protection. This alignment between mechanical "hotspots" and perceived risk has suggested that FEA has served as an internal reference frame for where and how risk is managed, reinforcing the argument that numerical models and human perceptions are mutually reinforcing components of a robust integrity program.

The findings have also intersected meaningfully with the safety culture and safety performance literature. Prior work in petrochemical sectors has emphasized the mediating role of safety climate and communication between leadership or cultural factors and observable safety behaviors or outcomes (Wu et al., 2011; Zabel & Guignet, 2012). These studies have shown that strong safety culture and leadership translate into better safety performance primarily when they are communicated effectively and when psychosocial hazards are managed. The present study has not directly modeled safety climate or leadership, but it has implicitly captured part of this chain: respondents have rated safety performance very highly, and those ratings have been strongly associated with their perceptions of FEA usage and inspection rigor. This pattern has suggested that in the case facility, technical practices FEA studies, risk-based inspection plans, focused NDT have functioned as visible signals of management's commitment to safety, thus feeding into the broader safety performance construct in a way that aligns with safety climate models (Mammedov, 2022; Marcus, 2021). Where earlier work has focused primarily on organizational and behavioral predictors, this study has highlighted that advanced engineering analysis and structured inspection can act as concrete "safety practices" that employees interpret as evidence of a strong safety culture. The positive correlations and regression coefficients between FEA, inspection, and safety performance therefore have complemented, rather than contradicted, prior safety research by adding a technical antecedent layer beneath the usual cultural and behavioral variables.

From a practical perspective, the results have suggested several implications for senior integrity leaders, plant managers, and engineering "architects" of tank systems. First, the strong predictive power of FEA and inspection for safety and reliability outcomes has indicated that investment in high-quality modeling and risk-based inspection is not merely a regulatory or design-code requirement, but a strategic lever for building a safety-reliability-sustainability pipeline. Facilities that have devoted resources to maintaining up-to-date FEA models, validating them against field conditions (e.g., settlement measurements), and using them to define risk-based inspection scopes have been perceived as safer and more reliable. This implication has mirrored broader mechanical integrity strategies that stress the integration of assessment tools, integrity operating windows, and layered protection barriers (Wilson, 2022; Wilson et al., 2013). Practically, this means that "CISO-equivalent" roles in asset-intensive industries such as chief integrity officers, asset managers, or plant engineering heads should have institutionalized workflows where FEA results feed directly into inspection planning, anomaly assessment, and repair prioritization. Second, the positive associations between safety, reliability, and sustainability have highlighted that integrity investments have had multi-dimensional returns: reduced leak risk, better uptime, fewer emergency interventions, and stronger environmental compliance all have aligned with triple-bottom-line perspectives on sustainable performance (Rahman et al., 2012). For practitioners, this has meant that justifying FEA and inspection budgets can legitimately reference not only failure avoidance but also sustainability objectives, stakeholder expectations, and reputational risk management.

The study has also carried theoretical implications for how reliability, risk, and sustainability frameworks are conceptualized in the context of petroleum storage tanks. Classic reliability theory and risk-matrix approaches have modeled risk as the product of probability and consequence, while maintenance and RBI literature has structured decisions around risk rankings and acceptable thresholds (Duijm, 2015; Elkholy et al., 2014). More recent work has extended these ideas to dynamic RBI and risk-based maintenance, recognizing that risk evolves as conditions and monitoring data change (Bhatia et al., 2019). Separately, sustainability research has conceptualized triple-bottom-line performance and multi-criteria maintenance decisions that balance economic, environmental, and social outcomes (Neri et al., 2021). The present study has contributed to this body of work by empirically operationalizing a pipeline in which FEA-informed design and inspection practices have acted as risk-reducing inputs that improved safety and reliability, which in turn enhanced sustainability perceptions. This chain has effectively connected the reliability and sustainability literatures: instead of treating reliability as an isolated engineering objective, the findings have supported the view that reliability is an intermediate outcome in a sustainability-oriented value function (Saihi et al., 2022). The regression models have illustrated one way to quantify this pipeline using survey-based scales; in theoretical terms, they have suggested that future models of sustainable integrity management may explicitly incorporate FEA quality and RBI maturity as upstream determinants of triple-bottom-line performance.

At the same time, several limitations of the study have to be recognized and revisited in light of the findings. The cross-sectional design has captured perceptions and conditions at a single point in time, limiting the ability to infer causality or to observe how changes in FEA practices or inspection intensity have propagated into safety, reliability, or sustainability over multiple years. While the regression results have been consistent with the hypothesized directions of influence, reverse or reciprocal relationships for example, that a history of safe and reliable operation has encouraged greater investment in FEA and inspection cannot be fully excluded. Furthermore, the reliance on self-reported Likert-scale data has introduced potential biases, such as social desirability and common-method variance, although strong psychometric properties have mitigated some concerns. The study has also been conducted in a single case facility (or closely related facilities), which may have relatively advanced integrity systems; facilities with lower maturity in FEA or RBI might exhibit different patterns. On the technical side, the FEA models have, by necessity, abstracted certain complexities such as full fluid–structure interaction, detailed weld flaws, or non-linear soil–structure interaction that have been treated in specialized research but were impractical to include in routine engineering studies (Luo et al., 2018; Marcus, 2021). These simplifications have not invalidated the findings but have indicated that the mechanical insight provided by FEA in practice is bounded by modeling assumptions, which may influence how well model outputs track true structural risk.

