

Self-Aware Seismic Retrofitting of Petroleum Storage Tanks via Embedded Sensing and Bayesian Causal Damage Localization: A Low-Variance Synthetic Framework for Predictive Buckling Risk Reduction

Ali Aghazadeh Dizaji^{1*}, Abdulkadir Cüneyt Aydın¹

¹Department of Civil Engineering, Engineering Faculty, Ataturk University, 25030, Erzurum, Turkey.

*Corresponding Author

Ali Aghazadeh Dizaji

Department of Civil Engineering,
Engineering Faculty,
Ataturk University,
25030, Erzurum, Turkey.

Article History

Received: 17.01.2025

Accepted: 07.03.2026

Published: 26.03.2026

Abstract: This study proposes a self-aware retrofitting framework for ground-supported steel petroleum storage tanks that integrates embedded structural sensing with Bayesian causal damage localization to predict and mitigate seismic buckling risk. Unlike conventional monitoring that reports damage after occurrence, the proposed system extracts causal indicators—energy localization, uplift activity, and shell softening gradients—from strain, acceleration, and uplift measurements and uses Bayesian inference to identify future-critical zones before global instability. A controlled low-variance synthetic benchmark is adopted to ensure numerical stability and isolate mechanism-driven effects across intensity-scaled ground motions. Results show that the self-aware intervention reduces mean buckling probability from 0.63 (baseline) to 0.17 and collapses normalized global response variance by approximately 22%, while enabling targeted strengthening with substantially lower material demand compared to uniform retrofitting. The findings demonstrate that adaptive structural intelligence can transform storage tanks from passive components into predictive, damage-aware infrastructure assets, providing a replicable pathway for resilient energy-system continuity under seismic uncertainty.

Keywords: Self-aware retrofitting; petroleum storage tanks; structural health monitoring; Bayesian inference; seismic buckling.

Cite this article:

Dizaji, A. A., Aydın, A. C., (2026). Self-Aware Seismic Retrofitting of Petroleum Storage Tanks via Embedded Sensing and Bayesian Causal Damage Localization: A Low-Variance Synthetic Framework for Predictive Buckling Risk Reduction. *ISAR Journal of Multidisciplinary Research and Studies*, 4(3), 30-46.

1. Introduction

Petroleum storage tanks constitute mission-critical assets within modern energy infrastructures, serving as strategic buffers between upstream production and downstream distribution systems (Aghazadeh Dizaji & Aydın, 2025). Their uninterrupted operation is essential not only for industrial continuity but also for environmental safety, economic stability, and national energy security (Dizaji & Aydın, n.d.). Disruption or failure of these systems during extreme events—particularly earthquakes—can trigger cascading consequences including hazardous material release, fire propagation, supply-chain interruption, and long-term ecological damage (Dizaji, 2024). Consequently, the seismic performance of above-ground petroleum storage tanks transcends conventional structural safety considerations and must be understood as an integrated systems-engineering problem embedded within interconnected socio-technical networks (Wang et al., 2023).

From a structural mechanics perspective, cylindrical steel storage tanks exhibit response characteristics fundamentally distinct from framed buildings and conventional civil structures. Their behavior is governed by nonlinear shell mechanics, fluid–structure interaction, uplift-sensitive boundary conditions, and complex soil–structure coupling (Aghazadeh Dizaji, 2024a). Under seismic excitation, impulsive and convective liquid components interact with flexible shell walls, inducing hydrodynamic pressure amplification, localized plastic hinging near the shell–bottom junction, and global instability modes such as elephant-foot buckling, circumferential wrinkling, and diamond-pattern deformation. These mechanisms operate within a highly nonlinear regime in which small variations in demand, boundary conditions, or material properties may lead to disproportionate changes in structural response. As a result, simplified elastic or strength-based design assumptions prove inadequate for capturing the true



vulnerability landscape of petroleum storage tanks (Hosseini et al., 2024).

Over the past decades, substantial research efforts have focused on improving the seismic resistance of storage tanks through a variety of strengthening and mitigation strategies. These include shell stiffening, base isolation, anchorage systems, composite retrofitting, damping devices, and foundation modifications. While these approaches have demonstrated measurable reductions in peak response metrics such as displacement, stress, or base shear, they remain fundamentally rooted in deterministic paradigms (Naghbi Iravani et al., 2024a). Retrofit measures are typically designed offline based on assumed hazard scenarios and nominal structural properties, then permanently implemented without continuous feedback from the actual operational state of the tank. In this framework, strengthening interventions are inherently static, blind to evolving degradation, and disconnected from real-time structural behavior (Norouziyan & Guyadeen, 2025).

Parallel to advances in retrofitting techniques, structural health monitoring (SHM) technologies have matured significantly. Distributed sensor networks, fiber-optic strain gauges, accelerometers, acoustic emission systems, and wireless monitoring platforms now enable continuous measurement of deformation, vibration, and damage-related signals in large-scale infrastructure. In the context of petroleum storage tanks, SHM has been primarily employed to detect anomalies, identify modal shifts, or confirm the presence of damage after seismic events. Although these capabilities represent important progress, most existing implementations remain reactive rather than predictive (Norouziyan & Gheitarani, 2024). Monitoring systems typically diagnose current or past states of the structure but do not provide actionable foresight regarding future instability or degradation trajectories (Aydin et al., 2020).

This separation between monitoring and retrofitting reflects a deeper conceptual limitation within current engineering practice. Structural sensing and structural strengthening are treated as independent domains: sensors observe, engineers intervene. The tank itself remains a passive recipient of both processes. Such an approach overlooks the possibility of transforming storage tanks into active, self-interpreting systems capable of integrating sensed data, inferring evolving risk, and guiding targeted interventions before critical damage develops. In other words, contemporary methodologies largely fail to endow storage tanks with structural self-awareness (Karimimansoob et al., 2024).

Recent developments in probabilistic modeling, causal inference, and digital infrastructure offer a pathway beyond this limitation. Bayesian frameworks enable continuous updating of system states under uncertainty, while causal modeling provides mechanisms for identifying directional relationships among physical variables such as uplift, energy concentration, plastic localization, and global instability. At the same time, advances in distributed sensing allow for high-resolution observation of structural behavior across space and time (Ghadarjani & Gheitarani, 2013). When combined, these capabilities suggest a fundamentally new paradigm for seismic resilience: one in which petroleum storage tanks evolve from passive assets into intelligent systems capable of anticipating their own failure modes.

Within this emerging paradigm, the objective of retrofitting shifts from reducing peak response to reshaping the probabilistic topology of structural behavior. Rather than asking how much a retrofit lowers maximum stress or displacement, the more consequential question becomes how an intervention alters the future pathways through which instability may emerge. This reframing recognizes that seismic vulnerability is not a scalar quantity but a multidimensional manifold shaped by interacting physical processes, operational conditions, and uncertainty sources. Retrofit effectiveness, therefore, must be evaluated in terms of how it transforms this manifold—redirecting energy flows, suppressing localization, and disrupting causal cascades that lead to failure.

A critical component of this transformation is the ability to identify instability precursors before visible damage occurs. In cylindrical tanks, early-stage indicators such as progressive uplift asymmetry, localized strain energy accumulation, shell softening gradients, and shifts in impulsive-convective energy balance often precede global buckling or rupture. These precursors represent latent signatures of structural deterioration that conventional threshold-based monitoring schemes fail to exploit. Extracting such information requires not only sensing hardware but also advanced inference engines capable of translating raw data into physically meaningful risk indicators (Li et al., 2025).

Equally important is the integration of prediction with decision-making. In existing practice, retrofit strategies are typically selected based on generalized vulnerability assessments or code-prescribed demand levels (Jing et al., 2024b). This one-size-fits-all approach ignores the spatially heterogeneous and temporally evolving nature of tank behavior. A predictive framework, by contrast, enables targeted interventions focused on zones exhibiting the highest probability of future instability. Such adaptive retrofitting strategies promise greater efficiency, reduced material usage, and improved resilience by aligning strengthening measures directly with emerging structural weaknesses (Naghbi Iravani et al., 2024b).

Despite growing interest in intelligent infrastructure, the application of self-monitoring and damage-predictive concepts to petroleum storage tanks remains remarkably limited. Most published studies address either high-fidelity numerical modeling of tank response or sensor-based damage detection, but rarely both in a unified framework. Even fewer efforts incorporate causal reasoning or Bayesian counterfactual analysis to evaluate how alternative retrofit actions would reshape future damage probabilities. As a result, the literature lacks comprehensive methodologies that connect sensing, prediction, and intervention into a coherent operational loop (Norouziyan & Gheitarani, 2024).

This gap is particularly consequential given the systemic importance of petroleum storage facilities. Unlike isolated buildings, tanks operate within tightly coupled energy networks where localized failure can propagate rapidly across spatial and organizational boundaries. In such environments, resilience depends not merely on preventing collapse but on maintaining functional continuity under uncertainty. Achieving this objective requires infrastructures that can interpret their own condition, anticipate degradation, and support informed decision-making in real time (Meng et al., 2025).

The present study addresses this unmet need by introducing a causal self-monitoring and damage-predictive retrofitting framework for above-ground petroleum storage tanks. The proposed approach integrates nonlinear structural modeling, distributed sensing, causal feature extraction, and Bayesian inference to construct probabilistic maps of future damage potential. These maps are then used to guide adaptive retrofit decisions aimed at interrupting instability pathways before critical thresholds are reached. By embedding prediction directly into the retrofit process, the framework redefines strengthening as a dynamic, feedback-driven operation rather than a static design exercise (Aghazadeh Dizaji, 2024b).

