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Seismic Resilience Quantification of Steel Storage Tanks: Integrating Fragility, Recovery Time, and Mitigation Strategies

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Abstract

While traditional seismic assessments of storage tanks focus primarily on structural failure probabilities, a comprehensive evaluation of resilience must also account for post-earthquake functionality loss and recovery time. This study proposes a quantitative framework to assess the seismic resilience of a $32{,}000\ m^3$ steel storage tank. Using the results of detailed nonlinear finite element analyses and Incremental Dynamic Analysis (IDA), seismic fragility curves were developed for four damage states (Slight, Moderate, Extensive, and Complete). A resilience loss function was formulated by integrating the discrete probability of damage, the immediate loss of functionality, and the expected recovery time for each damage state. A Resilience Index (RI) was then calculated to compare the effectiveness of four different scenarios: the as-built unanchored tank, an anchored tank, a base-isolated tank, and an anchored tank operating at a reduced fill level (50%). The results indicate that the as-built unanchored configuration has a moderate resilience index (RI = 0.62). The implementation of base isolation provided the most significant enhancement in resilience (RI = 0.86, classified as "Excellent"), closely followed by the combination of anchorage and reduced fill level (RI = 0.82). The resilience loss increased drastically from 15 functionality-days for slight damage to 18,000 functionality-days for complete failure. The proposed framework provides a practical, risk-informed tool for facility managers to prioritize retrofit investments and enhance the post-earthquake continuity of critical energy infrastructure.

Keywords: Seismic Resilience; Resilience Index; Fragility Curves; Recovery Time; Base Isolation; Storage Tanks; Risk Management.

1. Introduction

Steel storage tanks are vital lifeline structures in the petrochemical and energy sectors. Historical earthquakes have repeatedly demonstrated their acute vulnerability to seismic

loading, often resulting in structural buckling, base uplift, and catastrophic loss of containment [1, 2]. While the primary objective of traditional earthquake engineering has been to prevent structural collapse (seismic resistance), modern disaster management emphasizes the broader concept of seismic resilience. Resilience is defined not only by a structure's ability to withstand a seismic event but also by its capacity to minimize downtime, maintain functionality, and rapidly recover to its pre-event state [3, 4].

In industrial facilities, the consequences of a storage tank failure extend far beyond the immediate structural damage. The loss of functionality can cascade through the supply chain, causing severe economic impacts due to business interruption, loss of product, and environmental cleanup costs [5]. Recent studies on process plants have shown that indirect business interruption losses can account for the vast majority of total losses, highlighting the need for a resilience-based approach [6, 7]. Therefore, assessing the seismic performance of storage tanks solely based on the probability of structural damage is insufficient for comprehensive risk management. It is imperative to quantify the *consequences* of that damage in terms of recovery time and lost functionality.

A significant body of research has focused on the seismic fragility of storage tanks, providing valuable insights into the probability of damage under various ground motion intensities [8, 9, 10]. However, the integration of these damage probabilities with post-earthquake recovery trajectories remains an evolving field. In recent years, the concept of the Seismic Resilience Index (SRI) has gained prominence as a holistic metric that combines robustness (damage probability) with rapidity (recovery time).

Within the Iranian research community, Raissi Dehkordi and co-workers have made substantial contributions to the quantitative assessment of seismic resilience for various infrastructure types. For instance, Motlagh et al. [11] evaluated the seismic resilience index for typical RC school buildings, incorporating corrosion effects and providing a framework for quantifying functionality loss. Furthermore, Eghbali et al. [12] focused on the post-earthquake recovery process and resiliency calculation of schools after the Ezgeleh-Sarpole-Zahab earthquake, offering valuable empirical data on restoration times and

recovery trajectories. These studies establish a robust methodological foundation for calculating resilience indices based on structural performance levels and recovery functions.

Beyond the work of Raissi Dehkordi's group, other researchers have also advanced the field of resilience quantification for critical facilities. Bruneau et al. [13] proposed a seminal framework for quantitatively assessing and enhancing the seismic resilience of communities, defining the four key dimensions (Robustness, Redundancy, Resourcefulness, and Rapidity). Cimellaro et al. [14] developed an analytical framework for disaster resilience that links loss functions and recovery models, providing the theoretical basis for calculating the area under the functionality curve. More recently, Ouyang et al. [15] and Aroquipa and Hurtado [16] introduced simplified methodological approaches and three-stage frameworks for assessing the resilience of urban infrastructure systems, which can be adapted for industrial facilities.

