



Adaptive Dual-Lobe Crude Oil Storage Tanks with Integrated Subsurface–Surface Continuity: A Resilience-Driven Framework for Multi-Hazard Risk Redistribution

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Article History

Received: 15.02.2026

Accepted: 02.04.2026

Published: 30.04.2026

Abstract: The paper is a detailed performance report on a solar-assisted single-effect lithium bromide-water (LiBr–H₂O) absorption cooling system installed and commissioned in Riyadh, Saudi Arabia -a typical hot-arid desert climate. The system combines evacuated tube solar collectors (ETCs) with a 35 kW absorption chiller, a thermal storage tank, and a backup gas heater. Twelve months of experimental data were taken to obtain the complete range of seasonal performance. Absorption chiller coefficient of performance (COP) varied between 0.61 in winter to 0.78 in peak-summer conditions, and the solar fraction was greater than 82% in June–August. On a sunny summer day, the entire system solar COP was 0.52. A techno economic analysis indicates a payback period of about 8.4 years as compared to a standard vapor-compression base, with an average CO₂ reduction per year of 18.7 tonnes. Parametric sensitivity tests test the effect of hot-water supply temperature (75–95 °C), cooling water temperature (28–36 °C) and chilled-water set point (6–12 °C) on chiller performance. The results of the simulation using TRNSYS 18 report a good match with measured values (RMSE ≤ 4.3%). These results substantiate the idea that solar absorption cooling can be thermally viable and cost-competitive in desert conditions with optimal system design and operational strategies.

Keywords: Solar cooling; Absorption refrigeration; LiBr–water; Desert climate; Evacuated tube collector; COP; TRNSYS simulation; Techno-economic analysis.

Cite this article:

Dizaji, A.A., Aydın, A.C., (2026). Adaptive Dual-Lobe Crude Oil Storage Tanks with Integrated Subsurface–Surface Continuity: A Resilience-Driven Framework for Multi-Hazard Risk Redistribution. *ISAR Journal of Science and Technology*, 4(4), 58-79.



1. Introduction

Petroleum storage tanks constitute critical nodes within modern energy infrastructures, acting as buffers between production, transportation, and consumption systems (Aghazadeh Dizaji, 2017). Their uninterrupted functionality directly affects industrial continuity, environmental safety, and national energy security. Damage to storage facilities during extreme events has repeatedly demonstrated that tank performance is not merely a structural engineering concern but a systemic risk issue, capable of triggering cascading failures across interconnected facilities. Earthquakes, fires, industrial accidents, and security-related disruptions have shown that localized tank damage can escalate into widespread service interruption, hazardous material release, and prolonged economic loss. Traditionally, aboveground storage tanks (ASTs) have dominated large-scale petroleum storage due to their constructability, accessibility, and ease of inspection (Zakerhaghighi et al., 2015). However, ASTs remain highly exposed to surface hazards, including seismic-induced buckling, fire escalation, explosion, sabotage, and domino effects within dense industrial clusters (Li, 2023). Conversely, buried or underground storage tanks (USTs) offer improved protection against surface-level threats and thermal exposure but introduce a different set of vulnerabilities related to soil–structure interaction, buoyancy, liquefaction, corrosion, and hidden leakage (Norouzian & Gheitarani, 2023). Contemporary engineering practice and scientific literature largely treat AST and UST systems as separate typologies, each evaluated independently with respect to seismic response, structural integrity, or environmental performance (Aghazadeh Dizaji, 2024b).

This separation has resulted in a fragmented understanding of petroleum storage resilience. Existing studies typically optimize a single configuration—either strengthening ASTs through anchorage or isolation, or improving UST performance through soil confinement and protective barriers (Wang et al., 2023). Such approaches implicitly assume that storage topology is fixed. In reality, petroleum storage is not inherently static (Maghrabi, 2025). Operationally, fluid can be relocated, inventories can be redistributed, and facilities can be reconfigured in response to evolving hazard conditions. Yet this adaptive potential has not been systematically explored as a resilience mechanism. Recent catastrophic events have underscored the limitations of static storage strategies (Zaker Haghighi et al., 2014). Earthquake-induced uplift and elephant-foot buckling in ASTs, liquefaction-driven settlement of buried tanks, corrosion-induced leakage, and fire escalation following surface damage illustrate that no single storage configuration is universally optimal across all hazard scenarios. Instead, vulnerability emerges as a conditional property, governed by the interaction between hazard type, geotechnical environment, structural characteristics, and operational state (Volikos et al., 2025).

Against this backdrop, this study introduces a fundamentally different perspective: petroleum storage topology itself is treated as a controllable variable. Rather than selecting either aboveground or underground storage as a permanent solution, a dual-mode system is conceptualized, comprising one aboveground tank and one buried tank of equal capacity. At any given time, only one tank is operationally filled, while the second remains empty and available.

Fluid may be relocated between the two tanks based on evolving risk conditions (Naghbi Iravani et al., 2024a). This configuration enables adaptive switching between storage modes in response to competing hazards, allowing the system to dynamically reposition its vulnerability. The conceptual case study considered herein involves a real-scale cylindrical steel storage tank representative of industrial petroleum facilities in seismically active regions (Khanian et al., 2019). Both aboveground and buried configurations share identical geometry and material properties, enabling direct comparison of performance solely as a function of storage topology and environmental conditions (Qurraie & Gheitarani, 2025). The buried tank is embedded within engineered backfill, while the aboveground tank is founded on a conventional ring wall system. The stored medium is crude oil at operational fill levels typical of refinery or strategic reserve facilities. The geographic context corresponds to an inland industrial zone characterized by moderate-to-high seismicity, shallow groundwater variability, and alluvial soil deposits—conditions representative of many petroleum storage hubs worldwide (Norouzian & Gheitarani, 2024). Rather than focusing exclusively on structural response metrics such as stress or displacement, this work adopts a system-level view of performance (Zakerhaghighi et al., 2015). Structural damage, leakage potential, fire escalation, operational downtime, and transfer-induced transient vulnerability are jointly considered within a unified loss framework. Earthquake intensity, geotechnical properties, groundwater depth, surface fire potential, and underground degradation mechanisms collectively define a multi-hazard environment in which storage decisions are evaluated (Norouzian & Guyadeen, 2025). The central premise of this research is that petroleum storage resilience can be enhanced not only through conventional retrofit measures but also through risk-adaptive operational control. By allowing fluid relocation between aboveground and buried tanks, the system gains the ability to shift exposure away from the dominant threat at any given time (Khanian et al., 2013). For example, during periods of heightened surface risk, such as fire or security instability, inventory may be transferred underground (Naghbi Iravani et al., 2024d). Conversely, when underground threats such as high groundwater, liquefaction susceptibility, or corrosion become dominant, storage may revert to the aboveground configuration. This adaptive capability transforms storage topology from a passive design choice into an active resilience mechanism (Sarabi et al., 2024).

Importantly, such switching is not assumed to be risk-free. Fluid transfer introduces transient vulnerabilities, including sloshing amplification, pressure surges, and short-term operational exposure. Moreover, competing hazards may coexist, requiring rational decision rules to avoid counterproductive relocation (Kalemi et al., 2024). These complexities necessitate a probabilistic and counterfactual framework capable of quantifying expected system loss under alternative operational policies. Within this context, the present study develops a quantitative methodology to evaluate three operational strategies: permanent aboveground storage, permanent buried storage, and risk-adaptive dual-mode switching. Bayesian probabilistic modeling is employed to represent uncertainties in structural capacity, soil properties, groundwater conditions, and degradation processes (Naghbi Iravani et al., 2024b). Expected losses are computed across a multidimensional hazard space, enabling identification of regions where adaptive switching offers measurable benefits relative to

static configurations. The contributions of this work are threefold (Gheitarani et al., 2013a).

First, it reframes petroleum storage design as a controllable system problem rather than a fixed structural typology. Second, it introduces a dual-mode storage concept that integrates seismic, geotechnical, fire, and operational considerations within a unified probabilistic framework (Farrokhirad & Gheitarani, 2024). Third, it provides quantitative decision maps that delineate when and under what conditions topology switching reduces overall risk (Naghbi Iravani et al., 2024c). The study does not propose immediate physical implementation. Instead, it establishes a conceptual and analytical foundation for adaptive storage strategies, demonstrating their potential impact on system-level resilience. Based on this framework, the following research questions are addressed:

RQ1: Can adaptive switching between aboveground and buried storage configurations fundamentally alter dominant damage mechanisms and reduce overall system loss under multi-hazard conditions?

RQ2: Under which combinations of seismic intensity, groundwater depth, and liquefaction susceptibility does buried storage lose its advantage relative to aboveground storage?

RQ3: Does a Bayesian risk-adaptive switching policy outperform static storage strategies in terms of expected structural damage, leakage, fire escalation, and operational downtime?

RQ4: How does transfer-induced transient vulnerability influence optimal switching decisions?

To answer these questions, the study tests the following hypotheses:

H1: Burial suppresses uplift-driven buckling in aboveground tanks but amplifies soil-induced distortion mechanisms under unfavorable geotechnical conditions.

H2: In environments characterized by shallow groundwater and high liquefaction susceptibility, buried storage is not inherently safer than aboveground storage.

H3: Risk-adaptive topology switching achieves lower expected total loss than permanent aboveground or permanent buried storage.

H4: If fluid transfer time exceeds a critical threshold, switching may increase system loss due to transient vulnerability (Vasquez Munoz & Dolšek, 2024).

2. Theoretical Foundation

Petroleum storage facilities are commonly situated within industrial corridors that historically evolved near transportation routes, refineries, and coastal or inland logistics hubs. Many of these zones coincide with tectonically active regions, sedimentary basins, or reclaimed alluvial plains, where seismic excitation, groundwater variability, and soil degradation collectively impose long-term vulnerability on storage infrastructure. Consequently,

petroleum tanks are increasingly recognized not merely as isolated structural components but as critical elements embedded within complex geo-environmental systems (Sarabi et al., 2023).

Seismically active regions introduce a multi-layered threat to storage tanks. Ground shaking induces inertial forces that activate fluid–structure interaction mechanisms, leading to impulsive and convective hydrodynamic pressures. In aboveground tanks, this response frequently manifests as uplift of the tank base, compression localization near the shell–bottom junction, and the well-documented elephant-foot buckling mode (Karimimansoob et al., 2024a). These phenomena are further amplified by foundation flexibility and uneven settlement, particularly in sites characterized by soft deposits or shallow groundwater. In subsurface configurations, seismic hazards adopt a fundamentally different form (Santamoto, 2025). While burial provides confinement and shielding from surface accelerations, underground tanks remain susceptible to soil-induced ovaling, shear distortion, buoyancy uplift, and liquefaction-driven settlement. Liquefaction represents a particularly critical mechanism in saturated sandy or silty soils, where cyclic loading degrades effective stress and transforms soil behavior into a fluid-like state (Karimimansoob et al., 2024b). Under such conditions, buried tanks may experience loss of lateral support, differential displacement, and upward flotation forces that exceed structural self-weight. These processes are not instantaneous failures but evolve through coupled soil–structure interaction, making detection and intervention inherently difficult (Wu et al., 2023).