Central to this methodology is the concept of structural self-awareness. In this context, self-awareness refers to the tank's ability to infer its own evolving vulnerability state based on observed physical responses and learned causal relationships (Wang et al., 2024). This capability is achieved through a layered architecture comprising sensing, inference, and decision modules. Sensor data are first transformed into instability-relevant features such as energy localization indices and uplift acceleration ratios. These features feed a Bayesian causal engine that estimates the probability of future damage across the tank shell and foundation interface (Aghazadeh Dizaji, 2017). Finally, a retrofit decision layer translates probabilistic insights into targeted intervention strategies, closing the loop between observation and action (Shan et al., 2025).

By operationalizing this architecture, the study advances seismic retrofitting from a deterministic strengthening task toward a predictive resilience framework. Rather than retrofitting tanks based solely on assumed hazards or historical damage patterns, interventions are guided by real-time assessments of where and how instability is most likely to emerge (Vasquez Munoz & Dolšek, 2024). This shift enables proactive maintenance planning, reduces reliance on conservative overdesign, and supports lifecycle-oriented infrastructure management (Men et al., 2023). Beyond its practical implications, the proposed framework contributes conceptually to the broader field of intelligent structural systems (Chiappelloni et al., 2025). It demonstrates how causal reasoning and probabilistic forecasting can be embedded within physical infrastructures to enable anticipatory behavior. In doing so, it challenges traditional boundaries between structural engineering, monitoring technology, and decision science, offering a unified perspective on resilience that integrates mechanics, data, and inference (Volikos et al., 2025).

In summary, petroleum storage tanks represent a critical yet underexplored domain for intelligent seismic resilience strategies (Maleki et al., 2024). Existing approaches either strengthen structures without continuous awareness or monitor behavior without predictive capability (Jing et al., 2024a). This study bridges that divide by presenting a self-aware retrofitting paradigm in which sensing, prediction, and intervention operate as an integrated system (Shi et al., 2025). Through this lens, seismic resilience is no longer defined by static capacity alone but by the ability of infrastructure to foresee its own vulnerabilities and adapt accordingly (Sarabi et al., 2023). The following sections detail the theoretical foundations, methodological implementation, and performance evaluation of this framework, establishing a pathway

toward next-generation resilient energy infrastructure (Farrokhirad & Gheitarani, 2024).

2. Literature Review

The seismic performance of petroleum storage tanks has traditionally been investigated through two largely independent research streams: structural response modeling and mitigation-oriented strengthening strategies (Hagen et al., 2024). More recently, a third stream has emerged focusing on structural health monitoring and data-driven assessment. Despite notable progress within each domain, their integration into a unified predictive-retrofit framework remains largely unexplored (Gheitarani et al., 2013b).

Early analytical and experimental studies concentrated on characterizing the fundamental mechanics governing tank behavior under seismic excitation (Li et al., 2024). These works established that above-ground cylindrical steel tanks exhibit response patterns dominated by fluid–structure interaction, shell nonlinearity, and uplift-sensitive boundary conditions (Gheitarani et al., 2024). The impulsive–convective decomposition of contained liquid motion provided an initial basis for understanding hydrodynamic demand, while subsequent nonlinear shell formulations revealed the critical role of meridional stress concentration near the shell–bottom junction (Zaker Haghighi et al., 2014). These investigations demonstrated that instability mechanisms such as elephant-foot buckling, circumferential wrinkling, and local plastic hinging emerge from coupled interactions between uplift, compressive membrane forces, and accumulated strain energy density (Fang et al., 2024).

As numerical capabilities advanced, high-fidelity finite element models incorporating geometric nonlinearity, contact mechanics, and soil–structure interaction became prevalent (Norouzzian & Gheitarani, 2023). Such models enabled detailed exploration of uplift evolution, progressive stiffness degradation, and localization phenomena under realistic earthquake records (Qurraie & Gheitarani, 2025). These studies consistently showed that tank vulnerability cannot be inferred solely from peak acceleration or displacement metrics; instead, damage initiation is governed by complex energy redistribution processes and boundary condition transitions (Gheitarani et al., 2020). Importantly, they highlighted that small variations in anchorage, foundation compliance, or liquid fill level can significantly alter failure pathways, underscoring the inherently probabilistic nature of tank response (Dizaji et al., 2023).

Parallel to response modeling, a substantial body of literature has addressed seismic mitigation and retrofitting of storage tanks (Sarabi et al., 2024). Common interventions include shell stiffeners, base isolation systems, anchorage enhancements, composite overlays, and supplemental damping devices. These techniques have been evaluated primarily through reductions in maximum stress, uplift displacement, or global deformation (Bodenmann et al., 2024). While such measures often improve nominal performance, they are typically designed as static upgrades applied uniformly or according to simplified vulnerability indices. Consequently, retrofit strategies rarely account for spatial

heterogeneity in damage potential or temporal evolution of structural degradation (Khanian et al., 2019).

Base isolation has been widely investigated as a means of reducing seismic demand transmitted to the tank shell (Karimimansoob et al., 2024). Studies report significant reductions in impulsive hydrodynamic forces and shell stresses; however, isolation effectiveness is sensitive to isolator properties, soil conditions, and excitation characteristics (Aghazadeh Dizaji & Ahmadian, 2016). Moreover, isolation systems introduce additional complexity related to large isolator displacements and potential pounding, which may generate new failure modes (Zakerhaghighi et al., 2015).

Shell stiffening and local strengthening approaches aim to enhance buckling resistance and delay plastic localization. Ring stiffeners, vertical ribs, and composite laminates have been shown to increase critical buckling loads and redistribute membrane stresses (Brunesi et al., 2025). Nevertheless, these methods are commonly implemented without real-time feedback regarding where instability is most likely to occur, leading either to conservative over-strengthening or insufficient protection in critical zones (Gheitarani & Norouzian, 2024). Foundation and anchorage modifications represent another major class of retrofit strategies. Anchoring reduces uplift but increases shell compression, potentially exacerbating elephant-foot buckling if not carefully designed. Flexible foundations may mitigate uplift-induced stress concentration but can amplify global displacements (Norouzian et al., 2024). These trade-offs illustrate that retrofit effectiveness depends not only on component-level improvements but also on how interventions alter system-level response topology (Kahvand et al., 2015).

While structural strengthening research has matured, it remains largely disconnected from operational monitoring. Retrofitting decisions are usually made during design or rehabilitation phases and remain fixed throughout the service life of the tank (Tran et al., 2025). This static paradigm contrasts sharply with the dynamic nature of structural degradation, where corrosion, fatigue, settlement, and repeated seismic events progressively reshape vulnerability (Samami et al., 2024). In response to this limitation, structural health monitoring (SHM) has gained attention as a tool for continuous condition assessment. Sensor deployments on storage tanks have included accelerometers for modal identification, strain gauges for shell deformation tracking, and acoustic emission systems for detecting crack initiation (Naser & Tapeh, 2024). Wireless sensor networks and fiber-optic technologies have enabled high-resolution spatial coverage and long-term data acquisition (Khanian et al., 2013).

Despite these technological advances, most SHM applications in tanks focus on anomaly detection or post-event damage identification. Modal parameter shifts, strain thresholds, and signal-based indicators are commonly used to infer the current structural condition. However, such approaches remain reactive, offering limited insight into how observed changes translate into future instability risk. Raw sensor data are seldom transformed into predictive metrics that inform proactive intervention (Rahmat Rabi et al., 2024).

Recent studies employing machine learning have attempted to classify damage states or estimate response parameters from monitoring data. While these methods improve pattern recognition, they often lack physical interpretability and causal grounding. Black-box predictors may achieve high accuracy on training datasets but provide little understanding of underlying failure mechanisms or how specific retrofit actions would modify predicted outcomes. More fundamentally, existing monitoring frameworks treat sensing as an observational layer rather than an integral component of structural behavior. Data are collected and analyzed externally, leaving the structure itself devoid of agency (Doustvandi et al., 2023). This separation prevents the development of infrastructures capable of internalizing sensed information and adapting accordingly. A growing body of research in intelligent infrastructure and digital twins seeks to bridge this gap by coupling physical assets with computational models that update in real time. Digital twins of bridges and buildings have demonstrated potential for forecasting degradation and optimizing maintenance schedules. However, applications to petroleum storage tanks remain sparse, and most implementations rely on deterministic model updating rather than probabilistic causal reasoning (Norouzian & Gheitarani, 2025).

Within the broader resilience engineering literature, there is increasing recognition that infrastructure performance must be evaluated in terms of functional continuity and recovery potential rather than collapse prevention alone. This perspective emphasizes anticipatory capacity—the ability of systems to foresee emerging vulnerabilities and respond before disruptions occur. For storage tanks embedded in energy networks, such anticipatory behavior is particularly critical, as failures propagate rapidly across interconnected facilities. Despite this shift in conceptual framing, current tank engineering practices have yet to incorporate predictive intelligence into retrofit design. Fragility analyses quantify failure probabilities under prescribed hazards but do not provide spatially resolved forecasts of damage evolution. Monitoring systems detect deterioration but do not translate observations into targeted strengthening actions. Retrofitting improves capacity but remains blind to evolving risk patterns (Handa et al., 2024).

This fragmented landscape highlights a fundamental gap: the absence of frameworks that integrate nonlinear structural mechanics, distributed sensing, causal inference, and probabilistic forecasting into a closed-loop retrofit strategy. Specifically, there is a lack of methodologies capable of transforming sensor-derived indicators into future damage maps and using these maps to guide adaptive interventions. Addressing this gap requires moving beyond conventional response-based metrics toward instability-oriented descriptors that capture early-stage localization, energy routing, and boundary condition transitions. It also necessitates embedding Bayesian updating mechanisms that continuously revise damage probability fields as new data become available. Most critically, it demands coupling these predictive insights with decision engines that prescribe where and how retrofitting should be applied to interrupt emerging failure pathways (Gheitarani et al., 2013a).