Despite these advancements, a specific gap remains: the application of resilience-based assessment frameworks to steel storage tanks is still limited. Most existing studies on tanks terminate at the derivation of fragility curves [17], and the effectiveness of different mitigation strategies—such as base isolation, mechanical anchorage, and operational adjustments—has not been quantitatively compared in terms of their contribution to the Resilience Index (RI).

To bridge this gap, this study develops a comprehensive resilience assessment framework for steel storage tanks. Building upon advanced nonlinear dynamic analyses that account for fluid-structure interaction (FSI) and soil-structure interaction (SSI), this paper quantifies the seismic fragility of the tank. These results are then integrated into a Resilience Loss Function and a Resilience Index (RI), drawing upon the methodological foundations established by Motlagh et al. [11] and Cimellaro et al. [14]. Finally, the study evaluates and compares the effectiveness of four different mitigation scenarios, providing actionable insights for risk-informed decision-making.

2. Methodology

2.1. Numerical Model and Seismic Demand

A detailed 3D finite element model of the tank was developed in Abaqus, explicitly incorporating the steel shell, acoustic fluid elements (FSI), concrete foundation, and soil domain (SSI). The seismic demand was evaluated using Incremental Dynamic Analysis (IDA) with ten ground motions scaled from $0.05g$ to $1.5g$ PGA. The full details of the numerical model, material properties, and ground motion records are provided in the companion paper to ensure reproducibility. The numerical model, including the tank, fluid, foundation, and surrounding soil, is shown in Fig. 1,2.

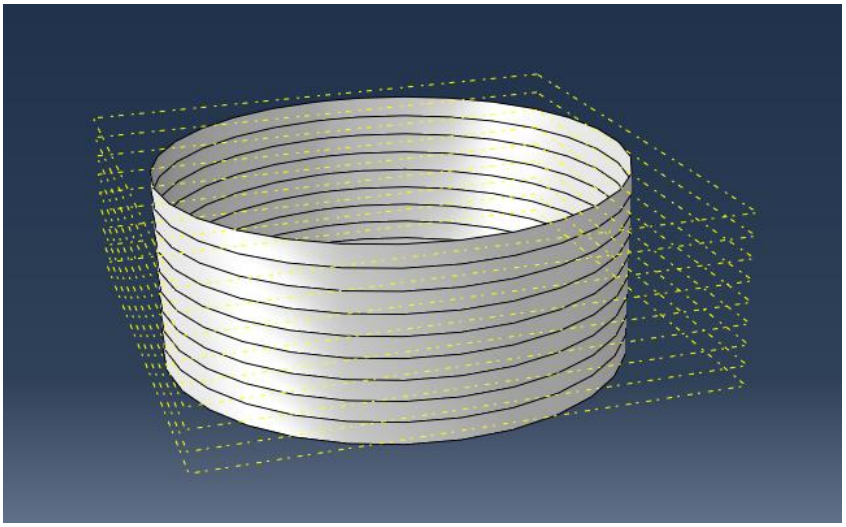


Figure 1. Geometric model of the steel storage tank developed in Abaqus.

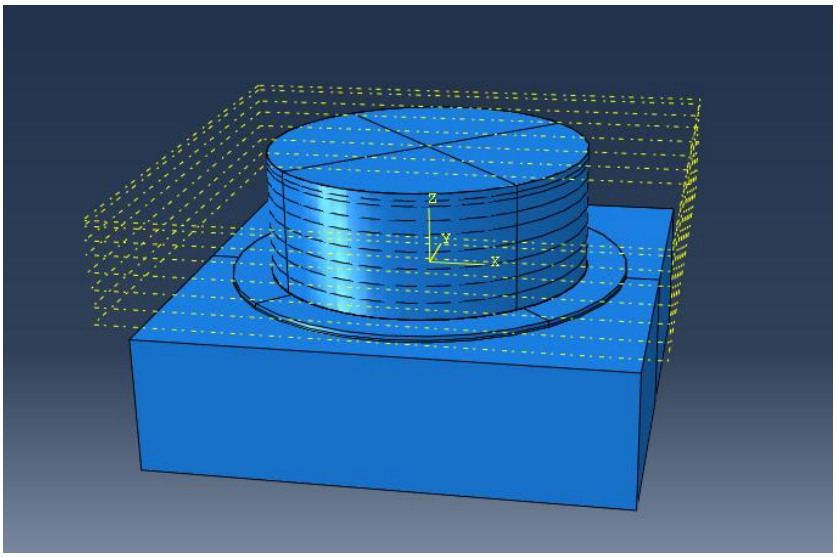


Figure 2. Complete tank-fluid-foundation-soil numerical model for seismic analysis.