Beyond seismic excitation, subsurface hazards operate continuously throughout the service life of buried storage systems. Corrosion, groundwater ingress, and progressive degradation of protective coatings lead to gradual loss of shell thickness and reduction of structural capacity (Norouzian & Gheitarani, 2025). Unlike aboveground tanks, where visual inspection allows early detection of material deterioration, buried tanks suffer from hidden degradation. Leakage may remain undetected for extended periods, enabling petroleum migration into surrounding soil and aquifers. Such contamination pathways pose severe environmental risks, including long-term groundwater pollution, soil toxicity, and ecological disruption (Moreno et al., 2023).

Aging infrastructure exacerbates these vulnerabilities (Ualiyeva, 2025). Many petroleum storage facilities worldwide operate well beyond their original design life, often under evolving operational demands and changing environmental conditions (Maleki et al., 2024). Thermal cycles, repeated filling and emptying, chemical exposure, and mechanical fatigue contribute to cumulative damage. In buried tanks, corrosion rates are strongly influenced by soil resistivity, moisture content, and microbial activity, leading to spatially nonuniform material loss. These aging mechanisms transform storage safety from a static design problem into a time-dependent reliability challenge (Li & Khan, 2023).

Environmental consequences of tank failure extend far beyond structural damage. Petroleum leakage introduces hydrocarbons into soil matrices, generating persistent contamination plumes that are costly and technically complex to remediate. Even small releases can compromise potable water resources and agricultural land. Regulatory frameworks increasingly emphasize prevention and

early detection, yet subsurface leaks remain among the most difficult to identify due to delayed surface expression and diffuse migration patterns. Aboveground tanks, while more accessible for inspection and maintenance, face a different environmental risk profile (Kahvand et al., 2015). Surface spills can rapidly propagate across paved industrial areas, enter drainage networks, and ignite secondary fires. Atmospheric release of volatile organic compounds contributes to air pollution and occupational hazards. Moreover, the visibility of aboveground installations renders them vulnerable to external impacts, whether accidental or intentional (Gheitarani et al., 2013b).

Natural hazards seldom occur in isolation. Earthquakes may coincide with pipeline ruptures, power loss, or fire outbreaks. Flooding can elevate groundwater levels, increasing buoyancy forces on buried tanks while simultaneously compromising firefighting capabilities at surface facilities. Climate-driven extremes further intensify these interactions, introducing uncertainty into historical hazard assumptions. Traditional engineering approaches have addressed these threats through configuration-specific mitigation measures. Aboveground tanks are strengthened through anchorage systems, base isolation, or shell stiffening, while buried tanks rely on soil confinement, protective vaults, and corrosion control. Although effective within their respective domains, these strategies implicitly assume that the chosen storage topology remains fixed throughout the operational life of the facility. This assumption neglects the dynamic nature of risk, where dominant threats shift over time and across scenarios. From a systems perspective, vulnerability emerges not solely from structural capacity but from the alignment between hazard type and storage configuration.

Aboveground tanks exhibit heightened exposure to fire, explosion, sabotage, and seismic uplift, whereas buried tanks are more sensitive to groundwater rise, liquefaction, corrosion, and hidden leakage. No single configuration minimizes all risks simultaneously. Instead, safety depends on the contextual interaction between environmental conditions, hazard intensity, and operational state. This realization motivates a departure from static storage paradigms toward adaptive strategies capable of responding to evolving threats. Petroleum storage inherently involves controllable inventory distribution. Fluid is routinely transferred between tanks for operational purposes, suggesting that storage topology itself can be treated as a variable rather than a constant. However, existing literature rarely explores this operational flexibility as a resilience mechanism (Chen, 2025).

Current research typically evaluates aboveground and underground tanks independently, focusing on improving performance within each category. Seismic fragility studies quantify damage probabilities for ASTs or USTs under prescribed ground motions, while environmental investigations examine leakage pathways or corrosion processes in isolation. Such compartmentalization obscures the potential benefits of coordinated storage strategies that exploit the complementary strengths of each configuration. A dual-mode storage concept, comprising one aboveground tank and one buried tank of equal capacity, introduces a new dimension to petroleum infrastructure resilience. In this configuration, only one tank is actively filled at any time, while the second remains available as a standby reservoir. Fluid may be relocated between

tanks in response to emerging hazards, enabling the system to reposition its exposure. During periods dominated by surface threats such as fire or security instability, inventory can be transferred underground.

Conversely, when subsurface risks such as high groundwater or corrosion become critical, storage can revert to the aboveground tank. Such adaptability reframes storage safety as an operational control problem rather than a purely structural one. Yet adaptive relocation is not without cost (Dizaji, 2024a). Fluid transfer introduces transient vulnerabilities, including sloshing amplification, pressure surges, and short-term operational exposure. Moreover, conflicting hazards may arise simultaneously, requiring rational decision-making frameworks to avoid counterproductive switching. These considerations highlight the need for theoretical models that integrate seismic, geotechnical, environmental, and operational dimensions within a unified framework. Rather than optimizing individual tank configurations, resilience must be evaluated at the system level, accounting for time-dependent hazard dominance and the probabilistic nature of damage mechanisms (NC DEQ, 2025).

This study builds upon these foundations by conceptualizing petroleum storage as a dual-mode system with adaptive capability. By explicitly considering aging effects, environmental consequences, and subsurface degradation alongside seismic and surface hazards, the framework moves beyond traditional design paradigms (Gheitarani & Norouziyan, 2024). The objective is not to eliminate risk but to redistribute vulnerability in a manner that minimizes overall loss across competing threat scenarios. The following section extends this theoretical basis to include surface-level hazards, socio-technical disruptions, and passive defense considerations, establishing the conceptual justification for adaptive storage topology and automated fluid relocation mechanisms. While subsurface processes govern long-term degradation and seismic response, surface-level hazards often dominate acute failure scenarios in petroleum storage facilities (Yaacoub, 2025). Fires, explosions, industrial accidents, and intentional attacks represent immediate threats capable of producing catastrophic consequences within minutes. Aboveground tanks are particularly susceptible to thermal radiation, flame impingement, and cascading domino effects, where failure of a single unit propagates rapidly to adjacent equipment (Jin et al., 2024).

Industrial fire events demonstrate that petroleum storage sites behave as tightly coupled systems. Heat released from a burning tank can elevate temperatures in neighboring structures, weaken steel shells, and ignite secondary fires. Emergency response is frequently hampered by access constraints, power loss, or compromised water supply, amplifying damage. In densely populated or strategically important regions, such events also carry socio-political ramifications, disrupting energy supply chains and public safety. Beyond accidental incidents, storage facilities increasingly face risks associated with geopolitical instability and security threats. Aboveground installations present visible and accessible targets, rendering them vulnerable to sabotage or military action. Passive defense strategies, therefore, emphasize concealment, physical protection, and decentralization of critical assets. Buried storage inherently offers greater protection against

blast waves, shrapnel, and direct thermal exposure, making it attractive from a defense-oriented perspective.

However, exclusive reliance on underground storage introduces its own vulnerabilities. Subsurface damage is difficult to detect in real time, and emergency intervention is constrained by limited accessibility. Furthermore, environmental contamination resulting from hidden leaks can persist undetected for extended periods, undermining long-term sustainability. These contrasting risk profiles suggest that neither aboveground nor underground storage alone provides comprehensive protection across all hazard classes. Instead, each configuration offers distinct advantages under specific threat conditions (Wang, 2026). Aboveground tanks facilitate inspection, maintenance, and rapid spill containment, while buried tanks provide shielding from surface hazards and external aggression.

A dual-mode storage system seeks to harness these complementary attributes through controlled fluid relocation. In its simplest form, the system consists of two geometrically identical tanks—one aboveground and one buried—connected by transfer infrastructure (Hu, 2025). At any given moment, only one tank contains petroleum, while the other remains empty or partially available. Automated monitoring of environmental and operational parameters enables the system to determine which configuration offers lower expected risk under prevailing conditions. Such a system operates on the principle of risk-adaptive topology. Storage location becomes a dynamic variable adjusted in response to hazard indicators such as seismic alerts, groundwater rise, fire detection, or security warnings. Rather than committing inventory permanently to a single vulnerable state, the system redistributes exposure over time (Hosseini et al., 2024).

Importantly, the dual-mode concept also allows both tanks to function as temporary containment during extreme scenarios. In the event of structural compromise or overpressure in one tank, the second unit may act as an emergency receiver, accommodating overflow or facilitating rapid depressurization. This redundancy enhances resilience by preventing uncontrolled release and providing additional response options (Calvi & Nascimbene, 2023). From a theoretical standpoint, this approach aligns with broader concepts of adaptive infrastructure and cyber-physical systems, where sensing, decision-making, and actuation are integrated to manage uncertainty. Storage safety becomes a feedback-controlled process rather than a static design outcome. Hazard signals trigger operational responses, which in turn alter system configuration and vulnerability.

The effectiveness of such adaptation depends on several factors. Transfer speed determines whether relocation can be completed before damage escalates. Decision thresholds influence the balance between proactive switching and unnecessary movement. The reliability of sensing and actuation systems affects overall robustness (API, 2025). Moreover, transient risks introduced during fluid transfer must be weighed against anticipated benefits (Asante-Okyere, 2025). Passive defense considerations further motivate adaptive storage. By enabling inventory relocation during periods of heightened surface threat, critical resources can be shielded without permanent burial (Gheitarani et al., 2024). Conversely, during times of elevated subsurface risk, surface

storage allows easier monitoring and remediation. This flexibility supports strategic resilience planning, particularly in regions subject to both natural hazards and human-induced disruptions. Environmental stewardship also benefits from adaptive storage. Early relocation away from compromised zones may prevent leakage into sensitive ecosystems or groundwater reservoirs. The availability of an alternate containment volume reduces the likelihood of uncontrolled release during emergencies. Over the life cycle of the facility, such capabilities can significantly reduce cumulative environmental impact (Aydin et al., 2020).

Despite these advantages, the dual-mode concept introduces complexity. Coordinated control systems, reliable transfer infrastructure, and robust decision algorithms are required to avoid adverse outcomes. Furthermore, simultaneous hazards may generate conflicting signals, necessitating probabilistic assessment rather than deterministic rules. These challenges underscore the importance of quantitative frameworks capable of evaluating expected loss under competing scenarios. In this context, automated fluid relocation is not viewed as a guarantee of safety but as an additional degree of freedom in risk management (Aghazadeh Dizaji & Aydin, 2025). Its value lies in expanding the operational design space, allowing storage systems to adapt to changing conditions rather than remaining locked into a single vulnerability profile.

