Implementing Seismic Protection Measures for Liquid Storage Tanks

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Liquid storage tanks in industrial facilities such as manufacturing plants, refineries, petroleum depots, and airports housing oil, gas, and chemicals can be vulnerable to a seismic event. A catastrophic failure of a tank during an earthquake could lead to serious, life-threatening consequences including leaks, spills, fires, and the release of hazardous chemicals into the atmosphere.

The notorious Ring of Fire covering the entire west coast of the United States, including Alaska and Hawaii, has always been a hotbed of ongoing seismic events, having experienced earthquakes of 6.7 to 9.0 magnitudes.

Hawaii, for example, experience thousands of earthquakes per year while Alaska has an average of 1,000 earthquakes per month, magnitude 7-8 quakes every year, and magnitude 8 or larger every 13 years.[1] In the meantime, residents in the Pacific Northwest constantly live on edge knowing that the region is overdue for a 9.0+ magnitude quake.

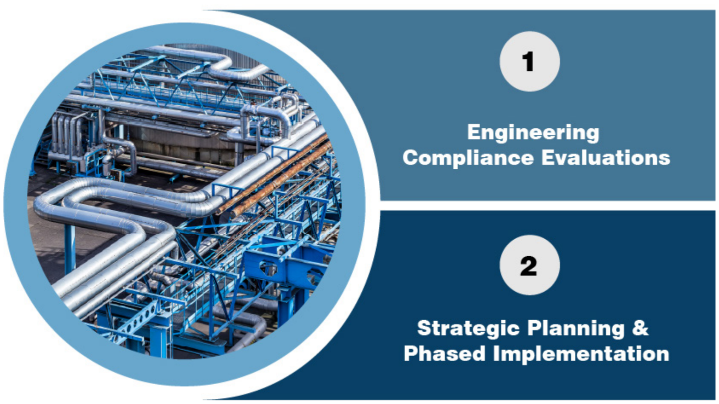
However, the Ring of Fire is not the only epicenter of quake activity. Large-scale tremors have rattled across multiple regions, including the well-documented Madrid fault line in the Midwest and other hazardous seismic zones across the U.S. and Eastern Seaboard.

Recent seismic events have prompted regulators to question whether liquid storage tanks at industrial sites will be able to withstand major ground force accelerations, especially seismic fragile tanks built over 75 years ago that are still operational today.

For this reason, Washington state is taking the lead in enacting new seismic resilience regulations that all state industrial owners/operators must comply with by June 2033. The new regulations underscore the need for proactive risk management which entails a multi-disciplinary structured and phased approach to completing all evaluations and seismic upgrades while minimizing operational disruptions.

Meeting the Deadline for New Seismic Government Regulations

The Washington State Department of Ecology (DoE) amended their administrative codes in 2023 to mandate seismic protection measures for all oil storage tanks and transfer pipelines. These changes align with broader regulatory frameworks and 2021 International Building Code (IBC) to increase seismic resilience in Class 1 storage facilities.



Under the new regulatory amendments, facilities must implement one or more of the following measures for storage tanks and separately for transfer pipelines:

Storage Tanks

- Piping flexibility analysis to prevent overstress during seismic activity.
- Installation of driven piles to stabilize tank foundations
- Anchoring tanks to resist overturning forces.
- Implementation of additional seismic protection measures based on site-specific risk assessments.

Transfer Pipelines

- Flexible mechanical connections between tanks and pipelines.
- Proper pipeline supports to prevent failure under seismic loads.
- Automatic emergency isolation mechanisms
- Additional site-specific seismic protection measures

4 Critical Seismic Vulnerability Areas of Concern

To properly address the vulnerabilities of tanks to potential major seismic events and to achieve compliance, engineers and designers must consider four critical areas of concern: (1) soil composition; (2) foundational stability; (3) tank design and performance; and (4) piping and nozzles.