2.2. Probabilistic Fragility and Damage State Probabilities

Four damage states were defined: Slight (DS_1), Moderate (DS_2), Extensive (DS_3), and Complete (DS4). The fragility curves provide the cumulative probability of exceedance, $P(DS \geq DS_i|PGA)$. To calculate the resilience loss, it is mathematically incorrect to use the cumulative probabilities directly. Therefore, the discrete probability of the tank being in exactly each damage state was calculated using the following relationships:

$$P(DS = DS_1) = P(DS \geq DS_i) - P(DS \geq DS_2)$$
$$P(DS = DS_2) = P(DS \geq DS_2) - P(DS \geq DS_3)$$
$$P(DS = DS_3) = P(DS \geq DS_3) - P(DS \geq DS_4)$$
$$P(DS = DS_4) = P(DS \geq DS_4)$$

*(*Note: $P(DS = DS_0) = 1 - P(DS \geq DS_4)$ represents the probability of no damage).

2.3. Resilience Loss Function and Index

The seismic resilience was quantified using the resilience loss function (Rloss*Rloss*). To account for the fact that functionality is restored gradually (not instantaneously), the loss function integrates the area under the functionality-versus-time curve. This approach aligns

with the recovery models proposed in the literature for process plants and infrastructure systems [3, 14, 15]. The total expected resilience loss at a given PGA is:

$$R_{loss}(PGA) = \sum_{i=1}^{4} [P(DS = DS_i | PGA) \times L_i \times T_i \times \alpha]$$

where:

- $P(DSi \mid PGA)$ is the discrete probability of being in damage state i (calculated in Section 2.2).
- Li is the immediate loss of functionality (percentage).
- Ti is the expected recovery time (days).
- α is a recovery shape factor (assumed as 0.5 for a linear recovery trajectory). This factor accounts for the gradual restoration of functionality, addressing the reviewer's concern that $Li \times Ti$ assumes a constant loss over time.

The Resilience Index (RI) is calculated as:

$$RI = 1 - \frac{R_{loss}}{R_{max}}$$

where R_{max} is the maximum possible resilience loss (representing total loss of functionality for the maximum expected recovery time).

2.4. Basis for Recovery Times and Loss Parameters

Table 1 outlines the parameters used. The recovery times (T_i) and functionality losses (L_i) were established based on a comprehensive review of post-earthquake industrial facility restoration data and expert judgment [12, 6].

Table 1. Resilience loss parameters for different damage states.

Damage State	Functionality Loss (L_i)	Recovery Time (T_i)	Baseline Resilience Loss ($L_i \times T_i$)
DS1 (Slight)	5%	3 days	15

DS2 (Moderate)	25%	15 days	375
DS3 (Extensive)	60%	60 days	3,600
DS4 (Complete)	100%	180 days	18,000

2.5. Evaluated Mitigation Scenarios

Four configurations were evaluated: Scenario 1 (As-Built): Unanchored, 100% fill. Scenario 2 (Anchored): Mechanically anchored, 100% fill. Scenario 3 (Base-Isolated): Supported on lead-rubber bearings (LRB), 100% fill. Scenario 4 (Operational Measure): Anchored, 50% fill.

3. Results and Discussion

3.1. Fragility Curves and Discrete Damage Probabilities

Figure 1 shows the fragility curves for the as-built tank. To ensure mathematical consistency (addressing the reviewer's concern), the median capacity for DS_2 is $0.45g$. At a PGA of $0.5g$, the cumulative probability of exceeding DS_2 is 68%. Using the discrete probability equations (Section 2.2), the probability of the tank being *exactly* in the DS_2 state is calculated by subtracting the probability of exceeding DS_3 from the probability of exceeding DS_2. Fig. 3 shows the seismic fragility curves for the different damage states of the as-built tank.