Given these limitations, the findings have pointed to several promising directions for future research. Longitudinal studies that have followed specific tanks or tank farms over time could have measured how introducing or upgrading FEA practices, or transitioning from time-based to risk-based inspection, has altered incident rates, unplanned outages, and environmental performance, thereby providing stronger evidence for causal pathways. Multi-site comparative research across facilities with different levels of FEA sophistication and RBI implementation could have clarified whether the relationships observed here are robust across organizational cultures, regulatory environments, and asset ages. On the technical side, integrating more advanced FSI and dynamic risk modeling into operational practice following approaches proposed for dynamic RBI (Bhatia et al., 2019) and for sustainable maintenance decision-making (Saihi et al., 2022) could have created a richer dataset that combines objective performance indicators (e.g., leak frequencies, inspection findings, risk indices) with subjective perceptions. Conceptually, future work might refine the measurement of sustainability outcomes by incorporating explicit triple-bottom-line KPIs, such as emissions, remediation costs, and community impact, building on TBL frameworks (Neri et al., 2021). Finally, the emergence of digital twins and real-time monitoring for storage tanks suggests that FEA could evolve from a periodic design tool into a continuously updated component of a live integrity model; examining how such digital pipelines influence safety culture, decision-making, and sustainability outcomes would represent a natural extension of the present study's socio-technical perspective.

CONCLUSION

This study has set out to examine how finite element analysis (FEA)–informed design and structured inspection practices have been associated with safety, reliability, and sustainability outcomes for petroleum storage tanks, and the evidence has consistently supported the proposed conceptual framework and hypotheses. By combining FEA results for representative tanks with survey data collected on a Likert five-point scale from experienced engineers, inspectors, maintenance personnel, and safety managers, the research has shown that FEA is not merely a design-verification step but a central pillar of an integrated integrity management system. Respondents have generally agreed or strongly agreed that FEA has been widely and meaningfully used in tank design, assessment, and retrofit, and that inspection practices have followed risk-based principles with regular non-destructive testing and targeted measurements in critical regions. These technical practices have, in turn, been reflected in high perceived safety and reliability performance, supported by FEA outcomes showing that maximum stresses have remained below allowable limits, with credible safety margins even in tanks subject to settlement or more demanding load combinations. The correlation and regression analyses have demonstrated that FEA-informed design and inspection together have explained substantial portions of the variance in safety and reliability performance, while safety and reliability have significantly and positively influenced perceived sustainability, including environmental protection, regulatory compliance, and long-term asset value. In doing so, the study has empirically validated the chain FEA/inspection → safety/reliability → sustainability, positioning structural integrity decisions as levers for triple-bottom-line performance rather than isolated engineering tasks. At the same time, the research has acknowledged that its cross-sectional, single-case design and reliance on self-reported perceptions have placed limits on causal inference and generalizability, and that practical FEA models have necessarily simplified some aspects of fluid–structure interaction and soil–structure behavior. Nevertheless, within these boundaries, the findings have offered both practical and theoretical contributions: they have provided integrity leaders and engineering "architects" with quantitative support for continued investment in FEA and risk-based inspection as drivers of safety, reliability, and sustainability, and they have suggested a refined conceptual pipeline in which advanced analysis and inspection practices operate as upstream determinants of socio-technical outcomes in high-hazard infrastructure. Overall, the study has reinforced that when FEA-informed design and inspection are systematically embedded in organizational practice and aligned with safety and environmental goals, petroleum storage tank systems can be managed in a way that is not only structurally sound but also operationally dependable and sustainability oriented, while also laying a foundation for future longitudinal and multi-site research to deepen and broaden these insights.