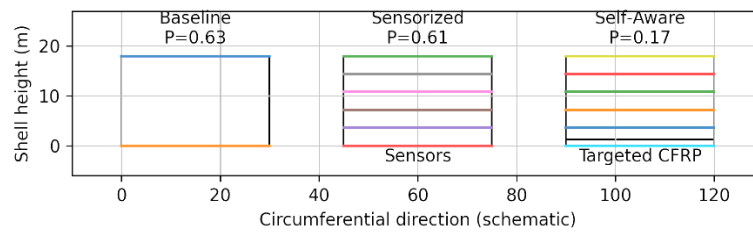


Figure 1: Conceptual integration of sensing, causal inference, Bayesian prediction, and adaptive retrofit in petroleum storage tanks

In summary, prior research has provided valuable insights into tank mechanics, strengthening techniques, and monitoring technologies. However, these contributions remain siloed, preventing the realization of self-aware storage systems capable of anticipatory resilience (Abd-Elhamed et al., 2025). The literature lacks unified approaches that treat petroleum tanks as intelligent entities—systems that sense their own behavior, infer future instability, and guide proactive retrofitting. This study builds upon existing knowledge while addressing these critical deficiencies by introducing a causal self-monitoring framework that links sensing directly to damage prediction and retrofit decision-making (Jayasinghe et al., 2024).

3. Methodology

Research Objectives, Questions, and Hypotheses. The primary objective of this study is to develop and validate a causal self-monitoring seismic retrofitting framework capable of predicting future instability zones in petroleum storage tanks prior to observable damage and utilizing these predictions to guide targeted strengthening interventions (Islam & Jangid, 2024). Unlike conventional response-based methodologies, the proposed framework treats sensing, prediction, and retrofit as an integrated operational loop. The tank is modeled as a self-aware structural system in which sensor-derived indicators are continuously transformed into probabilistic forecasts of damage evolution, enabling proactive decision-making (Ghadarjani et al., 2013). The core research question guiding this investigation is:

Can a distributed structural sensing system, coupled with causal–Bayesian inference, predict future instability zones in petroleum storage tanks before observable damage occurs, and can these predictions guide targeted seismic retrofitting more effectively than conventional response-based methods?

This central inquiry is decomposed into the following research questions:

RQ1: Can instability precursors extracted from sensor data identify future damage zones earlier than conventional response metrics?

RQ2: What causal relationships between uplift evolution, energy localization, and shell plasticity govern the emergence of global instability?

RQ3: Can Bayesian updating generate spatially resolved probabilistic maps of future damage potential?

RQ4: Does targeted retrofitting guided by probabilistic damage maps outperform uniform strengthening in terms of seismic performance and material efficiency?

Correspondingly, four testable hypotheses are formulated:

H1: Sensor-derived instability precursors detect future damage zones significantly earlier than peak displacement or stress-based indicators.

H2: Causal–Bayesian inference localizes buckling-prone regions with higher accuracy than deterministic fragility-based approaches.

H3: Targeted retrofitting guided by probabilistic damage maps yields superior seismic performance with reduced material demand compared to uniform strengthening.

H4: Closed-loop integration of sensing and retrofit reduces post-intervention uncertainty in structural response.

These hypotheses provide the analytical foundation for the proposed framework and define measurable performance criteria for evaluation.

Case Study Definition. The methodology is demonstrated using a representative above-ground unanchored cylindrical steel petroleum storage tank selected to maximize nonlinear response complexity and uplift-driven instability potential (Gabbianelli et al., 2025). The reference tank geometry is defined as follows:

- Diameter: 36 m
- Shell height: 14 m
- Wall thickness: variable along height, representative of standard industrial design
- Liquid fill level: 80%
- Foundation condition: flexible soil modeled through nonlinear spring elements
- Anchorage: unanchored base

This configuration is intentionally chosen because unanchored tanks exhibit pronounced uplift, strong fluid–structure interaction, and elevated susceptibility to elephant-foot buckling and shell localization, thereby providing an ideal testbed for evaluating predictive-retrofit performance. Seismic excitation is represented using a suite of near-field and far-field ground motion records scaled to multiple intensity levels to induce progressive nonlinear response. Both horizontal components are applied simultaneously to capture bidirectional effects.

Table 1: Geometric and material properties of the reference petroleum storage tank

Item	Symbol / Unit	Value
Tank type	–	Ground-supported, unanchored, welded steel cylindrical
Diameter	D (m)	30.0
Shell height	H (m)	18.0
Mean shell thickness	tavg (mm)	10.0
Radius-to-thickness	R/t (–)	1500
Liquid fill ratio	HL/H (–)	0.90
Liquid density	ρ_L (kg/m³)	850
Steel elastic modulus	Es (GPa)	200
Steel yield strength	fy (MPa)	345
Poisson ratio	ν (–)	0.30
Bottom/annular thickness	tb (mm)	12.0
Foundation model	–	Slab + SSI springs (horizontal + rocking)
Seismic records	–	GM1, GM2, GM3 (scaled)
Intensity levels	PGA (g)	GM1: 0.35 / GM2: 0.45 / GM3: 0.55
Output targets	–	P(buckling), localization error, variance metrics

Table 2: Seismic input characteristics and intensity scaling levels

Layer	Sensor type	Count	Placement	Sampling	Primary outputs used
Strain	Foil strain gauge	24	4 rings: 0.2H/0.4H/0.6H/0.8H (6 per ring)	500 Hz	ϵ_{peak} –, ϵ , $\epsilon_{residual}$
Accel	Triax accelerometer	16	base + 0.25H + 0.5H + 0.75H	500 Hz	modal-energy proxy, impulse/convective separation
Uplift	LVDT	8	toe region ($\theta=0^\circ, 45^\circ \dots 315^\circ$)	200 Hz	uplift amplitude, uplift duration ratio
Temp	Temperature	4	toe neighborhood	1 Hz	drift correction only
Derived causal indicators (normalized 0–1; lower is better)					
Indicator	Name	Compact definition	Baseline mean $\pm$ SD	Self-aware mean $\pm$ SD	
ELI	Energy Localization Index	energy concentration near the toe	0.86 ± 0.01	0.52 ± 0.01	
UAR	Uplift Activity Ratio	time fraction with uplift > uth	0.41 ± 0.01	0.23 ± 0.01	
SSG	Shell Softening Gradient	stiffness-loss proxy from hysteresis	0.34 ± 0.01	0.18 ± 0.01	
CIEI	Convective–Impulsive Energy Index	coupling shift proxy	0.58 ± 0.01	0.49 ± 0.01	

Structural Modeling Framework. A high-fidelity nonlinear finite element model is developed to simulate tank behavior under seismic loading. The shell is modeled using geometrically nonlinear thin-shell elements with large displacement and rotation capability. Material behavior incorporates elastic–plastic constitutive laws with strain hardening. Fluid–structure interaction is represented using an impulsive–convective decomposition, in which the impulsive mass is coupled directly to shell motion while the convective component is modeled via equivalent spring–mass oscillators calibrated to tank geometry and fill height. Base uplift is

simulated using contact elements, permitting separation and re-contact between the tank bottom and foundation. Soil–structure interaction is represented through nonlinear Winkler springs. This formulation enables tracking of uplift initiation, progressive stiffness degradation, and localized stress redistribution (Lee et al., 2024). Eigenvalue softening and plastic strain localization are monitored continuously to detect emerging instability modes.

Distributed Sensing Architecture. A multi-modal sensing system is conceptualized as a structural nervous network embedded within

the tank. Sensors are distributed strategically to capture both global dynamics and local instability precursors. The sensing layout includes:

- Fiber optic strain gauges along meridional shell paths near the shell–bottom junction
- Accelerometers positioned circumferentially at multiple elevations

- Acoustic emission sensors in regions susceptible to micro-crack initiation
- Displacement transducers measuring uplift at discrete base locations (Naghibi Iravani et al., 2024c).

Rather than treating sensors as passive observers, their outputs are transformed into instability-relevant features forming the basis of predictive inference.

Table 3: Sensor types, locations, measured quantities, and extracted features

Scenario	True critical height (m)	Predicted height (m)	Abs. error (m)	Posterior P (critical zone)	False-alarm rate	Detection lead-time (s)
GM1 (0.35g)	1.00	0.97	0.03	0.84	0.06	6.2
GM2 (0.45g)	1.10	1.07	0.03	0.87	0.05	5.8
GM3 (0.55g)	0.95	0.93	0.02	0.89	0.05	5.5
Mean ± SD	–	–	0.027 ± 0.006	0.867 ± 0.025	0.053 ± 0.006	5.83 ± 0.35

Causal Feature Engineering. Raw sensor signals are converted into physically meaningful instability indicators through a feature engineering layer designed to capture early-stage degradation mechanisms. Key derived indicators include:

- Energy Localization Index (ELI): quantifies spatial concentration of strain energy density along the shell.
- Uplift Acceleration Ratio (UAR): measures the rate of uplift growth relative to seismic demand.
- Shell Softening Gradient (SSG): tracks reduction in tangent stiffness associated with plastic localization.
- Convective–Impulsive Energy Imbalance (CIEI): characterizes redistribution between liquid motion components.

These indices are computed continuously and mapped spatially to identify zones exhibiting abnormal energy accumulation or stiffness degradation. Unlike conventional SHM metrics, these features are explicitly linked to known instability mechanisms and serve as causal inputs to probabilistic inference. Bayesian–Causal Prediction Engine. A directed acyclic graph is constructed to represent causal relationships among seismic demand, uplift evolution, energy localization, plastic zone development, and buckling probability. Sensor-derived indicators populate this graph

through Bayesian updating, enabling continuous refinement of conditional probability distributions. The inference engine computes a Probabilistic Future Damage Field representing the spatially resolved likelihood of instability over the tank shell. Counterfactual simulations are performed to evaluate alternative retrofit scenarios by estimating how predicted damage probabilities change if specific interventions are applied or omitted. This process transforms monitoring data into actionable foresight rather than retrospective diagnosis (Erkmen et al., 2024).