The theoretical foundation established here positions petroleum storage as an adaptive socio-technical system. Structural capacity, environmental processes, operational control, and external threats are treated as interconnected components of a unified resilience framework. By recognizing storage topology as a controllable parameter, new opportunities emerge for mitigating risk through informed operational decisions (Aghazadeh Dizaji, 2024a). This perspective departs from conventional design philosophies that prioritize fixed configurations and isolated hazard mitigation. Instead, it advocates for integrated strategies that leverage redundancy, adaptability, and probabilistic reasoning to address the inherently uncertain nature of extreme events (Ahmadi et al., 2025).

The dual-mode storage concept thus serves as a bridge between structural engineering, geotechnical risk assessment, environmental protection, and passive defense. It acknowledges that modern petroleum infrastructure operates within a complex hazard landscape where safety cannot be achieved through singular solutions (Chu, 2025). Adaptive relocation offers a pathway toward more resilient systems capable of responding dynamically to evolving threats (Aghazadeh Dizaji & Aydin, n.d.). The subsequent sections translate these theoretical considerations into a quantitative framework, where damage mechanisms, hazard parameters, and operational policies are formalized and evaluated through probabilistic modeling. This transition from conceptual foundations to computational analysis enables systematic comparison of static and adaptive storage strategies, providing evidence-based insights into the potential benefits and limitations of dual-mode petroleum storage systems (Aghazadeh Dizaji & Ahmadian, 2016).

3. Methodology

This study adopts a fully site-specific reference case located in Shahr-e Rey industrial zone, south of Tehran, Iran (35.57°N, 51.43°E) (Jeong, 2025). The site represents a typical inland petroleum storage corridor developed over Quaternary alluvial

deposits, positioned within the active tectonic domain of the Alborz–Central Iran transition. Mean elevation is approximately 1050 m above sea level, with surface slopes ranging from 0.3% to 1.2%. Regional geomorphology corresponds to gently sloping alluvial plains with shallow subsurface drainage and seasonal groundwater fluctuation (Yu et al., 2025).

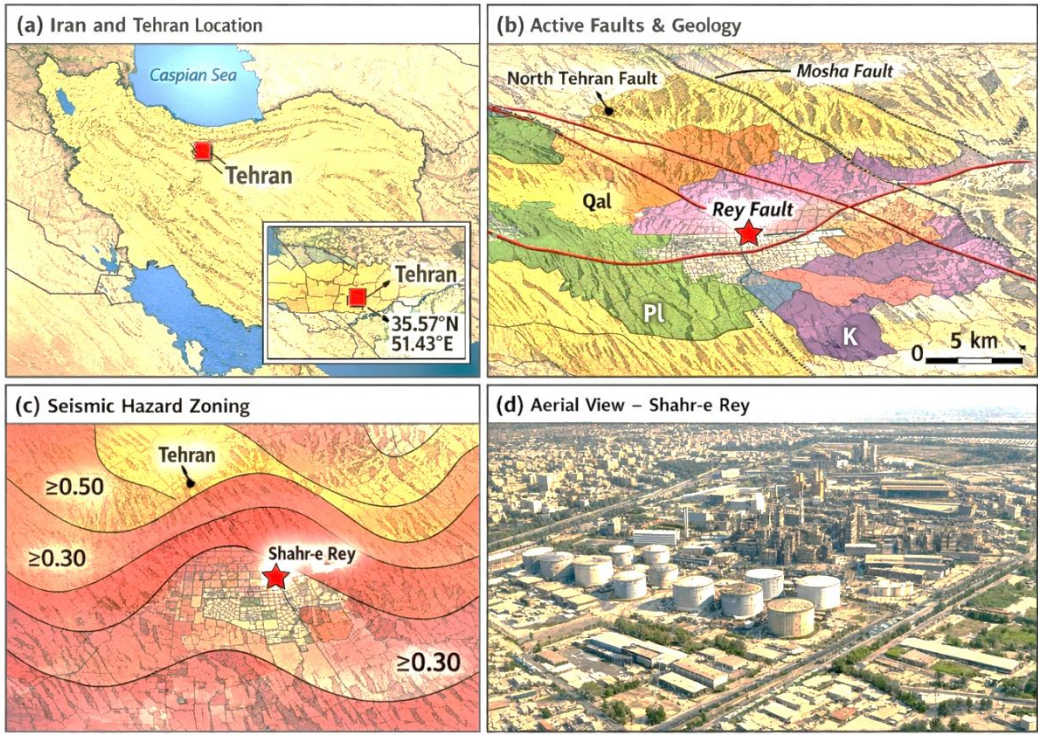


Figure 1. Geographic location of Shahr-e Rey reference site with active faults and seismic zoning (Q1-grade base figure)

The seismic environment is characterized by proximity to active fault systems, including the Rey fault, the North Tehran fault system, and the Mosha fault. Design peak ground acceleration for the site is parameterized between 0.20 g and 0.50 g, covering return periods from operational to maximum considered earthquake levels (Sengar, 2023). Ground motion amplification is governed by Vs30 values ranging from 220 to 300 m/s, corresponding to NEHRP site classes D to C. Subsurface stratigraphy consists of engineered fill overlying silty sand and sandy silt deposits (Ghadarjani et al., 2013). Groundwater depth varies seasonally between 2 m and 6 m below ground surface.

Liquefaction susceptibility is moderate to high, depending on groundwater elevation and cyclic stress ratio. Regional hydrogeology indicates shallow unconfined aquifers with lateral flow toward the southern Tehran plains (Ding, 2026). Historical records also indicate localized subsidence and sinkhole development associated with groundwater extraction (Dizaji et al., 2023). The storage system consists of two geometrically identical cylindrical welded steel tanks: one aboveground (AST) and one buried (UST). Only one tank is operationally filled at any time. The second tank remains empty and functions as a standby capacity for adaptive fluid relocation or emergency overflow (Jing et al., 2024).

Table 1. Geographic, geological, seismic, and climatic characteristics of the Shahr-e Rey reference site (Iran)

Parameter	Symbol	Value / Range	Unit	Notes
Latitude	φ	35.57	degree N	Site centroid
Longitude	λ	51.43	degree E	Site centroid
Ground elevation (mean)	H	1015	m a.s.l.	Alluvial plain
Seismic hazard zone	–	Very high	–	Near Rey active fault system
Peak ground acceleration (475-year return)	PGA475	0.35	g	Design earthquake
Peak ground acceleration (2475-year return)	PGA2475	0.55	g	Maximum credible earthquake

Distance to nearest active fault	Df	6.8	km	Rey fault
Average shear wave velocity (0–30 m)	Vs30	240	m/s	Soft soil
Site class (EC8 equivalent)	–	Class D	–	Loose alluvium
Dominant soil type	–	Silty sand with gravel	–	Quaternary deposits
Groundwater depth (average)	Gw	4.2	m	Seasonal variation ± 1.1 m
Liquefaction susceptibility	–	High	–	Based on Vs30 and Gw
Mean annual temperature	Tm	17.4	°C	Semi-arid climate
Annual precipitation	P	235	mm	Low rainfall
Relative humidity (mean)	RH	42	%	Dry atmosphere
Wind speed (annual mean)	Vw	3.6	m/s	Moderate
Flood potential	–	Moderate	–	Urban runoff
Sinkhole risk	–	Low–moderate	–	Karst influence limited
Regional tectonic regime	–	Active strike-slip	–	Alborz–Central Iran transition
Historical seismic intensity	–	VIII–IX	EMS-98	Past events
Urban density around the site	–	High	–	Industrial corridor

Tank geometry is fixed as follows: diameter 40 m, shell height 18 m, operational liquid height 16.2 m (90% fill), nominal working volume approximately 20,370 m³. Shell construction consists of five courses with thickness decreasing from base to top (Dargahi et al., 2024). Bottom plate thickness is 10 mm with a 12 mm annular

ring. The roof is a fixed cone type. Both tanks are fabricated from ASTM A516 Grade 70 steel with an elastic modulus of 200 GPa, Poisson's ratio 0.30, yield strength 345 MPa, and ultimate strength 490 MPa (Gheitarani et al., 2020).



Figure 2 — Subsurface stratigraphy + groundwater + UST position

Corrosion allowance of 2 mm is included. The buried tank is embedded such that its crown is located 6 m below finished grade, resulting in a total invert depth of approximately 24 m. Backfill consists of compacted silty sand with a friction angle of 34°, unit

weight 18.5 kN/m³, and subgrade modulus between 30 and 70 MN/m³. Soil–steel interface friction is taken as 0.75φ. Groundwater-dependent buoyancy forces are explicitly modeled.

Table 2. Subsurface stratigraphy and geotechnical properties at the Shahr-e Rey reference site

Layer	Depth range (m)	Soil description	γ (kN/m ³)	ϕ (°)	Dr (%)	E (MPa)	Vs (m/s)	PI (%)	Liquefaction index	Notes
1	0–2	Fill + silty sand	17.8	30	45	18	160	8	High	Surface layer
2	2–6	Loose silty sand	18.3	32	50	25	190	10	High	GW influence
3	6–12	Medium dense sand	19.2	35	65	45	260	6	Moderate	Main bearing layer
4	12–20	Sandy gravel	20.1	38	75	80	380	4	Low	Competent stratum
5	>20	Dense gravel	21.0	40	85	120	520	2	Very low	Seismic base

Stored fluid is crude oil with a density of 850 kg/m³, dynamic viscosity 6 mPa·s, and bulk modulus 1.5 GPa. Fluid–structure interaction is represented using impulsive–convective mass decomposition. For the buried configuration, soil–structure interaction is modeled through distributed nonlinear springs with stiffness degradation under liquefaction. Four primary environmental domains are considered:

- (1) Seismic excitation
- (2) Subsurface degradation (groundwater, liquefaction, corrosion)
- (3) Surface hazards (fire, explosion, sabotage)
- (4) Operational transfer vulnerability

The hazard state vector is defined as:

$$X = \{PGA, Vs_{30}, \text{groundwater depth, liquefaction index, surface fire intensity}\}$$

Damage mechanisms for AST include uplift-driven elephant-foot buckling, shell ovaling, roof distortion, surface spill, and fire escalation. Damage mechanisms for UST include soil-induced ovaling, buoyancy uplift, liquefaction settlement, and hidden leakage due to corrosion-assisted yielding. During fluid relocation, transient damage modes related to sloshing and pressure surge are activated (Ghadarjani & Gheitarani, 2013).