Soil Composition

Tanks may be built on soft soil that could be amplify seismic waves and increase the intensity of shaking, possibly leading to liquefaction. To enhance soil stability, it is important to examine the composition of the soil (e.g., gravel, sand, clay, silt, or fill) or a mixture of different types of soils and determine if the soil would be compromised during a seismic activity.

Another area that critically impacts tank stability is ground water under the tank site. If there is evidence of ground water, engineering analyses should determine how deep the water goes and if any ground improvements were done prior to tank construction. If so, the plan going forward might include ground improvement techniques, such as deep soil mixing or driven piles, to enhance stability.

Foundational Stability

Reinforcing tank supports includes looking for evidence of settlement around the tank footing and surrounding pipe supports as well as foundational damage or noticeable degradation from a variety of factors including age, service, weather, soil washout or environmental events. It is also critical that engineers determine that design load for self-anchored tanks be stable enough to not tip over during a seismic event.

Tank Design and Performance

To verify the structural integrity of a tank, engineers must first conduct a field walk to see if there are any signs of settlement, corrosion, or structural degradations. The results of these observations can be used to refine the input data for the seismic analysis and to corroborate the findings with engineering tools. Data must also be gathered documenting the historical performance of the tank which can shed light on areas of vulnerability.

A comprehensive seismic evaluation, conducted in accordance with government and industry standards, includes the following test results, analyses, and information:

- Simulation results of a tank's performance during a seismic event. This requires capturing displacement estimates that predict the tank's movement during an earthquake to ensure that the movement will not lead to structural failure.

- Piping stress analysis and tank nozzle evaluations to identify potential areas of critical failure.

- Original fabrication drawings, material properties, and seismic parameters.

- Types of structural attachments (e.g., stairways and ladders, top platforms, wind girders, roof framing).

- Whether the seismic shell stress, shell core thickness, weight, liquid design level, base shear, and hoop stress are all within allowable limits or current government and industry seismic design requirements for its specified fill height.

Calculating Tank Seismic Loads

Tank Seismic loads can be calculated based on the following inputs:

Site-Specific Seismic Data: Seismic parameters such as spectral acceleration (SDS) and site coefficients (Fa and Fv) can be derived from the site classification (Site Class D) and seismic hazard data specific to the facility's location.

Tank Geometry and Liquid Properties: Input the tank's geometry, including its diameter, height, and liquid fill level, into the TANK software to determine the seismic forces. The properties of the stored liquid, including density and depth, can also be considered in the analysis.

Foundation and Soil Interaction: Use the interaction between the tank's foundation (ring wall footing) and the supporting soil to account for stability during an earthquake. Evaluate the foundation's ability to resist seismic forces through friction (comparing the applied design base shear vs shear resistance force).

Piping and Nozzles

Another common storage tank failure that occurs during an earthquake are the piping connections to the tank. As a tank shifts and shakes during an event, the connections may fail and rupture, resulting in a

Engineering Tools Used to Conduct Seismic Upgrades:

Hexagon's TANK software evaluates seismic performance per API 650 Annex E, calculating base shear, overturning moments, and hoop stresses. The analysis incorporates both impulsive and convective liquid forces and considers tank-foundation interaction.

CAESAR II software assesses piping flexibility and stress levels, including tank nozzle loads from seismic forces. Results are validated against API 650 Annex E.7.3 compliance limits.

FEPipe software performs Finite Element Analysis (FEA) on tank nozzles under seismic loading, integrating CAESAR II stress outputs to ensure compliance with API 650 Annex E.7.3.

rapid loss of liquid inside of the tank. Pipe stress models would determine if the stress levels and flexibility analysis of the piping system connected to the tank could handle a potential earthquake and if there are any deformations in the piping materials.

Nozzles are another critical area of concern. Analyses can confirm that nozzles comply with API 650 Annex E.7.3 in their current configuration and Finite Element Analysis (FEA) models can verify that the nozzles follow the rules of ASME BPVC Sec. VIII, Div. 2, Part 5.