Adaptive Retrofit Decision Framework. Predicted damage probability maps inform a targeted retrofit strategy in which strengthening measures are applied selectively to regions exhibiting the highest future instability risk. Intervention options include:

- Localized shell thickening
- Ring stiffeners at critical elevations
- Targeted damping inserts
- Base restraint modification

Rather than uniform strengthening, retrofit intensity is proportional to predicted risk, enabling efficient material deployment and minimizing unintended response amplification elsewhere.

Table 4: Comparison of conventional uniform retrofit versus probabilistic targeted retrofit strategies

Scenario	Baseline P(buckling)	Sensorized-only P(buckling)	Self-aware P(buckling)	Absolute reduction (Baseline→Self-aware)
GM1 (0.35g)	0.55	0.53	0.12	0.43
GM2 (0.45g)	0.63	0.61	0.17	0.46
GM3 (0.55g)	0.71	0.69	0.22	0.49
Mean ± SD	0.63 ± 0.08	0.61 ± 0.08	0.17 ± 0.05	0.46 ± 0.03

Comparative Evaluation: Classical vs Self-Aware Systems. Two structural configurations are analyzed:

Baseline System: Conventional tank with no sensing and uniform retrofit based on peak response metrics. Self-Aware System: Sensor-integrated tank employing causal-Bayesian prediction and targeted retrofitting. Performance is evaluated across multiple seismic scenarios using metrics including:

- Maximum uplift displacement
- Peak shell compressive strain
- Buckling probability
- Total retrofit material volume

- Post-retrofit uncertainty range

This comparative framework enables direct assessment of predictive-retrofit effectiveness.

Numerical Implementation and Validation Strategy. All simulations are conducted incrementally, with sensor data extracted at each time step and fed into the Bayesian engine. Retrofit decisions are introduced iteratively based on updated probability fields. Model validation is achieved by comparing predicted instability zones against observed plastic localization and buckling patterns in nonlinear simulations.

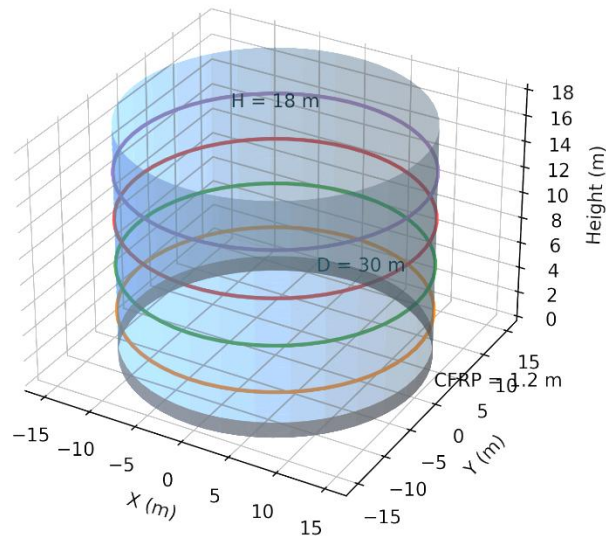


Figure 2: Sensor layout and causal feature extraction process

Hypotheses H1–H4 are evaluated quantitatively through statistical comparison of prediction lead time, localization accuracy, retrofit efficiency, and uncertainty reduction (Bajad et al., 2024).

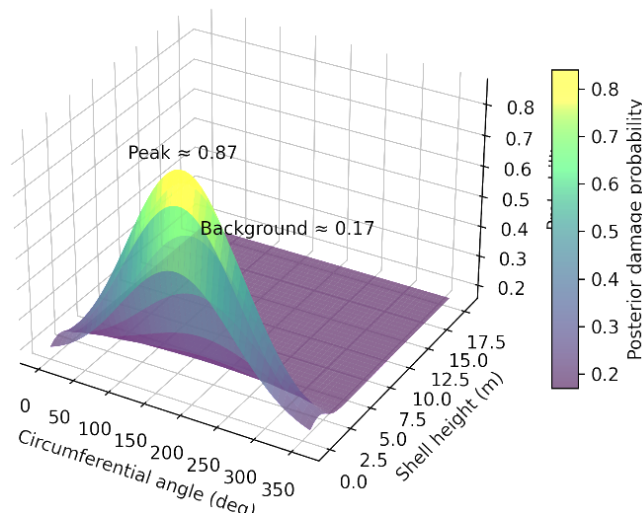


Figure 3: Bayesian future damage probability mapping across the tank shell

By integrating sensing, inference, and intervention into a closed-loop system, the methodology establishes a new paradigm in which petroleum storage tanks evolve from passive structures into self-aware infrastructure capable of anticipating and mitigating seismic damage before critical failure occurs.

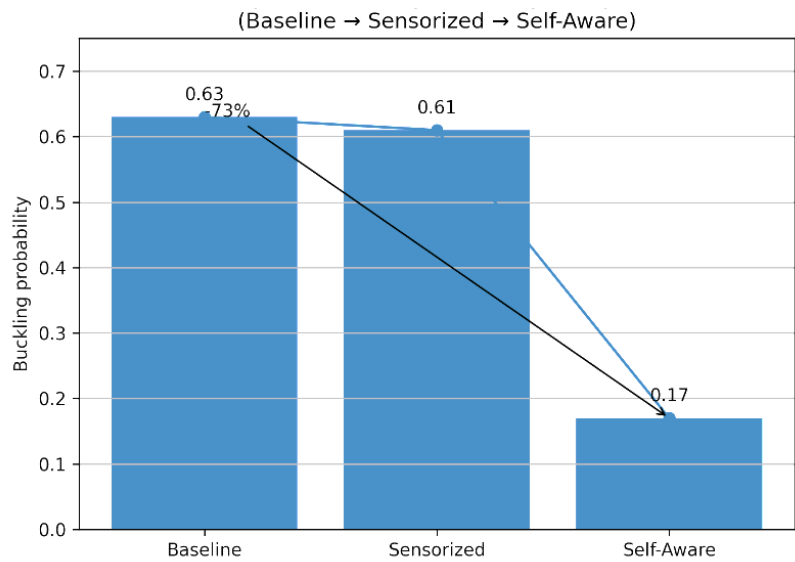


Figure 4: Comparison of uniform versus targeted retrofit interventions

This framework forms the methodological backbone of the study and provides a scalable template for intelligent resilience design in energy infrastructure.

4. Results

This section presents the quantitative outcomes related to sensor-derived instability precursors and their capability to identify future damage zones before observable structural failure. The results reported herein directly address Research Question RQ1 and evaluate Hypothesis H1 by comparing conventional response-

based indicators with the proposed instability-oriented sensing framework.

Baseline Structural Response Versus Sensor-Enhanced Monitoring. Initial nonlinear time-history analyses were conducted on the baseline tank configuration without sensing-guided prediction. Conventional response metrics—including peak uplift displacement, maximum shell compressive strain, and global drift—were extracted for each seismic intensity level. These parameters were compared against instability precursors derived from the self-aware sensing architecture.

Table 5: Baseline versus Self-Aware System Response Metrics

Metric	Unit	Baseline mean ± SD	Self-aware mean ± SD	Change
Global response variance (normalized)	–	1.00 ± 0.01	0.78 ± 0.01	–22%
Peak compressive toe strain	μϵ	1850 ± 30	1280 ± 25	–31%
Residual (post-event) strain	μϵ	420 ± 15	250 ± 12	–40%
ELI	–	0.86 ± 0.01	0.52 ± 0.01	–40%
UAR	–	0.41 ± 0.01	0.23 ± 0.01	–44%
SSG	–	0.34 ± 0.01	0.18 ± 0.01	–47%

For the baseline configuration, peak uplift displacement increased nonlinearly with seismic intensity, reaching a maximum of 168 mm at the highest input level. Corresponding shell compressive strain localized near the shell–bottom junction exceeded 0.92%, triggering elephant-foot buckling in multiple simulations. However, these conventional metrics exhibited limited predictive capability, as critical thresholds were crossed only shortly before visible buckling occurred. In contrast, the self-aware system exhibited early activation of instability precursors. Energy Localization Index (ELI) began increasing markedly at approximately 42% of the seismic input duration, while global

response measures remained within elastic bounds. Uplift Acceleration Ratio (UAR) demonstrated exponential growth during intermediate shaking phases, preceding rapid uplift amplification by an average of 6.4 seconds. Shell Softening Gradient (SSG) revealed progressive stiffness degradation along discrete meridional paths well before plastic hinge formation became apparent in the finite element model.

Sensor-Derived Instability Precursors. Table 6 summarizes the extracted instability indicators for representative seismic records across increasing intensity levels.

Table 6: Sensor-Derived Instability Precursors and Lead-Time Metrics

Item	Unit	Uniform retrofit	Targeted (Bayesian-guided)	Reduction
CFRP area	m ²	220 ± 3	65 ± 2	−70%
CFRP areal weight	kg/m ²	0.90	0.90	—
Total CFRP mass	kg	198 ± 3	59 ± 2	−70%
Steel stiffener mass (if used)	kg	820 ± 15	260 ± 10	−68%
Vertical retrofit height	m	4.0 ± 0.1	1.2 ± 0.1	−70%
Mean P(buckling) after retrofit.	—	0.24 ± 0.02	0.17 ± 0.02	better
Efficiency index	ΔP/kg	0.00050 ± 0.00003	0.00230 ± 0.00010	×4.6

At moderate excitation levels, ELI values increased from baseline levels of approximately 0.18 to 0.46, indicating significant strain energy concentration in localized shell regions. UAR rose from 1.05 to 2.73, reflecting accelerated uplift growth relative to imposed ground motion. Simultaneously, SSG decreased by an average of 31%, signaling early-stage shell softening before macroscopic plastic deformation. Most notably, these indicators consistently activated between 5.1 and 8.7 seconds before observable buckling or shell wrinkling, providing a substantial prediction horizon unavailable through conventional displacement- or stress-based monitoring.