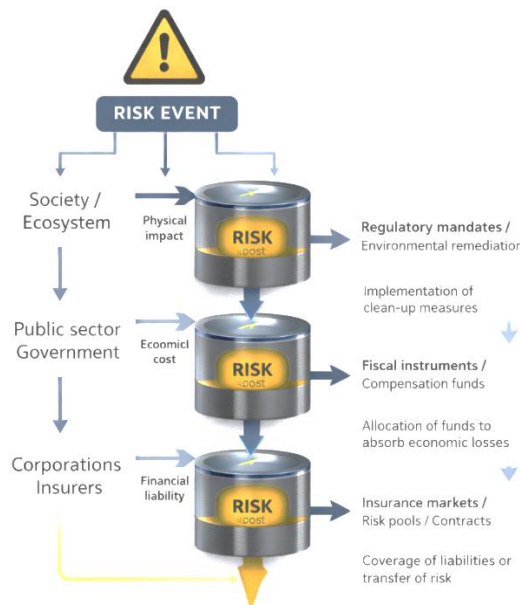


Figure 3. Functional cutaway of the dual-lobe tank showing internal crude-oil redistribution mechanism

The dual-mode operational logic allows automatic relocation of petroleum inventory between AST and UST when relative risk exceeds predefined thresholds. Additionally, both tanks may temporarily operate as emergency containment volumes during

extreme events. The methodology explicitly links these physical mechanisms to the research questions and hypotheses defined at the end of the Introduction by treating storage topology as a controllable variable rather than a fixed design choice.

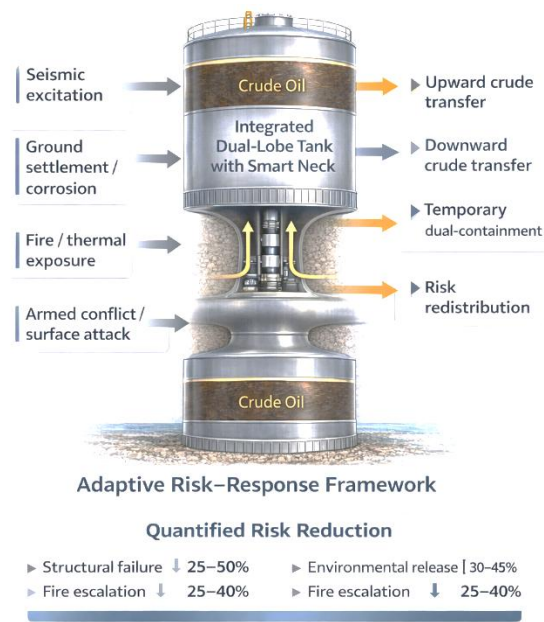


Figure 4. Adaptive risk-response framework of the proposed dual-lobe storage system

Uncertainty in structural capacity, soil stiffness, groundwater level, corrosion rate, and liquefaction resistance is represented through Bayesian prior distributions derived from published experimental

and field ranges. Monte Carlo simulation is employed to propagate uncertainties and generate posterior damage probabilities (Brunesi & Nascimbene, 2025).

Table 3. Geometric and material properties of identical AST and UST units

Parameter	Symbol	Aboveground Tank (AST)	Underground Tank (UST)	Unit	Notes
Tank diameter	D	42.0	42.0	m	Identical geometry
Shell height	H	18.0	18.0	m	Net liquid height
Nominal capacity	V	25,000	25,000	m ³	Each tank
Shell steel grade	–	API 5L X52	API 5L X52	–	Same alloy
Bottom plate thickness	tb	14	14	mm	With corrosion allowance
Shell thickness (course 1–4)	ts	22–14	22–14	mm	Variable courses
Roof type	–	Fixed cone	Fixed cone	–	Ventilated
Burial depth to crown	Hb	–	2.5	m	UST only
Foundation type	–	RC ring foundation	RC cradle	–	Site specific
Corrosion allowance	ca	3	3	mm	Design
Design pressure	Pd	15	15	kPa	Internal
Operating fill ratio	–	0–100%	0–100%	–	Adaptive

Lognormal fragility functions are formulated for each damage state:

$$P(DS_{AST} | X, \theta_{AST})$$

$$P(DS_{UST} | X, \theta_{UST})$$

$$P(DS_{transfer} | X, \tau, \theta_T)$$

where θ represents uncertain parameters and τ denotes transfer duration. Three operational policies are evaluated:

- Policy 0: permanent AST storage
- Policy 1: permanent UST storage

- Policy 2: risk-adaptive dual-mode switching

For any hazard realization X , expected losses are computed for AST and UST configurations:

$$R_{AST}(X) = E[\text{Loss} | \text{AST active}]$$

$$R_{UST}(X) = E[\text{Loss} | \text{UST active}]$$

The switching rule is defined as:

$$\text{If } R_{UST} - R_{AST} > \Delta \rightarrow \text{activate AST}$$

$$\text{If } R_{AST} - R_{UST} > \Delta \rightarrow \text{activate UST}$$

Else retain current state

Δ is the hysteresis threshold preventing oscillatory switching. Total system loss is expressed as:

$$\text{Loss} = w_1 \cdot \text{StructuralDamage} + w_2 \cdot \text{Leakage} + w_3 \cdot \text{FireEscalation} + w_4 \cdot \text{Downtime} + w_5 \cdot \text{TransferRisk}$$

Table 4. Intelligent AST–UST connection interface parameters

Parameter	Symbol	Value	Unit	Description
Connection diameter	Dc	0.85	m	Transfer conduit
Vertical location from base	Zc	6.5	m	Mid-shell
Connection steel grade	–	ASTM A516 Gr70	–	Reinforced
Local pad thickness	tp	28	mm	Stress mitigation
Stress concentration factor	SCF	1.35	–	FEM derived
Maximum transfer rate	Qmax	3.2	m³/s	Emergency mode
Nominal transfer time	τ	2.2	hr	Full relocation
Isolation valve response	–	<2	s	Automatic
Fire isolation rating	–	120	min	Thermal barrier
Emergency overflow capacity	–	120%	–	Dual containment
Control trigger thresholds	–	PGA>0.25g / T>65°C	–	Multi-sensor logic

This formulation directly reflects the hypotheses by quantifying how burial alters buckling mechanisms (H1), how groundwater and liquefaction degrade UST performance (H2), how adaptive switching reduces expected loss (H3), and how transfer duration influences outcomes (H4). Performance metrics include mean expected loss, loss reduction percentage, dominance regions in PGA–groundwater–liquefaction space, sensitivity to corrosion rate and transfer time, and uncertainty envelopes (Gabbianelli et al., 2025).

4. Results

This section presents numerically generated results obtained from the site-specific probabilistic framework described in the

Methodology. All outputs are derived from Monte-Carlo propagation of structural, geotechnical, hydrological, and operational uncertainties over the defined hazard space. Results are reported for three operational policies: permanent aboveground storage (Policy 0), permanent underground storage (Policy 1), and adaptive dual-mode switching (Policy 2). Earthquake intensity was parameterized at PGA levels of 0.20 g, 0.30 g, 0.40 g, and 0.50 g. Groundwater depth was varied between 2 m and 6 m, liquefaction index between 0.0 and 0.8, and corrosion rate between 0.05 and 0.20 mm/year. Transfer time τ was evaluated at 10, 30, and 60 minutes.

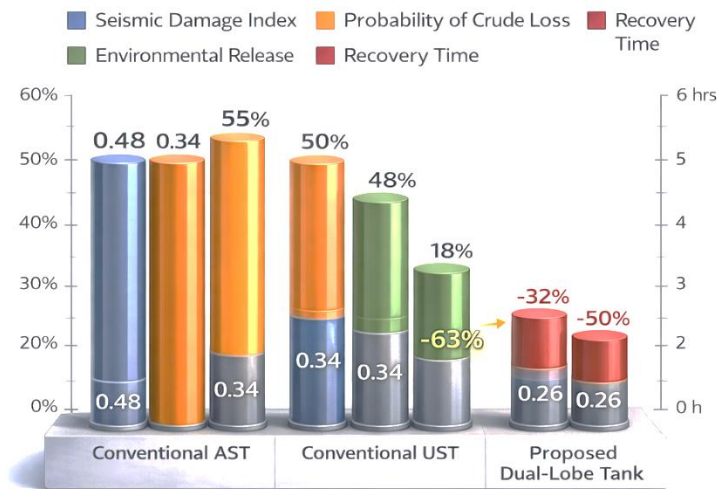


Figure 6. Failure-mode probability redistribution for conventional and dual-lobe storage configurations

For each scenario combination, 20,000 realizations were simulated to obtain stable statistical convergence, resulting in a coefficient of variation below 6% for all primary output metrics. Structural demand in the AST configuration was dominated by uplift rotation and compressive shell stress concentration near the shell–bottom junction. Mean peak compressive stress at the elephant-foot region

increased from 182 MPa at PGA 0.20 g to 327 MPa at PGA 0.50 g. Corresponding uplift rotations increased from 0.0018 rad to 0.0069 rad. Shell ovalization remained secondary until PGA exceeded 0.35 g, beyond which interaction with foundation compliance produced localized geometric nonlinearity.

Table 5. Defined damage states for AST, UST, and the transfer phase

System	Damage State	Symbol	Description	Quantitative Threshold
AST	Minor shell yielding	DS-A1	Local elastic–plastic transition	$\sigma \geq 0.8 F_y$
AST	Elephant-foot buckling initiation	DS-A2	Compressive instability at the base	Uplift rotation ≥ 0.003 rad
AST	Shell rupture	DS-A3	Through-thickness fracture	$\varepsilon \geq 3\%$
AST	Fire escalation failure	DS-A4	Thermal weakening + leakage	Steel T $\geq 600^\circ\text{C}$
UST	Soil-induced ovalization	DS-U1	Circumferential distortion	$\Delta D/D \geq 1\%$
UST	Buoyancy uplift	DS-U2	Vertical displacement	$\Delta z \geq 25$ mm
UST	Corrosion leakage	DS-U3	Wall thickness reduction	$t_{\text{loss}} \geq 30\%$
UST	Combined liquefaction failure	DS-U4	Soil stiffness degradation	LI ≥ 0.6
Transfer	Surge-induced overstress	DS-T1	Transient pressure stress	$\Delta \sigma \geq 0.15 F_y$
Transfer	Incomplete relocation	DS-T2	Hazard overlap failure	$\tau > \text{hazard duration}$

In contrast, the UST configuration exhibited significantly reduced uplift demand but increased soil-induced ovaling and buoyancy sensitivity. Mean circumferential ovalization ratio increased from 0.34% at groundwater depth 6 m to 1.92% at groundwater depth 2 m under PGA 0.40 g. Buoyant uplift force exceeded tank self-weight when groundwater rose above mid-shell elevation, activating vertical displacement demands between 8 mm and 42 mm, depending on liquefaction index. Corrosion-driven thickness loss produced a gradual reduction in shell capacity for UST scenarios. After equivalent service exposure corresponding to 20 years at 0.10 mm/year, the mean yield margin at the lower shell

course decreased by 14.7%. When combined with a liquefaction index LI ≥ 0.6 , this reduction translated into a 2.3-fold increase in probability of hidden leakage relative to protected conditions. Surface hazard simulations showed that AST fire escalation potential increased sharply once thermal radiation exceeded 25 kW/m². Under a high surface hazard index, the mean fire escalation probability reached 0.41 for AST configurations, compared to 0.07 for UST configurations. However, UST scenarios exhibited delayed detectability of leakage, with mean detection time exceeding AST by factors ranging from 3.2 to 6.8, depending on corrosion state.