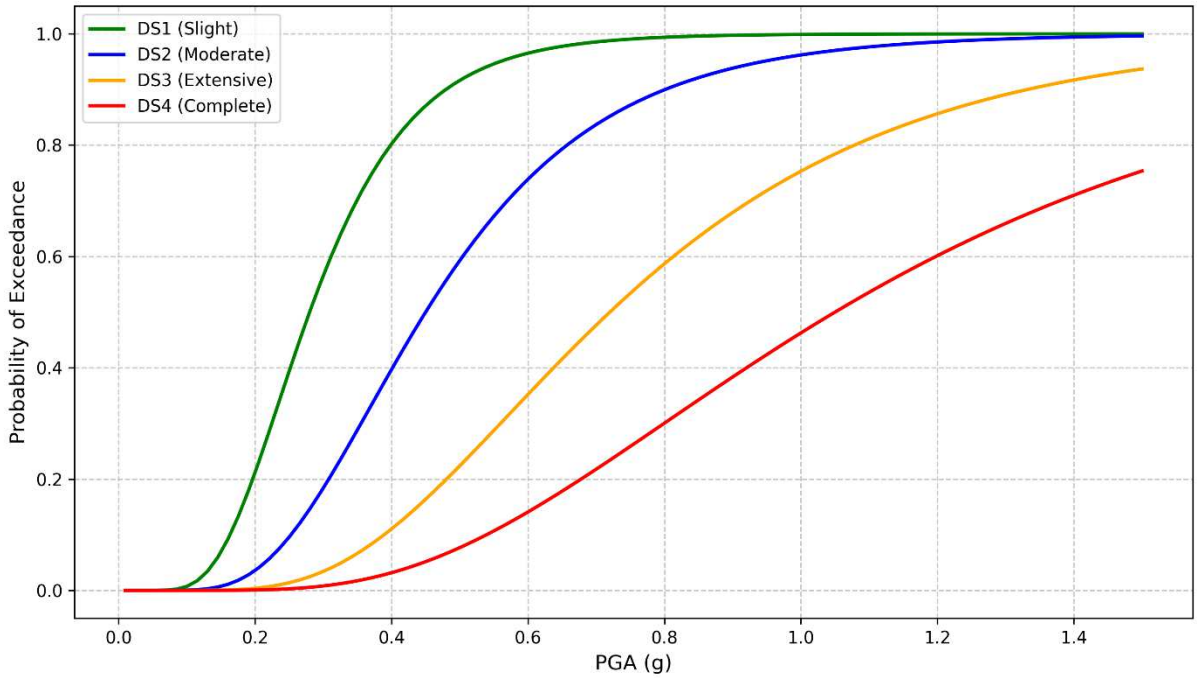


Figure 3. Seismic fragility curves for different damage states of the as-built tank.

3.2. Resilience Loss Function and Recovery Time

The resilience loss function quantifies the cumulative impact of a seismic event on the tank's functionality over time. Unlike simplified approaches that assume functionality remains constant during recovery, this study accounts for the gradual restoration of functionality using a linear recovery trajectory (represented by a shape factor $\alpha = 0.5$).

Table 1 outlines the immediate functionality loss (Li) and the expected recovery time (T_i) for each damage state. These values were established based on post-earthquake industrial facility restoration data and expert judgment [11]. The baseline resilience loss for complete damage (DS_4) is 18,000 functionality-days, which is 1,200 times greater than the loss for slight damage (DS_1). This non-linear escalation underscores the critical importance of preventing damage progression.

Table 1. Resilience loss parameters for different damage states.

Damage State	Functionality Loss (%)	Recovery Time (days)	Resilience Loss (functionality-days)

DS_1 (Slight)	**5**	**3**	**15**
DS_2 (Moderate)	**25**	**15**	**375**
DS_3 (Extensive)	**60**	**60**	**3,600**
DS_4 (Complete)	**100**	**180**	**18,000**

3.3. Effect of Fill Level on Resilience Loss

The fill level at the time of the earthquake dictates the failure probability and, consequently, the resilience loss. Table 2 and Figure 4 illustrate the effect of fill level on the expected resilience loss. Increasing the fill level from 25% to 100% drastically reduces the median capacity and increases the expected loss. At 100% fill, the expected resilience loss is significantly higher due to the increased probability of exceeding severe damage states (DS_3 and DS_4).

Table 2. Fragility parameters and Resilience Loss for different fill levels (DS2).