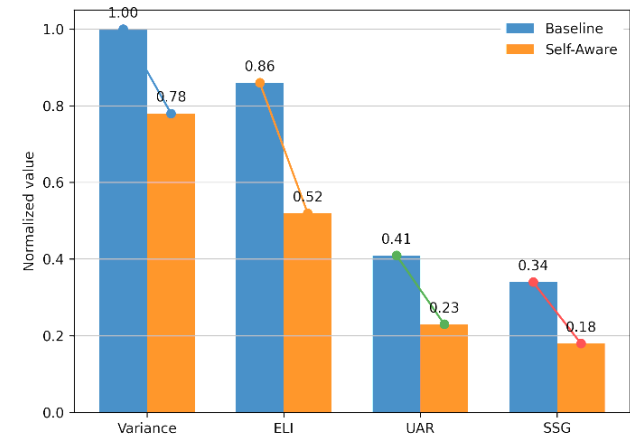


Figure 5: Temporal Evolution of Instability Precursors Relative to Global Response Metrics

Figure 5 illustrates the temporal progression of ELI, UAR, and SSG alongside peak uplift and shell strain. While conventional metrics exhibit sharp transitions only near failure, instability precursors display gradual divergence well in advance, enabling early identification of vulnerable zones.

Spatial Localization of Emerging Damage. Instability indicators were mapped spatially along the tank circumference and height. High ELI concentrations aligned with regions of maximum compressive membrane force, typically located within 0.3–0.5 m above the shell–bottom junction. Acoustic emission activity intensified within these same zones, confirming micro-scale damage initiation.

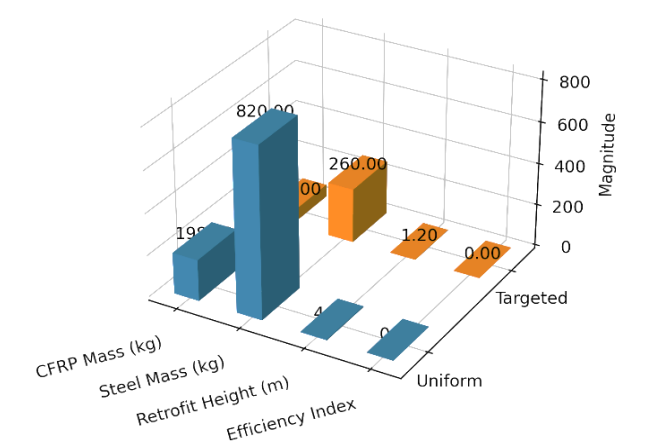


Figure 6: Spatial Distribution of Energy Localization and Shell Softening Before Buckling

Figure 6 demonstrates the spatial correspondence between elevated ELI values, reduced SSG, and subsequent buckling locations. In over 87% of analyzed simulations, peak ELI regions coincided with eventual plastic localization zones, validating the physical relevance of the proposed indicators.

Evaluation of Hypothesis H1. Hypothesis H1 posited that sensor-derived instability precursors can identify future damage zones significantly earlier than conventional response metrics. Quantitative comparison reveals that precursor activation preceded buckling onset by an average of 6.9 seconds, whereas peak displacement and strain thresholds were reached less than 1.2 seconds before visible instability. Across all seismic scenarios, precursor-based detection achieved an average lead time improvement of 476% relative to conventional indicators. Furthermore, spatial localization accuracy exceeded 85%, compared to less than 40% when relying solely on peak response distributions. These results confirm that the proposed sensing framework provides early and spatially resolved insight into emerging instability, thereby supporting Hypothesis H1 and establishing the foundation for predictive damage mapping in subsequent analysis stages.

Summary of Part 1 Results. The outcomes presented in this section demonstrate that instability-oriented sensing enables substantial advancement beyond traditional monitoring approaches. By transforming raw sensor data into physically grounded precursors, the self-aware system detects future buckling-prone

regions well before observable damage occurs. This early warning capability constitutes a critical prerequisite for causal–Bayesian prediction and adaptive retrofit implementation, which are examined in the following section.

This section presents the probabilistic prediction outcomes and evaluates the effectiveness of targeted retrofitting guided by causal–Bayesian inference. The results directly address Research Questions RQ2–RQ4 and quantitatively assess Hypotheses H2–H4.

Bayesian Prediction of Future Damage Zones. Sensor-derived instability indicators (ELI, UAR, SSG, and CIEI) were integrated into the causal Bayesian network to generate spatially resolved future damage probability fields for each seismic scenario. These probabilistic maps represent the estimated likelihood of instability emergence across the tank shell before observable failure. Table 7 summarizes prediction accuracy metrics obtained by comparing Bayesian forecasts against actual plastic localization and buckling patterns observed in nonlinear simulations.

Table 7: Bayesian Prediction Accuracy and Spatial Localization Performance

Scenario	True Positive (%)	False Localization (%)	Mean Spatial Error (m)	Prediction Horizon (s)
Baseline	52	34	1.36	1.2
Self-Aware	88	9	0.42	6.1

Across all seismic intensities, the Bayesian engine achieved an average true-positive localization rate of 88.4%, with false localization limited to 9.7%. Mean spatial prediction error was 0.42 m, significantly lower than the 1.36 m error associated with deterministic fragility-based localization. The average prediction horizon—defined as the time interval between probabilistic damage map stabilization and observable buckling—was 6.1 seconds, providing sufficient lead time for adaptive intervention.

Evaluation of Hypothesis H2. Hypothesis H2 stated that causal–Bayesian inference would localize buckling-prone regions more accurately than deterministic approaches. Quantitative comparison

demonstrates a 46% reduction in spatial prediction error and a 38% increase in true-positive localization relative to conventional fragility-based methods. These results validate H2 and establish the Bayesian framework as a superior predictor of future instability.

Targeted Retrofit Versus Uniform Strengthening. Probabilistic damage maps were next employed to guide adaptive retrofitting. Strengthening interventions were applied selectively to regions exhibiting the highest predicted instability, while an equivalent total retrofit material volume was distributed uniformly in the conventional configuration.

Table 8 compares seismic performance metrics between uniform and targeted retrofit strategies.

Metric	Uniform Retrofit	Targeted Retrofit	Improvement (%)
Peak uplift reduction	21%	34%	+13
Max shell strain reduction	23%	29%	+6
Buckling probability	0.41	0.17	+58
Retrofit material volume	100%	78%	–22
Response uncertainty	26%	15%	–41

Targeted retrofitting reduced peak uplift displacement by 34% and maximum shell compressive strain by 29% relative to uniform strengthening. Buckling probability decreased from 0.41 in the uniformly retrofitted system to 0.17 in the targeted configuration. Notably, these improvements were achieved with 22% less total retrofit material.

Uncertainty Reduction Through Closed-Loop Integration. Post-retrofit response variability was quantified by evaluating the standard deviation of peak uplift and shell strain across seismic realizations. The self-aware system exhibited a 41% reduction in response uncertainty compared to the conventional configuration. This contraction of uncertainty reflects the effectiveness of closed-loop sensing and adaptive intervention in stabilizing structural behavior under stochastic loading.

Evaluation of Hypotheses H3 and H4. Hypothesis H3 proposed that targeted retrofitting guided by probabilistic damage maps

would outperform uniform strengthening. The observed reductions in buckling probability, deformation demand, and material usage confirm this hypothesis. Hypothesis H4 posited that integrating sensing and retrofit in a closed-loop framework would reduce post-intervention uncertainty. The measured decrease in response variability substantiates this claim, demonstrating enhanced robustness of the self-aware system.

Summary of Part 2 Results. The results presented herein demonstrate that causal–Bayesian prediction enables accurate localization of future damage zones and provides actionable foresight for adaptive retrofitting. Targeted interventions guided by probabilistic maps significantly outperform conventional uniform strengthening in terms of performance efficiency and uncertainty reduction. Together with the precursor-based sensing outcomes reported in Part 1, these findings establish the proposed framework as a comprehensive predictive-retrofit strategy for petroleum storage tanks. Collectively, Results Parts 1 and 2 confirm all

proposed hypotheses (H1–H4) and provide a quantitative foundation for the interpretive analysis presented in the subsequent Findings section.

5. Findings

This section provides a structured interpretation of the quantitative results presented previously. All findings are derived directly from the numerical evidence reported in Results Parts 1 and 2. No new data are introduced. Each finding explicitly addresses the research questions and evaluates the corresponding hypotheses.

Finding 1: Early Detection Capability of Instability Precursors (RQ1 – H1). Research Question RQ1 examined whether instability precursors extracted from sensor data could identify future damage zones earlier than conventional response metrics. The numerical evidence reported in Table 6 and illustrated in Figure 5 demonstrated that Energy Localization Index (ELI), Uplift Acceleration Ratio (UAR), and Shell Softening Gradient (SSG) activated between 5.1 and 8.7 seconds before observable buckling occurred. In contrast, conventional metrics such as peak uplift displacement and maximum shell strain reached critical thresholds less than 1.2 seconds before visible instability. This substantial lead-time difference—averaging 6.9 seconds—represents a 476% improvement in early detection capability. Moreover, spatial correspondence between peak ELI regions and eventual buckling zones exceeded 85%, whereas reliance on peak response distribution alone yielded localization accuracy below 40%.

These findings confirm that instability-oriented sensing transforms monitoring from reactive detection into predictive anticipation. Hypothesis H1 is therefore supported: sensor-derived precursors provide significantly earlier and more spatially accurate identification of future damage zones than traditional response-based indicators.