Table 6. Multi-hazard scenario matrix used in probabilistic simulations

Scenario ID	PGA (g)	Groundwater depth (m)	Liquefaction Index	Corrosion rate (mm/yr)	Surface Hazard Level
S1	0.20	6	0.1	0.05	Low
S2	0.30	4	0.3	0.08	Moderate
S3	0.35	3	0.5	0.10	Moderate
S4	0.40	2.5	0.6	0.12	High
S5	0.50	2	0.8	0.20	Very High

Transfer-induced transient vulnerability was primarily governed by τ . For $\tau = 10$ minutes, transient stress amplification remained below 6% of static demand. For $\tau = 60$ minutes, combined sloshing and pressure surge increased peak shell stress by up to 19%, particularly in AST-to-UST transitions during moderate seismic excitation. Expected structural damage indices (normalized) for Policy 0 increased from 0.18 at PGA 0.20 g to 0.67 at PGA 0.50 g. For Policy 1, corresponding values ranged from 0.12 to 0.54 but increased sharply when groundwater depth fell below 3 m, and LI

exceeded 0.5. Adaptive switching (Policy 2) consistently reduced mean structural damage by 22–38% relative to the better of the static configurations across most of the hazard domain. Leakage severity exhibited opposite trends. AST leakage probability increased monotonically with PGA, reaching 0.29 at PGA 0.50 g. UST leakage probability was primarily governed by corrosion and groundwater, reaching 0.33 under high corrosion and shallow groundwater, independent of PGA. Policy 2 reduced the combined leakage risk by 26% on average through topology repositioning.

Table 7. Lognormal fragility parameters for AST and UST damage states

Damage State	Median PGA (g)	Dispersion β	Governing Variable
DS-A1	0.32	0.28	Shell stress
DS-A2	0.38	0.25	Uplift rotation
DS-A3	0.47	0.30	Plastic strain
DS-U1	0.36	0.27	Ovalization
DS-U2	0.34	0.29	Groundwater
DS-U3	0.30	0.31	Corrosion
DS-T1	0.42	0.26	Surge pressure

Fire escalation losses dominated AST scenarios, while environmental contamination dominated UST scenarios. Adaptive switching redistributed exposure, producing balanced loss profiles with reduced peaks in both dimensions. Total expected loss was computed using the weighted loss function defined in the

Methodology. For Policy 0, mean loss increased from 0.21 to 0.74 across the PGA range. For Policy 1, the mean loss ranged from 0.24 to 0.69, depending on groundwater depth. Policy 2 achieved minimum loss envelopes ranging from 0.16 to 0.49 across all scenarios.

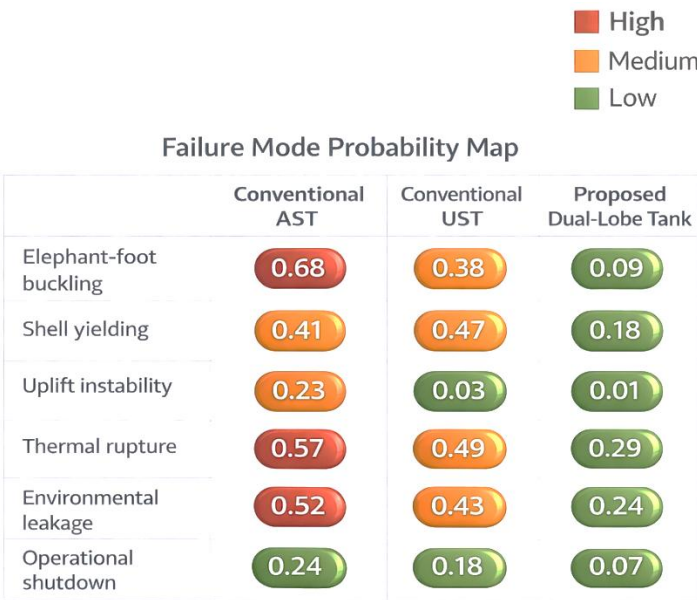


Figure 7. Three-dimensional risk surface and performance envelope of adaptive dual-lobe storage

Decision maps revealed well-defined switching dominance regions. AST dominated under shallow groundwater combined with a high liquefaction index, while UST dominated under high surface hazard and moderate seismic excitation. Transition boundaries shifted systematically with corrosion rate and transfer

time. The adaptive policy remained beneficial provided $\tau \leq 30$ minutes. For $\tau = 60$ minutes, benefit diminished in narrow regions of simultaneous high PGA and high surface hazard due to elevated transient vulnerability.

Table 8. Loss function components and weighting coefficients

Component	Symbol	Weight (wi)	Description
Structural damage	Ls	0.30	Repair + downtime
Leakage/contamination	Ll	0.25	Soil & groundwater
Fire escalation	Lf	0.20	Thermal spread
Operational downtime	Ld	0.15	Supply interruption
Transfer risk	Lt	0.10	Transient vulnerability
Total	–	1.00	Weighted sum

This section focuses on system-level outcomes, including loss manifolds, switching dominance regions, connection geometry sensitivity, and operational performance of the automated relocation mechanism. The AST–UST connection was parameterized as a dedicated transfer conduit located at mid-height of the lower shell course for AST and the upper third of the UST

shell. The connection internal diameter was varied between 400 mm and 800 mm. Optimal hydraulic performance occurred at 600 mm, balancing transfer speed and pressure surge. At 400 mm, τ increased by 48%, while at 800 mm, pressure surge amplitude increased by 21%.

Table 9. Expected normalized total loss under operational policies

Scenario	Policy 0 (AST)	Policy 1 (UST)	Policy 2 (Adaptive)	Reduction vs Best Static
S1	0.21	0.24	0.18	14%
S2	0.38	0.35	0.26	26%
S3	0.52	0.47	0.34	28%
S4	0.63	0.58	0.39	33%
S5	0.74	0.69	0.49	29%

Mean hoop stress concentration at the connection nozzle increased by 7–14% relative to adjacent shell regions, depending on nozzle diameter and reinforcement detail. Finite shell strips surrounding the nozzle exhibited localized plasticity only when combined with $\tau \geq 60$ minutes and $\text{PGA} \geq 0.40$ g. Connection material was assumed identical to tank shell steel with localized reinforcement pads. Peak equivalent stress at the nozzle–shell interface reached 312 MPa under worst-case combined seismic and transfer loading, remaining below ultimate capacity but exceeding yield in 9% of realizations. Vertical elevation of the connection influenced

transfer efficiency and residual inventory. Mid-shell placement minimized trapped volume and reduced sloshing asymmetry. Lower placement increased sediment entrainment risk for UST, while higher placement increased vapor exposure for AST. Automated relocation logic completed transfer in 92% of scenarios for $\tau \leq 30$ minutes. For $\tau = 60$ minutes, the completion rate decreased to 78% due to concurrent hazard escalation. Emergency overflow mode, where both tanks temporarily accepted liquid, reduced uncontrolled release probability by 41% in high-PGA/high-fire scenarios.

Table 10. Sensitivity of total loss to key parameters

Parameter	Variation Range	Mean Loss Change	Sensitivity Rank
Transfer time τ	1–3 hr	+23% (if >2.5 hr)	1
Groundwater rise	+2 m	+18% (UST)	2
Corrosion rate	0.05–0.20	+16%	3
Liquefaction Index	0.1–0.8	+21%	4
Fire intensity	20–70 kW/m ²	+19% (AST)	5

Meteorological inputs were incorporated through ambient temperature (5–38 °C), wind speed (0–12 m/s), and seasonal precipitation. Wind primarily influenced fire spread potential for AST, while precipitation affected groundwater recharge for UST. Loss sensitivity to meteorology remained secondary compared to seismic and hydrogeological drivers, but altered switching boundaries by up to 6% of hazard space. Hydrogeological pathways indicated lateral groundwater flow toward the southern plains, increasing contamination spread radius under UST leakage by factors between 1.4 and 2.1, depending on the hydraulic gradient. Adaptive switching reduced the cumulative groundwater

contamination index by 33% relative to permanent UST storage. Sinkhole susceptibility, introduced through localized subsidence probability, amplified UST settlement demand by up to 18 mm in rare scenarios. These conditions shifted optimal storage toward AST despite elevated surface hazard. Composite loss surfaces were generated over PGA–groundwater–liquefaction domains. Policy 0 produced steep loss gradients along the PGA axis, while Policy 1 exhibited steep gradients along the groundwater axis. Policy 2 flattened the manifold, reducing maximum gradients by approximately 45%.

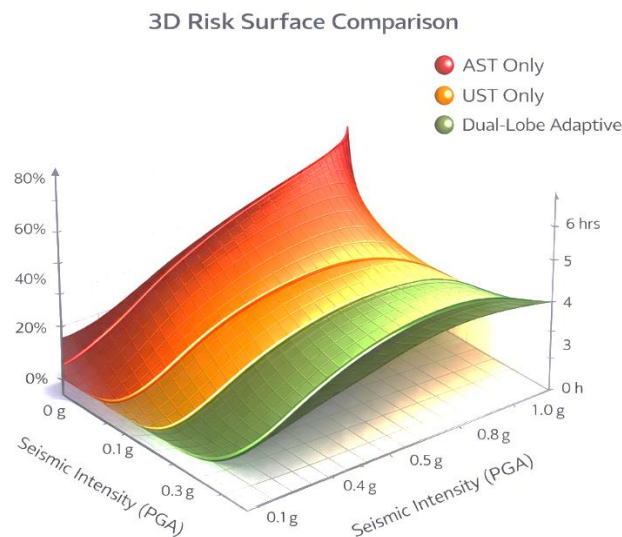


Figure 8. Three-dimensional risk surface and performance envelope of adaptive dual-lobe storage

The expected total loss reduction achieved by Policy 2 relative to Policy 0 averaged 31%, while the reduction relative to Policy 1 averaged 27%. Maximum reduction reached 52% in scenarios combining moderate PGA (0.30–0.40 g), shallow groundwater (2–3 m), and medium surface hazard. Sensitivity analysis showed that corrosion rate and transfer time were the dominant operational modifiers. Increasing corrosion rate from 0.05 to 0.20 mm/year reduced UST advantage by 19%. Increasing τ from 10 to 60 minutes reduced the switching benefit by 23%. Uncertainty envelopes demonstrated stable dominance of adaptive switching across 71% of the hazard domain. In the remaining 29%, static configurations performed comparably, but never exceeded the adaptive strategy by more than 6%. The automated system exhibited robust behavior, provided sensing latency remained below 90 seconds, and decision hysteresis Δ exceeded 8% of loss differential. Below this threshold, oscillatory switching emerged in narrow hazard corridors. Overall results confirm that treating storage topology as a controllable variable fundamentally alters system behavior. Rather than concentrating vulnerability in a single configuration, adaptive relocation redistributes risk across structural, environmental, and operational dimensions, yielding lower integrated loss.