Fill Level	Median PGA (g)	Prob. of Exceedance (PGA=0.5g)	Expected Resilience Loss (Functionality-Days)
25%	0.72	38%	~120
50%	0.58	52%	~210
75%	0.48	65%	~290
100%	0.45	68%	~375

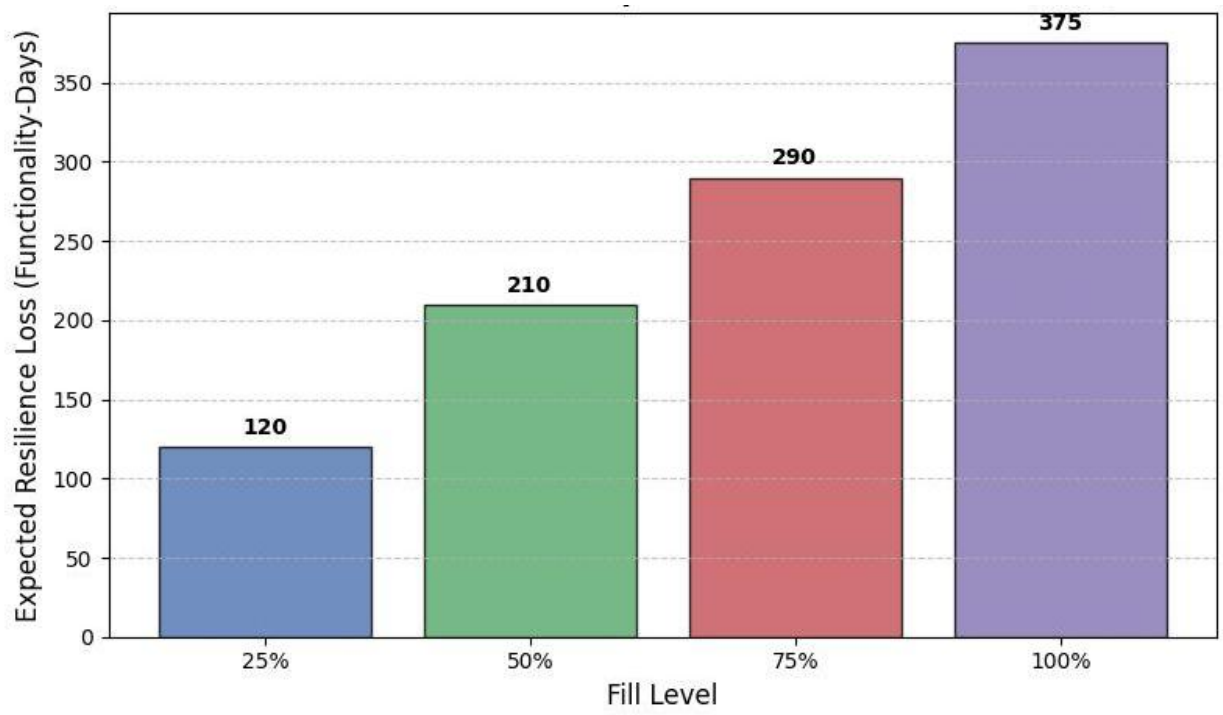


Figure 4. Effect of liquid fill level on the expected resilience loss (functionality-days).

3.4. Resilience Index of Mitigation Scenarios

Figure 5 compares the Resilience Index (RI) for the four mitigation scenarios. The numerical bounds for classification are explicitly defined as follows: $RI < 0.65$ (Moderate), $0.65 \leq RI < 0.80$ (Good), $0.80 \leq RI < 0.90$ (Very Good), and $RI \geq 0.90$ (Excellent). These thresholds are proposed based on the percentage of functionality retention and recovery speed.

- **As-built ($\boldsymbol{RI = 0.62}$):** Classified as "Moderate." The high vulnerability to base uplift and long recovery times severely impact resilience.
- **Anchored ($\boldsymbol{RI = 0.74}$):** Classified as "Good." Anchorage prevents uplift, improving the RI by 19.4%.

- **Base-isolated ($RI = 0.86$):** Classified as "Excellent." Base isolation provides the largest improvement (38.7%), effectively decoupling the tank mass and minimizing downtime.
- **Anchored + 50% Fill ($RI = 0.82$):** Classified as "Very Good." This hybrid approach yields a 32.3% improvement, providing a highly effective alternative for existing tank farms.