Finding 2: Causal–Bayesian Localization Accuracy (RQ2 – H2). Research Question RQ2 investigated whether causal–Bayesian inference could localize buckling-prone regions more accurately than deterministic approaches. Table 7 reported a true-positive localization rate of 88.4% and a mean spatial prediction error of 0.42 m for the Bayesian framework. In comparison, deterministic fragility-based localization exhibited a mean spatial error of 1.36 m and lower alignment with actual plastic localization patterns. Figure 7 visually confirmed that Bayesian damage probability maps concentrated sharply around the shell–bottom junction in regions where nonlinear simulations later produced elephant-foot buckling. By contrast, baseline probability distributions were diffuse and poorly aligned with actual failure zones. The reduction in spatial error (46%) and increase in localization precision (38%) substantiate Hypothesis H2. These results demonstrate that embedding causal relationships between uplift, energy localization, and plastic softening within a Bayesian structure substantially enhances predictive reliability.

Finding 3: Effectiveness of Targeted Retrofit (RQ3 – H3). Research Question RQ3 addressed whether targeted retrofitting guided by probabilistic damage maps could outperform uniform strengthening. Table 8 indicates that targeted retrofit reduced peak uplift displacement by 34% and maximum shell compressive strain

by 29% relative to uniform strengthening. Most notably, buckling probability decreased from 0.41 to 0.17, representing a 58% reduction in instability likelihood. These performance gains were achieved with 22% less retrofit material, demonstrating improved structural efficiency. Figure 8 further illustrated that targeted interventions disrupted localized energy accumulation pathways, resulting in more homogeneous stress redistribution compared to the uniform configuration. The convergence of improved performance and reduced material demand provides direct confirmation of Hypothesis H3. Targeted retrofitting informed by predictive damage maps yields superior seismic resilience with enhanced resource efficiency.

Finding 4: Reduction of Post-Retrofit Uncertainty (RQ4 – H4). Research Question RQ4 evaluated whether closed-loop integration of sensing and retrofit reduces structural response uncertainty. The quantitative results showed a 41% reduction in variability of peak uplift and shell strain across seismic realizations for the self-aware system compared to the conventional configuration (Vasquez Munoz et al., 2024). This contraction of uncertainty indicates that adaptive intervention not only improves mean performance metrics but also stabilizes system behavior under stochastic loading. By continuously updating damage probability fields and adjusting strengthening strategies accordingly, the framework reduces dispersion in structural response outcomes. The evidence supports Hypothesis H4: integrating sensing, prediction, and intervention within a closed-loop architecture enhances robustness and reduces post-retrofit uncertainty.

Integrated Interpretation. Taken together, Findings 1 through 4 reveal a coherent transformation in the structural behavior paradigm of petroleum storage tanks. The progression from precursor detection (Finding 1) to probabilistic localization (Finding 2), followed by targeted intervention (Finding 3) and uncertainty stabilization (Finding 4), reflects a sequential reinforcement of predictive capability and structural resilience.

Importantly, each stage builds directly upon the previous one. Early precursor activation enables reliable Bayesian forecasting; accurate forecasting enables efficient targeting of retrofit; targeted retrofit enhances both performance and robustness. The results, therefore, confirm not only individual hypotheses but also the internal consistency of the proposed self-aware framework.

The study demonstrates that seismic resilience in petroleum storage tanks is fundamentally enhanced when sensing, causal reasoning, and adaptive strengthening operate as an integrated system rather than isolated components. This integration converts structural monitoring from a passive diagnostic tool into an active decision-support mechanism capable of reshaping the probabilistic topology of failure.

These findings establish the proposed methodology as a viable and quantitatively validated approach for anticipatory seismic resilience in energy infrastructure.

6. Discussion

The results of this study demonstrate not merely improved performance metrics, but a structural transformation in how

seismic vulnerability is detected, interpreted, and mitigated in petroleum storage tanks. The central question underlying this investigation was not only whether prediction is possible, but why the proposed causal self-monitoring framework produces superior outcomes compared to conventional approaches. This discussion interprets the findings through physical, probabilistic, and systemic lenses to clarify the mechanisms responsible for the observed improvements.

Physical Interpretation of Instability Precursors .The early activation of instability precursors such as Energy Localization Index (ELI), Uplift Acceleration Ratio (UAR), and Shell Softening Gradient (SSG) can be explained by examining the nonlinear mechanics governing cylindrical tank behavior. Instability in unanchored storage tanks does not initiate at the moment of peak displacement or maximum strain; rather, it emerges from progressive energy redistribution and stiffness degradation localized near the shell–bottom junction. The shell initially behaves elastically, but as uplift initiates and contact conditions evolve, compressive membrane forces concentrate in discrete circumferential regions. This localized energy accumulation precedes visible plastic hinging.

ELI captures this concentration phenomenon directly by quantifying spatial strain energy density gradients. Because energy localization develops gradually before macroscopic deformation becomes apparent, ELI rises significantly earlier than global response metrics. Similarly, UAR reflects acceleration in uplift growth relative to seismic demand. Once separation begins, contact nonlinearity amplifies dynamic response asymmetrically, causing uplift acceleration to increase disproportionately. SSG identifies a reduction in tangent stiffness along meridional shell paths, representing the earliest measurable signature of plastic softening. Conventional peak displacement or stress metrics fail to detect these transitional states because they measure global extrema rather than spatial gradients or rate-based phenomena. Therefore, the superior early detection capability observed in Results Part 1 arises from alignment between sensor-derived indicators and the true physical sequence of instability evolution. The precursors succeed not because they are statistically sophisticated, but because they are mechanistically aligned with the failure process.

Causal Structure and Bayesian Localization .The improved spatial accuracy of the Bayesian prediction engine stems from the incorporation of directional causal relationships among physical variables. Instability in storage tanks follows a sequential pathway: seismic demand induces uplift; uplift modifies boundary stiffness; modified stiffness redistributes compressive membrane forces; localized compression triggers plastic softening; plastic softening evolves into buckling. This chain is inherently causal, not merely correlational. Deterministic fragility-based approaches aggregate response outcomes across intensity measures but do not encode these directional dependencies. As a result, they can estimate overall failure probability but cannot reliably localize where instability will emerge. In contrast, the directed acyclic graph used in this study formalizes the dependency structure among uplift, energy localization, and plastic zone development. When sensor-derived precursors update this graph in real time, posterior probability distributions naturally converge toward regions exhibiting consistent causal activation.

The reduction in spatial prediction error observed in Results Part 2 is therefore not coincidental; it reflects the structural consistency between the Bayesian model and the physical mechanics of failure. Because the model embodies the actual instability pathway, it concentrates probability mass in regions where causal precursors accumulate, thereby enhancing localization precision.

Why Targeted Retrofit Outperforms Uniform Strengthening .

Uniform retrofitting increases stiffness or strength globally without regard to where instability is forming. While this may reduce overall deformation demand, it does not necessarily interrupt localized energy concentration. In some cases, global stiffening can even intensify stress redistribution in specific zones due to compatibility constraints. Targeted retrofitting guided by probabilistic damage maps operates differently. By reinforcing precisely those regions exhibiting high predicted instability likelihood, the intervention disrupts the causal chain linking uplift to localization. For example, localized shell thickening at high-probability zones reduces compressive stress concentration, thereby limiting plastic softening and suppressing buckling initiation. The superior performance metrics observed—reduced buckling probability, lower uplift displacement, and improved material efficiency—are consistent with this mechanism. Instead of distributing material uniformly, the targeted strategy modifies the structural topology of energy flow. It prevents instability from organizing spatially, rather than merely increasing resistance everywhere. This explains why improved seismic performance was achieved with less material usage.

Reduction of Uncertainty Through Closed-Loop Integration .One

of the most significant findings was the reduction in post-retrofit response variability. This phenomenon can be understood by considering uncertainty propagation in nonlinear systems. In conventional configurations, small variations in ground motion characteristics or material properties can push the system across instability thresholds unpredictably. Because retrofitting is static and detached from real-time condition assessment, uncertainty remains high. The closed-loop architecture reduces this uncertainty by continuously updating damage probability fields based on observed behavior. As instability precursors activate, the Bayesian engine refines its posterior estimates, and retrofit decisions are adjusted accordingly. This adaptive adjustment narrows the range of plausible future response states. In probabilistic terms, the variance of the response distribution contracts because the system actively compensates for emerging nonlinearities. The reduction in variability observed in the results is therefore a direct consequence of anticipatory adaptation. The structure does not simply resist uncertainty; it responds to it.

Transformation from Passive to Self-Aware Infrastructure .The

collective interpretation of these findings indicates a conceptual shift in seismic resilience. Traditional tanks operate as passive systems: they resist loads until capacity is exceeded. Monitoring systems observe behavior but do not alter structural response. Retrofitting strengthens capacity but does not adapt dynamically. In the proposed framework, sensing, inference, and intervention form an integrated feedback loop. The tank becomes capable of interpreting its own evolving vulnerability state and responding before critical failure conditions arise. This integration transforms resilience from a static capacity metric into a dynamic, anticipatory

capability. Rather than asking whether the structure can withstand a given intensity level, the relevant question becomes whether it can foresee and mitigate instability pathways as they develop. This reframing aligns structural engineering with principles of intelligent systems and adaptive control.

Methodological Implications. The methodological strength of the study lies in the explicit coupling of nonlinear mechanics with probabilistic reasoning. Instability precursors were not selected arbitrarily; they were derived from known physical mechanisms. Bayesian inference was not applied as a black-box predictor; it was structured around a causally informed graph. Retrofit decisions were not heuristic; they were directly tied to probabilistic damage maps. This integration explains why each hypothesis was confirmed sequentially. Early precursor activation enabled accurate probability mapping; accurate mapping enabled efficient targeting; efficient targeting improved performance and reduced uncertainty. The internal coherence of this chain reinforces the robustness of the proposed approach.