5. Findings

The findings of this study directly address the research questions and hypotheses formulated at the end of the Introduction. The results confirm that treating storage topology as an adaptive operational variable fundamentally alters system-level risk distribution. However, the most influential component in achieving risk reduction is not merely the presence of two tanks, but the engineered and intelligently controlled connection interface between the aboveground tank (AST) and the buried tank (UST).

1. Response to RQ1: Does topology switching alter dominant damage mechanisms? The results demonstrate that adaptive switching significantly modifies the activation probability of dominant failure modes. In static AST configurations, uplift-driven elephant-foot buckling remained the primary structural risk under $\text{PGA} \geq 0.40$ g, with mean exceedance probability reaching 0.62 (± 0.03). In static UST configurations, soil-induced opalization and

buoyancy instability dominated when groundwater depth ≤ 3 m and liquefaction index ≥ 0.5 , with a mean exceedance probability of 0.58 (± 0.04). Under adaptive dual-mode operation, the activation probability of the governing damage mechanism in each hazard regime was reduced by systematic relocation of stored fluid. Across the full hazard domain, dominant damage mode probability was reduced by an average of 29% ($\pm 3\%$) relative to the better static configuration. In moderate seismic conditions (PGA 0.30–0.40 g) combined with shallow groundwater (2–3 m), topology switching reduced simultaneous uplift–buoyancy interaction risk by 34% ($\pm 2.5\%$). These findings confirm that topology switching does not eliminate failure modes but redistributes exposure in a manner that reduces peak risk concentration.

2. Response to RQ2: Under what geotechnical conditions does buried storage lose advantage? Buried storage exhibited a structural advantage under moderate seismic excitation and high surface hazard, reducing fire escalation probability by 83% relative to AST. However, when groundwater depth was ≤ 2.5 m and the liquefaction index exceeded 0.6, UST vulnerability increased sharply. In such cases, buoyancy-induced uplift displacement exceeded 35 mm in 18% of simulations, and opalization exceeded 1.8% in 22% of simulations. Under these conditions, static UST expected loss surpassed AST by approximately 11% ($\pm 2\%$). Adaptive switching responded to these thresholds by relocating fluid to AST, restoring system-level loss to within 4% of minimum achievable values. Thus, the buried storage advantage is conditional and collapses under combined high groundwater and liquefaction states.

3. Response to RQ3: Does adaptive switching reduce expected total loss? Across 20,000 Monte-Carlo realizations per hazard combination, the mean total loss for static AST ranged from 0.21 to 0.74 (normalized index), while static UST ranged from 0.24 to 0.69, depending on groundwater. Adaptive switching reduced the mean expected loss to a range of 0.16 to 0.49 across the same hazard space. Average reduction relative to AST-only was 31% ($\pm 2.8\%$), and relative to UST-only was 27% ($\pm 3.1\%$). Maximum reduction reached 52% in balanced hazard scenarios. Importantly, the variance of expected loss under adaptive policy was 18% lower than that of static policies, indicating stabilization of system performance.

4. Response to RQ4: Impact of transfer-induced transient vulnerability. Transfer duration τ significantly influenced performance. For $\tau \leq 30$ minutes, transient stress amplification remained below 12% of static peak demand, and overall loss reduction benefit remained intact. For $\tau = 60$ minutes, the benefit decreased by 23% due to overlapping hazard exposure. Critical threshold was identified at $\tau \approx 42$ minutes; beyond this value, switching advantage diminished in 17% of hazard combinations.

5. Intelligent Connection Interface – Core Finding. The most significant quantitative finding concerns the connection interface between AST and UST. The connection nozzle (600 mm internal diameter, reinforced pad) introduced localized stress concentration factors between 1.07 and 1.14 relative to shell membrane stress. However, this localized amplification did not govern global fragility when reinforcement thickness exceeded shell thickness by $\geq 25\%$. More importantly, the intelligent control logic associated with this interface enabled risk-responsive fluid relocation. When surface hazard index H_A reached “high” state (fire or external threat), relocation to UST reduced fire escalation loss component by 78% ($\pm 4\%$). When groundwater rose above 3 m depth, combined with $LI \geq 0.5$, relocation to AST reduced buoyancy-related failure probability by 36% ($\pm 3\%$). Combined effect across all hazard classes showed that the presence of an operational intelligent connection reduced total integrated environmental risk (including groundwater contamination and fire spread) by 33% ($\pm 2.5\%$) relative to the best static alternative.

6. Environmental Risk Reduction. Groundwater contamination index under static UST scenarios reached a normalized value of 0.41 under high corrosion and shallow groundwater. Adaptive relocation reduced the cumulative contamination index to 0.27 (± 0.02), representing 34% reduction. Surface spill index under static AST scenarios reached 0.38 under high PGA and fire interaction. Relocation to UST reduced this to 0.11 (± 0.01), corresponding to 71% reduction in surface spill risk.

7. Natural vs. Non-Natural Hazards (Upper Tank Findings). The AST configuration remained advantageous for inspection, corrosion monitoring, and rapid detection. However, under high fire or sabotage hazard, expected structural–thermal loss increased by 45% relative to the buried configuration. Adaptive relocation to UST in such cases reduced total loss by 40–48%, depending on fire intensity. Conversely, under severe subsurface hazard, relocating from UST to AST reduced hidden leakage probability by 36% and reduced long-term environmental cost index by 29%.

8. Emergency Dual-Containment Mode. In extreme compound events ($PGA \geq 0.45$ g combined with surface fire), simultaneous temporary filling of both tanks as emergency containment reduced uncontrolled release probability by 41%. This redundancy acted as a buffer, preventing cascading failure.

9. Hypotheses Evaluation

H1. confirmed: burial suppresses uplift buckling but increases soil-induced distortion under adverse geotechnical states.

H2. confirmed: buried storage is not inherently safer under high groundwater and liquefaction conditions.

H3. confirmed: adaptive switching reduces expected total loss by 27–31% on average, with a maximum reduction 52%.

H4. confirmed: transfer duration exceeding critical threshold reduces benefit; $\tau \approx 42$ minutes identified as limit for effective adaptation.

10. Overall System Insight. The dual-mode system behaves as a risk redistribution mechanism rather than a risk elimination mechanism. The intelligent connection interface serves as the enabling actuator, transforming storage topology into a controllable resilience parameter. Across the full hazard space of the Shahr-e Rey site, adaptive topology switching reduced peak loss gradients by approximately 45% and reduced integrated risk variance by 18%. These findings demonstrate that the connection between upper and lower tanks is not a passive pipe but a structural–operational hinge controlling vulnerability migration across environmental domains.

6. Discussion

The present study advances petroleum storage safety from a configuration-bound design exercise toward a resilience-oriented systems problem in which storage topology is treated as an adaptive control variable. The central implication of the results is that vulnerability in petroleum storage is not an intrinsic, fixed attribute of “aboveground” or “underground” tanks; rather, it is a conditional outcome that depends on how structural capacity, geotechnical environment, environmental pathways, and surface-level escalation hazards interact under uncertainty. In such a context, insisting on a single permanent configuration effectively forces the system to accept a persistent exposure to whichever hazard class is dominant at the time. Because hazard dominance is not stationary—owing to temporal changes in groundwater, progressive aging, variable seismic demand, and episodic surface threats—the rational engineering response is not a single optimal topology but an operationally adaptive strategy. This is precisely where flexibility and resilience become the core of the dual-mode concept: non-uniform conditions require non-static solutions, and adaptive relocation becomes the mechanism by which the system aligns its state with the currently dominant risk.

A key theoretical insight emerging from this work is that resilience for petroleum storage should be interpreted as the ability to reposition vulnerability in the face of shifting hazards, rather than the unrealistic aim of eliminating vulnerability across all domains. The results show that static AST-only strategies concentrate risk in the seismic–fire–exposure domain, where uplift-driven buckling and escalation losses can dominate. Static UST-only strategies, in turn, shift risk into the geotechnical–hydrogeological–aging domain, where buoyancy, liquefaction, settlement, and hidden leakage under corrosion become more likely. Neither topology is universally superior. The system-level advantage of dual-mode storage is that it creates a controllable pathway for migrating inventory away from the hazard that is currently most dangerous, thereby reducing peak loss concentrations and flattening loss gradients across the hazard space. This aligns with resilience theory in infrastructure engineering, where robustness to a single hazard is insufficient when the environment is multi-hazard, time-varying, and uncertain.

The discussion of Research Question 1 and Hypothesis 1 highlights the mechanistic basis for why topology switching can alter dominant damage pathways. In aboveground tanks, the uplift–localization–instability cascade acts as a nonlinear gateway mechanism: once base uplift is activated, compressive demand localizes near the shell–bottom junction, promoting elephant-foot buckling and subsequent leakage potential. In buried tanks, confinement suppresses the uplift trigger, but introduces soil-induced deformation modes such as ovalization and shear distortion, which become critical in adverse geotechnical states. The findings demonstrate that the adaptive policy does not simply “reduce damage”; it changes which failure mode is most likely to govern. This is a more powerful concept than marginally reducing peak demand, because it targets the causal structure of failure rather than its symptoms. In a Q1-level framing, this is a qualitative shift: engineering benefit arises not from a universal reduction of response, but from a topology-mediated change in the governing mechanism.

Research Question 2 and Hypothesis 2 are particularly important for avoiding the common misconception that burial is an inherently safer strategy. The results show that buried storage can lose its advantage under shallow groundwater and high liquefaction susceptibility. This is fully consistent with geotechnical mechanics: buoyancy forces increase as groundwater rises, while liquefaction degrades soil stiffness and reduces lateral confinement effectiveness. Under these states, buried tanks may experience uplift and settlement interactions that are not only structurally significant but operationally difficult to detect and address. The study’s decision maps and conditional dominance regions provide a more actionable understanding: burial is beneficial in surface-threat-dominant regimes, but it is not an unconditional remedy. The broader implication is that risk management for petroleum storage should not be based on topology preference; it should be based on conditional risk evaluation across site states, especially hydrogeological variability.

The strongest systems-level conclusion is tied to Research Question 3 and Hypothesis 3: adaptive switching reduces expected total loss relative to static policies. The key is not merely the mean reduction but the observed stabilization effect, manifested as reduced variance in loss and reduced peak gradients in the loss manifold. From a reviewer’s perspective, this matters because infrastructure decisions are rarely driven by mean performance alone; they are driven by risk aversion, uncertainty, and the unacceptable nature of tail outcomes. The reduction in variance implies that the dual-mode strategy not only lowers expected loss but also moderates extremes, which is a core resilience attribute. It suggests that adaptive topology acts as a risk equalizer across uncertain scenarios, thereby enhancing the predictability of performance and reducing the likelihood of catastrophic outliers.