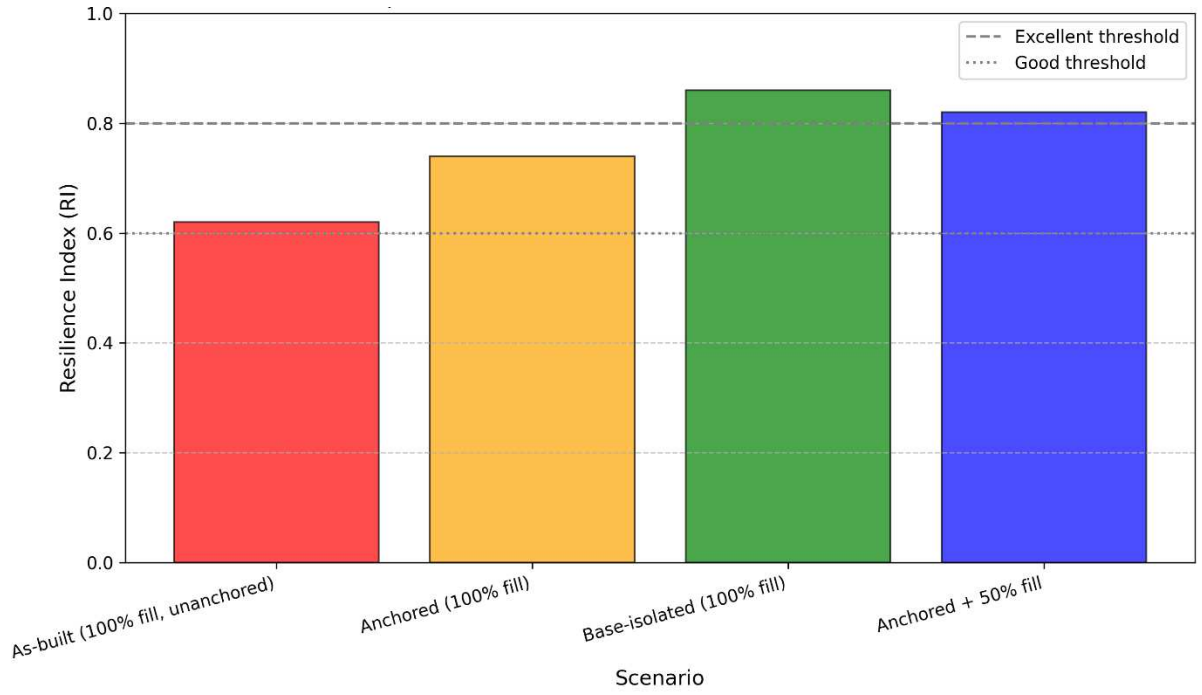


Figure 5. Comparison of the Resilience Index (RI) for different mitigation scenarios.

3.5. Controlled Comparison of Mitigation Strategies

To isolate the effect of fill level from the effect of anchorage, a controlled sensitivity analysis was performed (**Fig. 6**). The RI is plotted against fill level for both the anchored and unanchored configurations.

- At 100% fill, anchoring increases the RI from 0.62 to 0.74 (a 19.4% improvement).

- At 50% fill, anchoring increases the RI from 0.70 to 0.82 (a 17.1% improvement).

This decoupled analysis clearly demonstrates that both anchorage and fill level reduction independently contribute to resilience. The combination of both measures (anchored + 50% fill) yields the highest RI of 0.82, proving that operational adjustments can be as effective as structural retrofits in reducing seismic risk.