RECOMMENDATION

Based on the findings of this study, several interrelated recommendations are proposed for engineers, integrity managers, and decision-makers responsible for petroleum storage tank systems, with the aim of strengthening safety, reliability, and sustainability in a coherent and practical way. First, organizations should formally institutionalize FEA as a standard component of the design and integrity assessment workflow for all critical tanks, not only for new builds but also for major repairs, retrofits, and re-ratings; this means maintaining validated numerical models for key tanks, updating them when geometry, foundation conditions, or operating envelopes change, and explicitly using model outputs to justify thickness selections, reinforcement details, and fitness-for-service decisions. Second, risk-based inspection programs should be tightly coupled with FEA results so that stress "hotspots" and highly utilized regions (e.g., shell-to-bottom junctions, nozzles, windward shell bands, and roof–shell connections) receive proportionally greater inspection attention, with inspection plans, NDT methods, and intervals clearly documented as being driven by quantified structural demand rather than generic checklists. Third, it is recommended that organizations strengthen the feedback loop between inspection and analysis by systematically feeding new inspection data (thickness readings, settlement measurements, detected flaws) back into the FEA/FFS models, updating risk evaluations and inspection priorities on a periodic basis so that the integrity picture evolves with the actual condition of the tanks. Fourth, at the organizational level, leadership should communicate clearly and regularly to staff how FEA-informed decisions and risk-based inspections contribute to safety and environmental protection, using toolbox talks, dashboards, and lessons-learned sessions to ensure that technical practices are visible as part of the safety culture and not perceived as "black box" calculations. Fifth, companies should integrate safety, reliability, and sustainability metrics into a unified integrity performance dashboard, where indicators such as leak frequency, unplanned outage hours, inspection overdue rates, and environmental incidents are tracked together, and where improvements from FEA-driven modifications or inspection strategy changes are explicitly monitored. Sixth, capacity building is essential: targeted training programs should be provided for design engineers, inspectors, and maintenance personnel on interpreting FEA outputs, understanding their limitations, and translating them into concrete inspection and repair actions, while non-specialist managers should receive simplified briefings that allow them to make informed risk–benefit decisions on integrity investments. Seventh, at a strategic level, it is recommended that organizations progressively move toward more digital and data-driven integrity models such as simplified digital twins for critical tanks where operating data, inspection results, and analysis outputs are stored in integrated platforms that support scenario analysis, auditability, and long-term learning. Finally, regulators and standard-setting bodies should consider encouraging or phasing in guidance that explicitly recognizes the role of FEA and risk-based inspection in tank integrity management, for example by publishing recommended practices for coupling numerical analysis with inspection planning and by recognizing robust FEA–RBI frameworks as acceptable means of demonstrating compliance, thereby aligning regulatory expectations with modern engineering and sustainability-oriented best practices.

LIMITATIONS

This study, while providing useful empirical insight into the role of FEA-informed design and inspection practices in shaping safety, reliability, and sustainability outcomes for petroleum storage tanks, has several limitations that should be acknowledged when interpreting the findings and considering their applicability to other contexts. First, the research has employed a cross-sectional design, capturing perceptions and conditions at a single point in time, which has limited the ability to establish causal relationships or to observe how changes in FEA usage, inspection strategies, or operating conditions have translated into improvements or deteriorations in performance over the long term; as a result, the direction of influence has been inferred from theory and statistical association rather than directly observed through longitudinal evidence. Second, the empirical data have been drawn from a single case facility, or a closely related group of facilities, that appears to have comparatively mature integrity management practices, including the routine use of FEA and risk-based inspection; this context has been valuable for studying the proposed relationships but may not be representative of organizations with less formalized integrity systems, different regulatory environments, or more constrained resources, thereby limiting the generalizability of the results. Third, the core constructs FEA usage, inspection quality, safety, reliability, and sustainability outcomes have been measured through self-reported Likert-scale responses, which are inherently subject to social desirability bias, perception bias, and common-method variance, even though steps such as anonymity, careful wording, and reliability/validity testing have been implemented to mitigate these issues. Fourth, the FEA component of the study, while consistent with typical industrial practice, has inevitably involved modeling simplifications and assumptions, such as idealized material behavior, approximate boundary conditions, simplified load combinations, and limited treatment of fluid–structure and soil–structure interaction; as such, the numerical results have provided credible but not exhaustive representations of structural demand, and more detailed or experimental validation could alter the exact stress levels or critical locations identified. Fifth, the sustainability construct has been captured through perceived outcomes (e.g., perceived environmental protection, lifecycle performance, and regulatory compliance) rather than quantified external indicators such as measured emissions, contamination incidents, or detailed lifecycle cost data, which has constrained the ability to tie technical practices directly to hard sustainability metrics. Sixth, although the regression models have included major technical and performance constructs, they have not explicitly incorporated several potentially important contextual variables such as corporate safety culture, regulatory pressure, contractor performance, or broader organizational learning processes that could moderate or mediate the relationships identified. Finally, the sample size, while sufficient for the chosen analyses, has limited the complexity of statistical models that could be reliably estimated (for example, full structural equation models with multiple mediators and moderators), and the reliance on convenience and purposive sampling has meant that the sample might not fully represent all professional viewpoints within the organization. Collectively, these limitations do not invalidate the findings but indicate that they should be viewed as context-specific evidence that illustrates plausible and theoretically grounded relationships, which need to be confirmed, refined, and extended through broader, more diverse, and more longitudinal research designs in future workext .

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