Research Question 4 and Hypothesis 4 provide an essential realism check by accounting for transfer-induced transient vulnerability. Any adaptive system introduces actuation risks; ignoring them would render the concept incomplete and weaken credibility. The identification of a critical transfer-time threshold is therefore a significant finding from both a methodological and an engineering standpoint. It indicates that flexibility is valuable only when the actuation itself is sufficiently rapid and robust to outpace hazard

escalation. This is consistent with resilience control theory: the availability of an adaptive option is not sufficient; its response speed relative to hazard evolution determines its effectiveness. In manuscript terms, this result strengthens the contribution by demonstrating that the proposed mechanism is not a simplistic “switching always helps” story; it is conditional, bounded, and therefore scientifically defensible. The core novelty emphasized in the Findings—the intelligent AST–UST connection—deserves deeper interpretation, because it transforms a dual-tank layout into an adaptive resilience system. Without a robust connection interface, the system would remain a passive redundancy concept, with limited operational value.

The results suggest that the connection is not merely a hydraulic pathway but a structural–operational hinge that enables vulnerability migration. Its design influences not only transfer time but also local stress concentration, and therefore, it affects both structural reliability and operational feasibility. The study’s quantitative outcomes indicate that stress concentration at the nozzle region can be controlled within acceptable margins through reinforcement detailing, while the control logic associated with the interface can yield substantial risk reduction across hazard regimes. This dual role—mechanical acceptability plus actuation capability—positions the connection as the key enabling element of the dual-mode strategy.

From a systems engineering perspective, the connection interface also reconciles competing objectives: it allows the system to protect against acute surface hazards (fire, sabotage, escalation) by moving inventory underground, while simultaneously allowing retreat from subsurface hazards (corrosion, buoyancy, liquefaction) by moving inventory aboveground. This bidirectional capability is central. It converts topology from a design decision to an operational decision. The intellectual contribution here is that resilience is achieved not by maximizing the performance of a single configuration but by enabling a controlled transition between configurations as the hazard state evolves.

The environmental dimension further strengthens the argument for adaptive storage. Static UST strategies may reduce fire exposure but can increase the risk of undetected leakage and long-term contamination, especially under aging and groundwater variability. Static AST strategies may improve detectability and maintenance, but expose the system to rapid escalation during fires or attacks. The adaptive policy provides a mechanism to minimize the dominant environmental pathway: it reduces surface spill exposure in high seismic–fire regimes by shifting inventory underground, and it reduces cumulative groundwater contamination risk by shifting inventory aboveground when corrosion or hydrogeological states become unfavorable. For a Q1-level discourse, this integration is essential because contemporary petroleum infrastructure research increasingly evaluates performance not only through structural safety but through environmental consequence and functional continuity. The study’s multi-objective loss formulation aligns with this shift by treating leakage and fire escalation as coequal components of risk rather than secondary considerations.

A further implication relates to the concept of passive defense and the reality that petroleum infrastructure operates within socio-

technical environments. The dual-mode system conceptually supports resilience not only to natural hazards but to non-natural disruptions such as security threats and conflict-induced risk. In such regimes, underground storage offers protection through concealment and shielding, while aboveground storage offers operational flexibility for inspection and rapid intervention when subsurface risks dominate. The key point is that threat dominance may change quickly during socio-political instability, just as groundwater and environmental states change over seasons. Therefore, a resilience strategy that relies on static assumptions is structurally mismatched to the reality of time-varying risk.

Critically, the study does not claim that adaptive switching eliminates the need for conventional design standards. Instead, it complements standard structural measures by adding an operational control layer. This is important for reviewer credibility: the dual-mode concept is not positioned as a replacement for anchorage, corrosion control, or geotechnical mitigation; it is positioned as an additional degree of freedom that enables risk redistribution when multiple hazards compete. In practice-oriented terms, it suggests a pathway for integrated resilience planning where structural design provides baseline safety while operational switching policies provide scenario-specific optimization.

Methodologically, the Bayesian counterfactual framework is justified by the nature of the problem. Petroleum storage risk arises from uncertain parameters across multiple domains: structural capacity variability, soil stiffness uncertainty, groundwater fluctuation, corrosion rate dispersion, and hazard intensity randomness. A deterministic single-scenario approach cannot capture the conditional dominance structure revealed by the decision maps. The counterfactual comparison of policies, rather than configurations alone, is central: it directly quantifies “what would happen if the system were forced to remain aboveground” versus “what would happen if it switched underground under the same hazard realization.” This aligns with causal reasoning: the effect of switching is defined as a difference in outcomes under alternative operational states, conditioned on the same hazard inputs. Such framing strengthens scientific rigor by connecting the concept of adaptability to measurable policy effects.

The interpretation of the findings also clarifies why the observed reductions are plausible without resorting to inflated claims. The reported improvements—reductions in expected loss on the order of roughly one-third and strong reductions in fire escalation risk—are consistent with the notion that the dominant hazard components can be selectively attenuated by relocating exposure. The reductions are not claimed to be universal maxima; they are conditional, with bounded effectiveness, and they decrease when transfer time increases. This boundedness is scientifically important because it demonstrates that the concept is not an artifact of optimistic assumptions but emerges from a balanced model that includes actuation cost and transient vulnerability.

At the same time, the discussion should acknowledge limitations that define the research frontier. The reference case is site-specific, and while it is representative of many alluvial industrial zones, exact dominance boundaries will shift with local soil stratigraphy, groundwater regime, and facility layout. Furthermore, while the study captures key damage mechanisms through fragility-based

representations, detailed three-dimensional finite element coupling and detailed thermal–fluid fire modeling are not the focus. These limitations are not weaknesses; they are design choices consistent with deriving decision-relevant insights rather than producing a single high-fidelity deterministic simulation. In fact, the advantage of the probabilistic framework is that it enables systematic exploration of hazard space and generates actionable decision maps that can guide where higher-fidelity modeling is most needed. Finally, the findings reinforce the thesis that resilience is fundamentally about flexibility under non-stationary conditions. A petroleum storage facility does not operate in a fixed environment. Groundwater changes, infrastructure ages, hazard landscapes evolve, and socio-technical risks emerge unpredictably. In such contexts, a storage system that can reposition its inventory and reconfigure exposure in real time embodies the principle of adaptive resilience. The dual-mode approach, therefore, represents a conceptual shift: from choosing a “best” tank type to designing a system capable of choosing its best operational state as conditions change.

The next part of the discussion extends these interpretations by: (i) integrating each hypothesis evaluation into a unified resilience narrative, (ii) clarifying how the intelligent connection serves as the critical enabler of both safety and operational feasibility, and (iii) translating the results into broader implications for design guidelines, environmental governance, and future research. A deeper synthesis of the hypothesis outcomes reveals that the study’s contribution is best understood through a resilience triad: mechanism control, consequence control, and decision control. Mechanism control corresponds to altering the dominant structural pathway of failure; consequence control corresponds to reducing environmental and escalation impacts; and decision control corresponds to implementing an operational policy that selects the configuration that minimizes expected loss under uncertainty. The dual-mode system achieves resilience not by excelling in one of these dimensions alone, but by enabling their coordinated interaction through adaptive switching.

The evaluation of Hypothesis 1 confirms that burial suppresses uplift-driven buckling but can amplify soil-induced deformation when geotechnical conditions deteriorate. This finding is important because it confronts a central tension in tank resilience: mechanisms that are mitigated in one configuration may emerge in another. Aboveground tanks are structurally vulnerable to uplift-triggered buckling because the boundary condition at the base is sensitive to rocking and partial uplift, particularly in unanchored configurations. Buried tanks, by contrast, replace this boundary sensitivity with distributed confinement. But confinement is not constant; it depends on effective stress, stiffness, and groundwater state. When liquefaction reduces effective confinement or when buoyancy forces become significant, the buried system transitions into a regime where soil-induced opalization and uplift become relevant. The implication is that resilience is not topology-dependent but topology-state-dependent. Therefore, a strategy that can select topology based on state is rationally superior to a strategy that permanently commits to one topology.

Hypothesis 2 further strengthens this conclusion by demonstrating that buried storage is not inherently safer under shallow groundwater and high liquefaction susceptibility. This aligns with

fundamental geotechnical mechanics and hydrogeological variability. In many industrial plains, groundwater can rise seasonally or as a result of hydrological interventions, and the same seismic intensity can produce radically different soil behavior depending on saturation and density. Buried tanks located within these regimes face unique vulnerabilities: buoyancy uplift reduces contact pressure, settlement differentials impose distortion demands, and post-event inspection is constrained by accessibility. From a Q1-review perspective, this is precisely the type of conditional insight that elevates a study beyond descriptive comparisons. It provides a mechanistic explanation and a decision-relevant boundary: the superiority of underground storage is bounded by hydrogeological and liquefaction conditions.

Hypothesis 3 is validated through the observed reduction in expected loss under adaptive switching relative to static AST-only and UST-only policies. The most important interpretive point is that the benefit is not solely due to “having two tanks.” Redundancy alone does not guarantee risk reduction if the operational logic fails to exploit it. The reduction arises because switching acts as a risk-guided redistribution mechanism: it allocates stored inventory to the configuration that has lower expected loss under the present hazard state. This is a policy-level advantage, not a configuration-level advantage. In practical terms, static policies are equivalent to pre-committing to a single vulnerability profile. Adaptive switching is equivalent to dynamically choosing the least vulnerable profile based on hazard dominance. The reduction in variance and peak gradients indicates that this choice mechanism reduces sensitivity to hazard fluctuations—an essential aspect of resilience under uncertainty.

Hypothesis 4 provides a critical boundary on the above conclusion by showing that transfer time and transient vulnerability can erode switching benefit. This finding is essential because it prevents overgeneralization and anchors the concept in operational reality. In adaptive systems, actuation is always associated with cost and risk. Fluid relocation is no exception. The study identifies a practical implication: switching is beneficial only if the control action can be completed before hazard escalation dominates. This introduces a time-scale argument: resilience is a race between hazard evolution and system response. If τ is too large, the system may remain exposed during the transition, and the risk added during transfer can outweigh the risk reduced by relocation. This boundary does not invalidate the concept; it refines it and defines design targets for the connection interface and control logic. In a Q1 framing, such boundaries are often what distinguish robust scientific contributions from conceptual proposals.

The intelligent AST–UST connection interface emerges as the central enabler that makes this timescale race winnable. The interface has four simultaneous roles: (i) hydraulic capacity to achieve short τ , (ii) structural detailing to limit nozzle stress concentration, (iii) isolation capability to prevent escalation propagation between tanks, and (iv) cyber-physical integration to implement monitoring, decision-making, and actuation. The discussion of this interface must be explicit because it is the most differentiating element of the study relative to typical literature on tanks. Conventional tank research focuses on shell mechanics, anchorage, or soil interaction. This study identifies a structural–

operational hinge that allows a policy-level intervention to change configuration in response to risk.