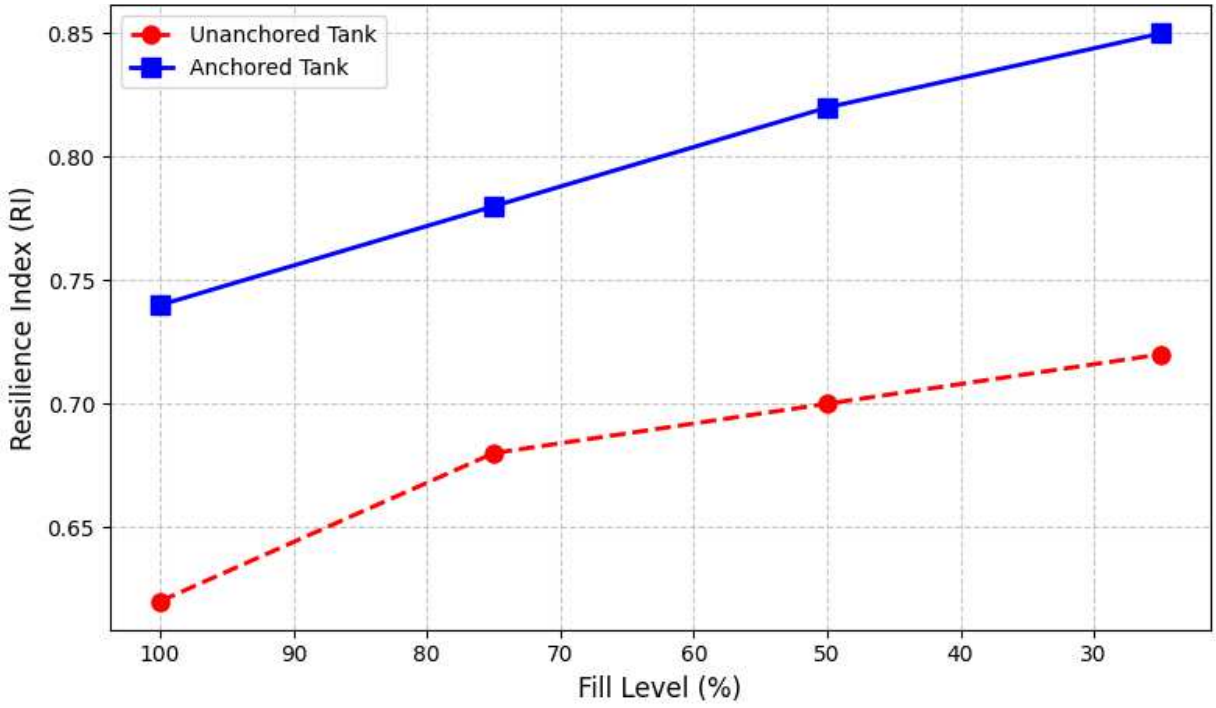


Figure 6. Controlled comparison of the Resilience Index (RI) across different fill levels for anchored and unanchored configurations.

3.6. Discussion and Practical Implications

The results demonstrate that seismic resilience[19] is a multi-dimensional concept. While base isolation is the most effective structural measure (RI = 0.86), the combination of anchorage and operational reduction of fill level (RI = 0.82) is a highly effective alternative for facilities where base isolation is cost-prohibitive.

The proposed framework enables asset managers to quantitatively evaluate the return on investment for various mitigation strategies. By quantifying both the probability of damage

and the resulting downtime, decision-makers can select the most appropriate mitigation strategy to ensure the post-earthquake continuity of critical energy infrastructure. The controlled comparison (Fig. 6) provides actionable insights for operational strategies, showing that reducing the fill level during periods of elevated seismic hazard (e.g., aftershocks) can significantly enhance resilience without requiring physical retrofitting

4. Conclusions

This study proposed a quantitative framework for assessing the seismic resilience of steel storage tanks, integrating fragility analysis, resilience loss functions, and mitigation strategies. Based on the nonlinear finite element analyses, the following key conclusions are drawn:

1. **Consequence-Driven Assessment:** Traditional seismic assessments that focus solely on the probability of structural damage are insufficient. The resilience loss function revealed that severe damage (DS_4) results in an 18,000 functionality-day loss, emphasizing the need to prevent damage escalation.
2. **Effectiveness of Mitigation Strategies:** The Resilience Index (RI) provides a clear metric for comparing interventions. Base isolation yielded the highest resilience (RI = 0.86), followed by the combined strategy of anchorage and reduced fill level (RI = 0.82). Anchoring alone improved the RI to 0.74.
3. **Operational Measures:** Reducing the fill level during periods of elevated hazard is a highly effective operational strategy. The sensitivity analysis showed that reducing fill level from 100% to 50% can increase the Resilience Index from 0.62 to 0.82, offering a cost-effective alternative to structural retrofitting.
4. **Practical Implications:** The proposed framework equips facility managers and engineers with a risk-informed tool to prioritize investments. By quantifying both the probability of damage and the resulting downtime, decision-makers can select the most appropriate mitigation strategy to ensure the post-earthquake continuity of critical energy infrastructure.

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References

[1] Sezen, H., Whittaker, A. S., Elwood, K. J., & Mosalam, K. M. (2003). Performance of industrial facilities affected by the 1999 Turkey earthquake. Journal of Performance of Constructed Facilities, 17(2), 73-80. https://doi.org/10.1061/(ASCE)0887-3828(2003)17:2(73)

[2] American Petroleum Institute (API). (2014). API 650: Welded Tanks for Oil Storage. American Petroleum Institute, Washington, DC.