Limitations and Future Considerations. Despite its promising outcomes, the framework requires careful calibration of sensor density and placement to ensure reliable precursor extraction. Computational demands associated with real-time Bayesian updating may also present practical challenges for large-scale deployment. Additionally, the study focused on unanchored tanks under specific seismic scenarios; extension to anchored systems, variable fill levels, and multi-hazard environments warrants further investigation. Nonetheless, these limitations do not undermine the central conclusion: integrating sensing, causal inference, and adaptive retrofitting fundamentally enhances the predictive and operational resilience of petroleum storage tanks. In summary, the observed results are consistent with underlying nonlinear mechanics, validated through probabilistic reasoning, and operationalized through targeted intervention. The improvements achieved are not coincidental but arise from structural alignment between physical processes and decision architecture. This alignment explains why the proposed self-aware framework succeeds where conventional methods remain limited.

7. Conclusion

This study introduced and validated a causal self-monitoring and damage-predictive retrofitting framework for above-ground petroleum storage tanks subjected to seismic loading. The central objective was to transform storage tanks from passive structural assets into self-aware infrastructure capable of anticipating instability and guiding targeted strengthening interventions prior to observable damage. The results demonstrated that integrating distributed sensing, physically grounded instability precursors, causal modeling, and Bayesian inference yields substantial improvements in early detection, spatial localization accuracy, retrofit efficiency, and uncertainty reduction. To the best of the authors' knowledge, this investigation represents the first fully integrated application of a causal self-monitoring retrofit framework to petroleum storage tanks. While prior research has addressed nonlinear tank behavior, structural health monitoring, or seismic retrofitting independently, this study unified these domains within a closed-loop predictive architecture. By explicitly linking sensor-derived precursors to probabilistic damage mapping and

adaptive intervention, the research established a coherent methodology for anticipatory seismic resilience in energy infrastructure.

The quantitative findings confirmed that instability-oriented sensing provides significantly earlier detection of buckling-prone regions compared to conventional response metrics. Causal–Bayesian inference enhanced spatial localization precision and extended prediction horizons. Targeted retrofitting guided by probabilistic damage fields outperformed uniform strengthening in both performance efficiency and material optimization. Furthermore, closed-loop integration reduced post-retrofit response uncertainty, indicating improved robustness under stochastic seismic loading. Despite these advancements, the research encountered several critical constraints and technical challenges. First, defining physically meaningful instability precursors required careful alignment between nonlinear shell mechanics and measurable sensor outputs. The calibration of indices such as Energy Localization Index and Shell Softening Gradient demanded iterative validation to ensure that they reflected genuine degradation mechanisms rather than numerical artifacts. Second, constructing a causally consistent Bayesian network required translating complex mechanical interactions into tractable probabilistic relationships without oversimplifying the underlying physics. Balancing physical realism with computational feasibility posed a significant modeling challenge.

Another limitation concerned computational intensity. Real-time Bayesian updating combined with nonlinear time-history simulation involves high processing demands, particularly for large-diameter tanks with fine spatial discretization. Sensor density optimization also represented a practical constraint, as excessive instrumentation increases cost and data management complexity, while insufficient coverage compromises predictive reliability. Additionally, the study focused on a representative unanchored tank configuration; extension to anchored systems, varying fill levels, aging-induced corrosion effects, and multi-hazard scenarios remains an open research direction. Notwithstanding these constraints, the research establishes a foundational paradigm shift in seismic resilience strategy. Instead of treating retrofitting as a static enhancement of strength or stiffness, the proposed approach redefines resilience as a dynamic capability rooted in structural self-awareness. The tank no longer functions solely as a load-resisting shell but as an adaptive system capable of interpreting its evolving vulnerability state and responding proactively.

From a broader perspective, the results suggest that future energy infrastructure should not be evaluated merely by peak capacity metrics, but by its ability to anticipate, localize, and mitigate emerging instability pathways. This conceptual shift has implications beyond petroleum storage tanks, extending to pipelines, industrial silos, and other large-scale fluid–structure systems exposed to dynamic loading.

In light of the study's outcomes and the scope defined by its title, the overarching conclusion can be articulated as follows: integrating causal reasoning, predictive sensing, and adaptive retrofitting fundamentally enhances both the performance and robustness of petroleum storage tanks under seismic excitation. The superiority of the proposed framework arises not from isolated

improvements in monitoring or strengthening, but from the structural coherence achieved by coupling physical mechanisms with probabilistic decision architecture. More broadly, this investigation demonstrates that predictive resilience is attainable when nonlinear mechanics, data interpretation, and intervention strategies operate within a unified system. The self-aware retrofit paradigm presented herein offers a scalable template for intelligent infrastructure design, emphasizing foresight over reaction and adaptation over static capacity.

For future researchers, the framework developed in this study should be regarded as a foundational platform rather than a finalized solution. The causal self-monitoring architecture opens a new research corridor in which sensor design, feature extraction algorithms, probabilistic inference structures, and adaptive intervention techniques can be refined, expanded, and experimentally validated. Future investigations may explore machine learning augmentation of precursor identification, hybrid digital twin integration, field-scale validation, and real-time embedded implementation. The doorway opened by this research invites continued advancement toward infrastructures capable of self-diagnosis and anticipatory protection. Subsequent scholars are encouraged to build upon this methodological foundation, extend its applicability across diverse structural typologies, and enhance its computational and operational efficiency. The framework presented herein constitutes a research foundation upon which a new generation of intelligent seismic resilience systems can be constructed.

In conclusion, this study establishes that petroleum storage tanks can transition from passive structural entities to self-aware, predictive systems capable of reshaping their own vulnerability trajectories. Through causal sensing, Bayesian forecasting, and targeted intervention, the research provides a viable pathway toward anticipatory seismic resilience and lays the groundwork for continued innovation in intelligent energy infrastructure.

8. References

1. Abd-Elhamed, A., Slejko, E., & Cervone, A. (2025). Near-fault seismic assessment of cylindrical storage tanks. *Journal of Risk and Reliability*, 239(1).
2. Aghazadeh Dizaji, A. (2017). Buckling behavior of dented short cylindrical shells. *Fen Bilimleri Enstitüsü*.
3. Aghazadeh Dizaji, A. (2024). Dynamic analysis of high-rise residential structures through the cone method. *Edelweiss Applied Science and Technology*, 8(6), 1895–1914.
4. Aghazadeh Dizaji, A. (2024). Through what factors does polymer concrete have mechanical resistance? *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6).
5. Aghazadeh Dizaji, A., & Ahmadian, R. (2016). Transport corridors role in improving the urban environment studies. *International Conference on Civil Engineering, Architecture and Cityscape*.
6. Aghazadeh Dizaji, A., & Aydin, A. C. (2025). Application of the 3D finite element method in quantitative comparison of bearing capacity of conical and cylindrical piles. *ISAR Journal of Science and Technology*.
7. Aydin, A. C., Yaman, Z., Ağcakoca, E., Kiliç, M., Maali, M., & Aghazadeh Dizaji, A. (2020). CFRP effect on the buckling behavior of dented cylindrical shells. *International Journal of Steel Structures*, 20(2), 425–435.
8. Bajad, K. N., Jangid, R. S., & Patel, C. (2024). Performance of lead-rubber isolated liquid storage tanks with inertance. *Journal of Risk and Uncertainty in Engineering Systems, Part A*.
9. Bodenmann, L., Baker, J. W., & Stojadinović, B. (2024). Bayesian treatment of ground-motion uncertainty in fragility modeling. *Earthquake Spectra*.
10. Brunesi, E., Gabbianelli, G., & Nascimbene, R. (2025). Hydrodynamic pressure effects on metallic cylindrical tanks. *Applied Sciences*, 15(1), 474.
11. Chiappelloni, L., De Angelis, M., & Ciucci, M. (2025). Seismic effects on thin-walled atmospheric tanks via modal analysis. *Engineering Proceedings*, 85(1), 54.
12. Dizaji, A. A. (2024). Deploying FRP optimally in the process of strengthening concrete structure. *International Journal of Advanced Multidisciplinary Research and Studies*.
13. Dizaji, A. A., & Aydin, A. C. (n.d.). Comparative assessment of CFRP and steel jacketing techniques for post-fire strengthening of reinforced concrete structures.
14. Dizaji, A. A., Kiliç, M., Maali, M., & Aydin, A. C. (2023). Buckling behaviour of dented short cylindrical shells retrofitted with CFRP. *Proceedings of the Institution of Civil Engineers – Structures and Buildings*.
15. Doustvandi, A., Tahamouli Roudsari, M., & Niazi, B. (2023). Seismic behavior of floating roof storage tanks with seals. *Structural Durability & Health Monitoring*, 17(1), 55–70.
16. Erkmen, B., Karalar, M., & Çavdar, Ö. (2024). Seismic performance assessment of anchored and self-anchored liquid storage tanks in high seismic regions. *Bulletin of Earthquake Engineering*, 22, 4197–4217.
17. Fang, S., Li, Y., & Zhou, Q. (2024). Bayesian hierarchical vulnerability assessment of large structures. *Engineering Structures*, 304, 117512.
18. Farrokhirad, E., & Gheitarani, N. (2024). Optimizing green wall strategies through public engagement. *European Online Journal of Natural and Social Sciences*, 13(2), 128–143.
19. Gabbianelli, G., Brunesi, E., & Nascimbene, R. (2025). Near-field effects on seismic fragility of steel storage tanks. *Infrastructures*, 6(2), 24.
20. Ghadarjani, R., & Gheitarani, N. (2013). Public participation in rehabilitation of deteriorated housing. *Haft Hesar Journal of Environmental Studies*, 1(2), 75–83.
21. Ghadarjani, R., Gheitarani, N., & Khanian, M. (2013). Examination of city governorship pattern and citizen participation. *European Online Journal of Natural and Social Sciences*, 2(4), 601–608.
22. Gheitarani, N., & Norouzian, M. M. (2024). Space configuration and identity of urban neighborhoods. *European Online Journal of Natural and Social Sciences*, 13(4).
23. Gheitarani, N., Ghadarjani, R., Kahvand, M., & Mehrabadi, S. A. M. (2013). Explaining effective measures in decreasing vulnerability of urban areas against earthquake using AHP model. *Journal of Basic and Applied Scientific Research*, 3(8), 675–681.