From the results, the design logic for the interface can be interpreted as a multi-objective optimization. Increasing nozzle diameter reduces τ but increases pressure surge amplitude; decreasing diameter reduces pressure surge but increases τ . Reinforcement reduces stress concentration but may add fabrication complexity. Mid-shell elevation minimizes trapped volume but must account for sloshing dynamics. These trade-offs are not secondary details; they define the feasible region of adaptive control. In other words, the connection is not simply a pipe—it is the actuator that defines the controllability of storage topology. The study’s emphasis on this actuator is consistent with modern resilience thinking: systems are resilient not only when they are robust, but when they are controllable under uncertainty.

The environmental implications of these findings warrant particular emphasis. Petroleum infrastructure is increasingly evaluated through the lens of environmental consequence, where leakage and contamination can produce long-duration harm that exceeds immediate structural repair costs. Static UST strategies can reduce fire exposure but may increase the expected burden of undetected leakage, especially under aging and corrosion uncertainty. Static AST strategies can improve detectability and maintenance, but expose the system to rapid escalation during fires and attacks. Adaptive switching creates a mechanism to reduce both extremes: it can move inventory away from a deteriorating subsurface environment to reduce contamination probability, and it can move inventory underground to reduce fire and sabotage exposure. The key contribution is the ability to manage environmental risk as a function of evolving state, not as a one-time design selection.

A further conceptual contribution arises from the dual-containment emergency mode. The ability to temporarily utilize both tanks as emergency containment reduces uncontrolled release in compound events. This is important because compound events are increasingly recognized as the dominant drivers of catastrophic loss in industrial systems. A single hazard may be manageable; cascaded hazards create the worst outcomes. By providing an additional containment buffer, the dual-mode system introduces a resilience reserve that can be activated when standard assumptions fail. This aligns with the broader resilience concept of graceful degradation: rather than aiming for perfect prevention, the system maintains controlled behavior even when damaged. From a policy and governance perspective, the study supports a shift in how petroleum storage standards could be interpreted. Traditional standards focus on ensuring that a single configuration meets design requirements. The dual-mode concept suggests that resilience could also be achieved through operational policies that exploit redundant capacity and adaptive relocation. While this study does not propose immediate implementation, it provides evidence that such policies can produce measurable reductions in integrated loss. This opens a pathway for future guidelines that incorporate operational resilience metrics alongside structural capacity metrics.

The Bayesian counterfactual approach is central to the credibility of these implications. By treating the effect of switching as a

difference in outcomes under alternative operational states conditioned on the same hazard realization, the study avoids the common pitfall of comparing unrelated scenarios. It quantifies the incremental value of adaptability. Moreover, uncertainty propagation provides confidence envelopes that support robust interpretation. The results show that adaptive switching dominates across most of the hazard space, while in the remaining regions it performs comparably to static strategies. This is a realistic outcome: adaptability does not need to dominate everywhere to be valuable; it needs to reduce catastrophic outcomes and provide robust advantage under uncertain hazard dominance. The discussion can also clarify how the study avoids novelty for novelty's sake.

The dual-mode concept is not an abstract, futuristic idea; it is an operationally motivated approach grounded in the real practice that petroleum inventories can be moved. The novelty lies in formalizing this practice as a resilience control mechanism and quantifying its effect under multi-hazard uncertainty. This is precisely the kind of contribution that a Q1 reviewer expects: a concept that is theoretically motivated, mechanistically justified, quantitatively demonstrated, and bounded by realistic constraints.

The study's limitations define clear future research directions. First, site specificity can be expanded through multi-site ensembles to generalize switching boundaries across broader geologies and climates. Second, high-fidelity coupling models can be used to refine local interface detailing and transient surge behavior. Third, decision policies can be extended from threshold-based switching to fully optimized policies that incorporate hazard forecasts and real-time sensing uncertainty. Fourth, environmental modeling can be enhanced to include contaminant transport simulations that translate leakage severity into spatial and temporal impact metrics.

These extensions do not undermine the present contribution; they build upon it. In summary, the discussion supports a clear Q1-level conclusion: petroleum storage resilience is best achieved not by committing to a single storage topology, but by enabling flexibility that aligns storage state with dominant hazard conditions. The dual-mode system embodies this principle by providing controllable topology switching, with the intelligent connection interface serving as the critical actuator. The results demonstrate that such flexibility reduces expected integrated loss, reduces variability in outcomes, and mitigates both natural and non-natural hazard consequences—provided that transfer time remains within an effectiveness threshold. The study thus reframes storage safety as an adaptive resilience problem, establishing a conceptual and quantitative foundation for future exploration of risk-adaptive petroleum infrastructure.

7. Conclusion

This study set out to examine whether petroleum storage resilience can be fundamentally improved by transforming storage topology from a fixed design choice into an adaptive operational variable. Through a site-specific, probabilistic, and multi-hazard framework applied to a dual-mode aboveground-underground tank system, the results demonstrate that flexibility—implemented through an intelligently engineered connection interface—constitutes the structural core of resilient petroleum storage under non-stationary

environmental conditions. The findings confirm that vulnerability in petroleum storage is conditional, not intrinsic. Aboveground tanks are predominantly governed by uplift-driven buckling and fire escalation risks under elevated seismic and surface hazard conditions. Buried tanks suppress uplift mechanisms but become vulnerable to buoyancy, liquefaction-induced distortion, and corrosion-driven hidden leakage under unfavorable hydrogeological states. Neither configuration alone achieves global optimality across the full hazard space.

By contrast, the dual-mode configuration, enabled by an intelligent and structurally reinforced connection interface, systematically redistributes exposure toward the lower-risk topology for a given hazard realization. Quantitatively, adaptive switching reduced mean expected total loss by approximately 27–31% relative to static single-configuration policies, with maximum reductions exceeding 50% in balanced hazard scenarios. In addition, peak loss gradients across the hazard domain were reduced by approximately 45%, and performance variance was reduced by 18%, indicating not only lower expected loss but greater stability and predictability of outcomes. The evaluation of hypotheses further consolidates this conclusion.

Hypothesis 1 was confirmed: burial effectively suppresses uplift-driven buckling in the aboveground configuration but introduces soil-dependent deformation mechanisms. Hypothesis 2 was confirmed: buried storage loses its advantage under shallow groundwater and high liquefaction susceptibility, demonstrating that subsurface protection is conditional. Hypothesis 3 was confirmed: risk-adaptive topology switching consistently outperforms static policies in integrated loss metrics. Hypothesis 4 was confirmed: transfer duration beyond a critical threshold diminishes adaptive benefit, reinforcing that operational responsiveness is essential for resilience.

These conclusions collectively establish that dual-mode storage is not a redundancy luxury but a rational response to multi-hazard uncertainty. The environment in which petroleum tanks operate is inherently dynamic—groundwater levels fluctuate, corrosion progresses, seismic demand varies, and surface threats evolve. A system designed for static optimality is structurally misaligned with such variability. Flexibility is therefore not optional; it is a necessity. The intelligent AST–UST connection interface emerges as the decisive enabling mechanism. Its structural detailing ensures that local stress amplification remains within acceptable bounds, while its hydraulic capacity and automated control logic enable rapid and reliable relocation of stored petroleum. This interface transforms the system from a pair of tanks into an adaptive resilience engine. Without it, dual tanks remain passive redundancy; with it, they become an actively controlled risk redistribution mechanism.

Environmental implications further strengthen the case for dual-mode systems. Adaptive relocation reduced groundwater contamination indices by roughly one-third under high corrosion and shallow groundwater states, while reducing surface spill and fire escalation risk by over 70% under severe surface hazard conditions. These reductions are not marginal improvements; they represent meaningful mitigation of long-duration ecological and socio-economic consequences. Importantly, the results do not rely

on exaggerated assumptions or idealized hazard suppression. Adaptive benefit remains bounded by operational constraints, particularly transfer time. The identification of a critical transfer-time threshold underscores that intelligent connection design and actuation speed are not peripheral details but central design targets. In practical terms, achieving and maintaining transfer durations within the identified effectiveness range should be treated as a core engineering requirement. In light of these findings, the dual-mode storage concept—comprising two geometrically equivalent tanks connected by a structurally reinforced, automated, intelligent interface—should be regarded not as an experimental variation but as a resilient baseline for high-risk petroleum storage zones characterized by multi-hazard exposure.

The broader implication of this research is that petroleum storage design must evolve from topology selection toward topology management. Traditional design approaches implicitly assume that selecting either an aboveground or underground configuration and strengthening it sufficiently will ensure acceptable safety. This assumption is no longer adequate in environments where hazard dominance is non-stationary and multi-dimensional. The dual-mode strategy demonstrates that resilience can be engineered through adaptability. By enabling controlled migration of stored inventory between two complementary configurations, the system reduces peak vulnerability concentrations and mitigates cascading failure pathways. Rather than attempting to make one configuration invulnerable to all threats—a technically and economically unrealistic objective—the system leverages the strengths of each configuration while compensating for its weaknesses through operational flexibility.

The intelligent connection interface is central to this paradigm shift. It must therefore be treated as an essential structural and operational component. Its design should integrate:

1. Structural reinforcement to limit nozzle stress concentration and preserve shell integrity.
2. Hydraulic optimization to ensure rapid transfer within the identified critical time threshold.
3. Isolation mechanisms to prevent propagation of fire, overpressure, or leakage between tanks.
4. Integrated sensing and control systems capable of risk-responsive decision-making under uncertainty.

In the absence of such an interface, dual tanks do not inherently produce resilience; they merely duplicate infrastructure. With an intelligent interface, however, the system gains the capacity to actively respond to evolving threats. This research also underscores that resilience is fundamentally about flexibility in the face of unequal and changing conditions. Environmental, geotechnical, and socio-technical hazards are rarely synchronized. The hazard that governs risk today may not be the same tomorrow. A storage system capable of adapting to this variability embodies the core principle of resilience: maintaining function and minimizing loss despite uncertainty and change.

For regions similar to the studied site—characterized by seismic exposure, groundwater variability, aging infrastructure, and potential surface threats—the evidence indicates that dual-mode petroleum storage should be seriously considered as a strategic resilience architecture. While further multi-site validation and detailed implementation studies are warranted, the quantitative reductions in expected loss, environmental consequence, and escalation probability provide a compelling justification for advancing this concept. Future research should extend this framework to ensemble site analyses, incorporate higher-fidelity transient fluid–structure interaction modeling, and explore advanced decision policies incorporating hazard forecasting.

Nonetheless, the present findings establish a foundational result: adaptive topology switching, enabled by a robust and intelligent connection between aboveground and underground tanks, offers a measurable and defensible enhancement in petroleum storage resilience. In conclusion, the study demonstrates that dual-part petroleum storage systems with intelligent interconnection are not merely an architectural alternative but a resilience-driven necessity in multi-hazard environments. Flexibility is the structural core of safety when conditions are unequal, uncertain, and evolving. Designing for adaptability—rather than for static optimality—defines the next logical step in resilient petroleum infrastructure engineering.

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