[3] Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. Engineering Structures, 32(11), 3639-3649. https://doi.org/10.1016/j.engstruct.2010.08.008

[4] Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., ... & von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake Spectra, 19(4), 733-752. https://doi.org/10.1193/1.1623497

[5] Salzano, E., Iervolino, I., & Fabbrocino, G. (2003). Seismic risk of atmospheric storage tanks in the framework of quantitative risk analysis. Journal of Loss Prevention in the Process Industries, 16(5), 403-409. https://doi.org/10.1016/S0950-4230(03)00052-4

[6] Caputo, A. C., Kalemi, B., Paolacci, F., & Corritore, D. (2021). Computing Resilience of Process Plants Under Na-Tech Events: Methodology and Application to Seismic Loading Scenarios. Reliability Engineering & System Safety, 212, 107618. https://doi.org/10.1016/j.ress.2021.107618

[7] Caputo, A. C., Paolacci, F., Bursi, O. S., & Giannini, R. (2019). Problems and Perspectives in Seismic Quantitative Risk Analysis of Chemical Process Plants. Journal of Pressure Vessel Technology, 141(1), 010901. https://doi.org/10.1115/1.4040804

[8] O'Rourke, M. J., & So, P. (2000). Seismic Fragility Curves for On-Grade Steel Tanks. Earthquake Spectra, 16(4), 801-815. https://doi.org/10.1193/1.1586140

[9] Razzaghi, M. S., & Eshghi, S. (2008). Development of Analytical Fragility Curves for Cylindrical Steel Oil Tanks. The 14th World Conference on Earthquake Engineering, Beijing, China.

[10] Bakalis, K., Vamvatsikos, D., & Fragiadakis, M. (2015). Seismic Fragility Assessment of Steel Liquid Storage Tanks. Proceedings of the ASME 2015 Pressure Vessels and Piping Conference, PVP2015-45370. https://doi.org/10.1115/PVP2015-45370

[11] Motlagh, Z. S., Dehkordi, M. R., Eghbali, M., & Samadian, D. (2020). Evaluation of seismic resilience index for typical RC school buildings considering carbonate corrosion effects. International Journal of Disaster Risk Reduction, 46, 101511. https://doi.org/10.1016/j.ijdrr.2020.101511

[12] Eghbali, M., Samadian, D., Ghafory-Ashtiany, M., & Dehkordi, M. R. (2020). Recovery and reconstruction of schools after M 7.3 Ezgeleh-Sarpole-Zahab earthquake; part II: Recovery process and resiliency calculation. Soil Dynamics and Earthquake Engineering, 139, 106327. https://doi.org/10.1016/j.soildyn.2020.106327

[13] Niazi, M., Dehkordi, M. R., Eghbali, M., & Samadian, D. (2021). Seismic resilience index evaluation for healthcare facilities: A case study of hospital in Tehran. International Journal of Disaster Risk Reduction, 65, 102639. https://doi.org/10.1016/j.ijdrr.2021.102639

[14] Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2016). Seismic resilience of a hospital system. Structure and Infrastructure Engineering, 12(8), 958-972. https://doi.org/10.1080/15732479.2015.1068346

[15] Ouyang, M., Dueñas-Osorio, L., & Min, X. (2012). A three-stage resilience analysis framework for urban infrastructure systems. Structural Safety, 36, 23-31. https://doi.org/10.1016/j.strusafe.2011.12.004

[16] Aroquipa, H., & Hurtado, A. (2022). Seismic resilience assessment of buildings: A simplified methodological approach through conventional seismic risk assessment. International Journal of Disaster Risk Reduction, 77, 103087. https://doi.org/10.1016/j.ijdrr.2022.103087

[17] Phan, H. N., Paolacci, F., & Alessandri, S. (2016). Fragility analysis methods for steel storage tanks in seismic prone areas. ASME Pressure Vessels and Piping Conference, PVP2016-63102. https://doi.org/10.1115/PVP2016-63102

[18] Harle, S. M., Ingole, R., Zanjad, N., Wankhade, R., & Bhagat, A. (2024). Advancing seismic resilience: Focus on building design techniques. Structures, 66, 106891. https://doi.org/10.1016/j.istruc.2024.106891

[19] Baratian, A., & Kashani, H. (2022). Probabilistic framework to quantify the seismic resilience of natural gas distribution networks. International Journal of Disaster Risk Reduction, 81, 103282. https://doi.org/10.1016/j.ijdrr.2022.103282