Mitigating Risks Associated with Piping and Tank Connections Containing Hazardous Chemicals

Seismic retrofits for piping and tank connections containing hazardous chemicals require a multi-faceted approach to reduce risk, ensure system integrity during a seismic event, and comply with seismic industry standards (i.e., PI 650 Annex E, API 653, and ASCE 7).

Key engineering design considerations include flexibility, bracing, reinforcing connections, and automatic shutoff valves.

Flexible Connections and Expansion Loops: Flexibility is key to withstanding substantial ground movement such as flexible joints, seismic expansion loops, or bellow to absorb movement and prevent tanks from leaking, floating or flexible piping supports to control displacement while maintaining containment integrity, and other seismic protection measures approved by the DoE.

Seismic Bracing and Anchorage: Engineering modifications must include pipeline seismic bracing systems, ensuring they remain within allowable displacement limits and reinforcing nozzle connections and stress-relief mechanisms to prevent excessive loads at vulnerable points.

Automatic Shutoff & Emergency Isolation: To immediately isolate hazardous chemicals during an earthquake, it is critical that piping and tank connections have seismically triggered automatic shutoff valves to immediately isolate hazardous chemicals and secondary containment where possible to minimize spill risk.

All design modifications are assessed and validated by Finite Element Analysis (FEA) and CAESAR II.

Meeting Seismic Requirements

Strategic Planning and Phased Implementation

To ensure compliance within the mandated timeframe, a structured evaluation process is required. This approach balances regulatory alignment, operational feasibility, and cost-effectiveness while maintaining flexibility for facility-specific requirements.

Initial Evaluations

Site Condition Review

- Conduct on-site assessments to document key tank and foundation characteristics.
- Identify potential areas requiring further engineering validation.
- Evaluate facility operations and long-term maintenance schedules to integrate engineering assessments efficiently, optimizing the process and minimizing operational disruptions.

Seismic Risk Screening

- Use industry-standard criteria to assess overall risk exposure.
- Determine priority areas for focused engineering analysis.

Regulatory & Engineering Compliance Review

• Perform a gap assessment between existing conditions and updated regulatory mandates.

• Identify areas where targeted mitigation strategies may be required.

Strategic Implementation Approach

Following initial evaluations, tailored engineering solutions will be developed based on specific facility needs. Key areas of focus include:

Structural & Stability Evaluations

• Apply advanced engineering tools to assess compliance with seismic protection measures.

• Determine whether additional reinforcements or modifications are required.

Seismic Load Considerations for Piping & Connections

• Evaluate piping system flexibility and connection integrity under seismic loads.

• Ensure compliance with applicable industry standards.

Phased Mitigation & Execution Planning

• Develop a structured, phased approach to implementing necessary modifications.

• Minimize operational disruptions while ensuring regulatory compliance.

Summary

A well-engineered design embeds safety to protect critical equipment and infrastructure during a seismic event. However, major earthquakes that have occurred over the last 25 years across the globe have resulted in damaged refinery storage tanks, fires, and the release of hazardous chemicals into the atmosphere. As a result, regulators are moving to replace yesterday's compliance standards with more stringent regulations to further enhance seismic resilience in industrial storage tanks and associated piping and structure.

These new seismic reliance regulations emphasize the need for proactive risk management which includes a multi disciplinary approach to conducting seismic evaluations, considering tank structure, foundation, soil composition, piping systems, and operational constraints.

Tools such as Hexagon's TANK, CAESAR II, and FEPipe are essential for modeling seismic impacts and ensuring compliance with API 650 Annex E. A well structured assessment not only addresses regulatory requirements but also minimizes operational disruptions.

Compliance is about integrating seismic upgrades into existing maintenance schedules to optimize execution and reduce downtime. A phased approach ensures cost effective modifications while maintaining operational integrity. Industrial facility owners/operators should start with initial evaluations to identify vulnerabilities, followed by targeted structural reinforcements and piping system upgrades to mitigate seismic risks efficiently.

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