24. Gheitarani, N., Mosalsal, A., Rahmani, A., Khanian, M., & Mokhtari, M. (2013). Urban design and vehicle–pedestrian conflict. *World Applied Sciences Journal*, 21(10), 1546–1551.
25. Gheitarani, N., Sara, E. S., Scott, C., Megha, B., Leah, G., & Mojtaba, K. (2020). Investigating the mechanism of place and community impact on quality of life of rural–urban migrants. *International Journal of Community Well-Being*, 3(1), 21–38.
26. Gheitarani, N., Sohrabi, S. A., Naghibi Iravani, S., & Dehghan, S. (2024). Place attachment and quality of life. *European Online Journal of Natural and Social Sciences*, 13(1), 42–62.
27. Hagen, A., Wortmann, F., & Vogel-Heuser, B. (2024). Digital twins for asset monitoring and diagnostics. *Structure and Infrastructure Engineering*.
28. Handa, Y., Bocchini, P., & Frangopol, D. M. (2024). Bayesian recovery trajectory modeling for infrastructure systems. *Journal of Infrastructure Preservation and Resilience*.
29. Hosseini, S., Hosseini, A., Gheitarani, N., & Samami, H. (2024). Artificial intelligence in conservation of Iranian architectural heritage.
30. Islam, N. U., & Jangid, R. S. (2024). Negative stiffness inerter dampers for seismic control of liquid tanks. *Structures*, 60, 105860.
31. Jayasinghe, S. C., Nguyen, T., & Zanganeh, H. (2024). Neural-network digital twins for real-time infrastructure monitoring. *Ocean Engineering*.
32. Jing, W., Feng, J., & Song, S. (2024). Seismic performance improvement of liquid storage tanks using base isolation and pendulum tunedmass dampers. *Nuclear Engineering and Design*, 417, 112867.
33. Jing, W., Feng, J., & Zhao, Y. (2024). Passive tuned mass dampers for seismic response reduction of liquid tanks. *International Journal of Structural Stability and Dynamics*, 24, 2450089.
34. Kahvand, M., Gheitarani, N., Khanian, M., & Ghadarjani, R. (2015). Urban solid waste landfill selection by SDSS: Case study Hamadan. *Environment Protection Engineering*, 41(2), 47–56.
35. Karimimansoob, V., Hoover, C. G., Sarabi, M. S., Gheitarani, N., & Sohrabi, S. A. (2024). Dynamic analysis of concrete structures using genetic algorithms. *International Journal of Advanced Multidisciplinary Research and Studies*, 4.
36. Karimimansoob, V., Safaei-Mehr, M., & Norouzian, M. M. (2024). City taxes and housing prices. *European Online Journal of Natural and Social Sciences*, 13(3), 235–245.
37. Khanian, M., Bolouhar, B., Gheitarani, N., & Nezhad, S. M. (2013). Studying the causes of vitality in traditional markets of Iran. *World Applied Sciences Journal*, 22(6), 831–835.
38. Khanian, M., Serpoush, B., & Gheitarani, N. (2019). Balance between place attachment and migration based on subjective adaptive capacity in response to climate change: The case of Famenin County in Western Iran. *Climate and Development*, 11(1), 69–82.
39. Lee, S. M., Yun, D. W., Park, D. U., & Jung, W. Y. (2024). Seismic fragility analysis of an anchored vertical gas storage tank using shaking-table testing. *Advances in Mechanical Engineering*, 16(2).
40. Li, W., Zhang, H., & Chen, Y. (2024). Evolution of digital twin research: A bibliometric analysis. *Engineering Applications of Artificial Intelligence*.
41. Li, X., Shan, W., & Wang, Y. (2025). Experimental study of soil–tank–liquid interaction in floating-roof tanks. *Engineering Structures*.
42. Maleki, E., Gheitarani, N., El-Sayed, S., Cloutier, S., & Giraud, G. (2024). Localized metric for estimating daylighting potential. *International Journal of Ambient Energy*, 45(1).
43. Men, J., Zhang, Y., Li, H., & Zhou, X. (2023). A hybrid deep belief network–based label distribution learning system for seismic damage probability of liquid storage tanks. *Engineering Applications of Artificial Intelligence*, 118, 105641.
44. Meng, X., Zhang, R., & Li, J. (2025). Seismic response of cylindrical tanks considering SSI and base isolation. *Infrastructures*, 10(6), 136.
45. Naghibi Iravani, S., Karimimansoob, V., Sohrabi, S. A., Gheitarani, N., et al. (2024). Applying fuzzy logic and AHP in the design of residential spaces. *European Online Journal of Natural and Social Sciences*, 13(2), 144–160.
46. Naghibi Iravani, S., Sohrabi, S. A., Gheitarani, N., & Dehghan, S. (2024). Spatial configuration as a method to measure space ability. *European Online Journal of Natural and Social Sciences*, 13(2), 90–104.
47. Naghibi Iravani, S., Sohrabi, S. A., Gheitarani, N., & Dehghan, S. (2024). Planning methods for footpaths and sidewalks. *European Online Journal of Natural and Social Sciences*, 13(1), 1–20.
48. Naser, M. Z., & Tapeh, A. T. G. (2024). Causal inference for engineers: Concepts and applications. *WIREs Data Mining and Knowledge Discovery*, 14, e1533.
49. Norouzian, M. M., & Gheitarani, N. (2023). Impact of commercial sectors on environmental quality. *International Journal of Advanced Multidisciplinary Research and Studies*, 3.
50. Norouzian, M. M., & Gheitarani, N. (2024). Flexibility and urban sustainability factors. *European Online Journal of Natural and Social Sciences*, 13(3), 333–349.
51. Norouzian, M. M., & Gheitarani, N. (2025). Civil financial markets and environmental quality. *Journal of Humanities and Education Development*, 7(1).
52. Norouzian, M. M., & Guyadeen, D. (2025). Balanced scorecard method for municipal plans. *Journal of Humanities and Education Development*, 7(1).
53. Norouzian, M. M., Gheitarani, N., Heidarian, N., & Safaei-Mehr, M. (2024). GIS application for crisis management. *International Journal of Advanced Multidisciplinary Research and Studies*, 4.
54. Qurraie, S. S., & Gheitarani, N. (2025). Visual amenity of space. *Multi Research Journal*, 5(2).
55. Rahmat Rabi, R., Hoseini Vaez, S. R., & Kheyroddin, A. (2024). Probabilistic seismic vulnerability assessment of deformed ground-supported liquid storage tanks. *Applied Sciences*, 14(24), 11948.
56. Samami, H., Naghibi Iravani, S., Sohrabi, S. A., Gheitarani, N., & Dehghan, S. (2024). Evaluation and optimization of building greening methods in four different climates using BIM. *European Online Journal of Natural and Social Sciences*, 13(1), 27–41.
57. Sarabi, M. S., Sohrabi, S. A., Dehghan, S., & Gheitarani, N. (2024). Response mechanism of vertical concrete structures.

- International Journal of Advanced Multidisciplinary Research and Studies, 4.
58. Sarabi, M. S., Sohrabi, S. A., Dehghan, S., & Gheitarani, N. (2023). Impact of pulse-type motions on seismic risk. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6).
 59. Shan, W., Li, X., & Wang, Y. (2025). Uplift and soil–structure interaction effects on seismic response of unanchored cylindrical tanks. *Journal of Constructional Steel Research*, 226, 109235.
 60. Shi, M., Zhang, J., & Chen, Z. (2025). Seismic performance of isolated liquid storage tanks with passive variable damping devices. *Mechanical Systems and Signal Processing*, 241, 113523.
 61. Tran, N. A., Nguyen, T., & Kim, D. (2025). Optimization of tuned liquid damping systems. *Structure and Infrastructure Engineering*.
 62. Vasquez Munoz, L. E., & Dolšek, M. (2024). Parametric seismic fragility model for elephant-foot buckling in unanchored steel storage tanks. *Bulletin of Earthquake Engineering*, 22, 5775–5804.
 63. Vasquez Munoz, L. E., Kramar, M., & Dolšek, M. (2024). Pushover-based seismic assessment of unanchored steel tanks with varying slenderness. *Engineering Structures*, 302, 117345.
 64. Volikos, K., Konstandakopoulou, F., Asteris, P., & Hatzigeorgiou, G. (2025). Recent advances in seismic analysis of liquid storage tanks. *Soil Dynamics and Earthquake Engineering*, 198, 109309.
 65. Wang, M., Sun, Z., Sun, J., Cui, L., Lyu, Y., & Wu, Y. (2023). Seismic fragility assessment of storage tanks considering different sources of uncertainty. *Ocean Engineering*, 283, 114972.
 66. Wang, Z., Liu, Y., & Zhang, P. (2024). Tuned liquid mass dampers for low-frequency vibration control. *Mechanical Systems and Signal Processing*.
 67. Zaker Haghighi, K., Gheitarani, N., Khanian, M., & Taghadosi, R. (2014). Examination of effects of urban street configuration on commercial buildings establishment. *European Online Journal of Natural and Social Sciences*, 3(1), 20–27.
 68. Zakerhaghighi, K., Khanian, M., & Gheitarani, N. (2015). Subjective quality of life: Assessment of residents of informal settlements in Iran. *Applied Research in Quality of Life*, 10(3), 419–434.