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SEISMIC EVALUATION OF WATER STORAGE TANKS CONSIDERING SOIL-STRUCTURE-FLUID INTERACTION EFFECTS

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ABSTRACT

This paper presents the framework for a performance-based seismic assessment of coupled soil-structure-fluid systems via integrated 3D finite element (FE) analysis. The proposed strain-based performance approach reduces the conservatism and uncertainty associated with the stress-based approaches while better aligning with the performance requirement of the structure to maintain its functionality. By optimizing the modeling approach based on the important system responses, the integrated FE model offers a comprehensive yet efficient approach to capture the seismic-induced local and global demands of the critical structural components while delivering a reasonable computational efficiency.

The proposed framework is used to evaluate the seismic performance of a safety-class water storage tank subjected to the Performance Category (PC)-3 design basis earthquake ground motions. These flat-bottomed storage tanks are common at Department of Energy (DOE) and Nuclear Regulatory Commission (NRC) regulated nuclear facilities.

For the example tank, the relatively massive water-filled tank is anchored to a concrete ring foundation around its perimeter while its draw-off piping system is light and supported by an independent concrete slab. During a seismic event, their differing dynamic characteristics and foundation configurations result in different soil-structure interaction (SSI) responses, leading to complex seismic-induced demands at the connection that cannot be captured using decoupled SSI analysis. The local interaction of the connection and its contained water contributes to the stress concentration and plastic deformation in the connection, underlying the need for a coupled fluid-structure interaction (FSI) analysis. Moreover, the tank support configuration influences the potential uplift and rocking response due to the concurrent interactions of the soil, foundation, and water, highlighting the importance of the coupled SSI-FSI analysis.

Therefore, a 3D integrated soil-structure-fluid interaction model of the tank and its piping system is developed for the seismic performance evaluation. The integrated FE model includes the soil domain as well as a high-resolution representation of the tank-piping connection, its contained fluid, and the anchor bolts to capture their local failure due to the coupled soil-fluid-structure effects. The performance of the tank-piping connection and the anchor bolts is evaluated by comparing the governing demands from the FE analysis to the corresponding capacities defined using the strain-based performance criteria.

The proposed framework can be used to evaluate the seismic performance of similar complex structures where the coupled response of the soil, fluid and structure cannot be captured by decoupled analyses. The proposed integrated FE modeling approach combined with the strain-based acceptance criteria provide the necessary tools for realistic seismic evaluation of such complex structures.

SEISMIC EVALUATION METHODOLOGY

The proposed seismic evaluation methodology consists of four steps: First, identify the structural components whose failure results in loss of system functionality. Code-based strength criteria and/or simplified FE models, among other methods, can be used to identify the critical components and governing local and global failure modes of the system. Second, define the acceptance criteria for each critical component, using a displacement/strain-based approach where applicable. Third, develop a FE model of the system with sufficient resolution to capture the responses driving the identified local and global failure modes of the system. Integrated FE models might be needed to eliminate the conservatism often associated with the decoupled analyses and more accurately capture the driving responses that are inherently coupled. Finally, the demands from the FE model are compared against the capacities to evaluate the performance of the system. This proposed framework is used to evaluate the seismic performance of a water tank and its piping system.

Previous decoupled studies identified the tank and draw-off piping connection, as well as the anchor bolts as the critical structural components whose failure may challenge the safety functionality of the tank and draw-off piping. Therefore, the tank evaluation in this study focuses on the seismic-induced demands at the tank and piping connection as well as the potential rupture of the anchor bolts. A strain-based acceptance criteria is developed as part of this evaluation to allow material response beyond yielding while maintaining an adequate margin on the required safety function of the tank (defined as maintaining the tank contents during and after the seismic event). Informed by previous tank evaluations, the performance-based acceptance criteria define the loss of functionality as:

1. Unacceptable cumulative plastic strains in the tank shell and the nozzle (the draw-off piping connected to and immediately adjacent to the tank wall)
2. Unacceptable elongation of the cast-in-place anchor bolts
3. Low-cycle fatigue failure of the cast-in-place anchor bolts

Based upon the previous tank assessment studies, it was recommended to re-evaluate the performance of the tank and piping system using a detailed FE analysis. A single integrated 3D FE model of the tank and piping system is developed in LS-DYNA (LSTC, 2015) considering the FSI and SSI effects. The integrated FE model accounts for the seismic-induced response of the water—which contributes to the local deformation of the tank-nozzle connection as well as the global rocking and uplift of the tank—through the explicit modelling of the fluid, tank, and the supporting soil medium. The modelling approach also accounts for the coupled but characteristically different responses of the relatively massive tank and its light piping system supported on independent foundations. The dynamic analysis considers the variability in the supporting soil properties and in the input ground motion through consideration of three sets of soil properties and five sets of input ground motions, resulting in 15 analysis cases.

The demand parameters of interest—which include the tank and nozzle cumulative plastic strain, anchor bolt elongation and anchor bolt low-cycle fatigue damage—are developed from the results of the 15 analysis cases and are compared against the corresponding capacities. A cumulative plastic strain capacity is developed from the strain-based acceptance criteria established in ASME Boiler & Pressure Vessel Code (ASME B&PVC Section III, 2019) and the strain limits defined in WSRC-RP-92-859 (1992). To preclude strain-controlled failures of the anchor connection or the tank-bottom-to-side-wall connection under excessive tank uplift, a conservative anchor bolt elongation limit is set based upon EPRI NP-6041-SL (1991) and the experience data from similar tanks. Low-cycle fatigue of the cast-in-place bolts is evaluated using the Manson-Coffin rule (Manson, 1953 and Coffin, 1954) for low-cycle fatigue and Miner’s rule (Miner, 1945) for cumulative damage to assess the effects of plastic strain cycles with varying amplitude.

FINITE ELEMENT MODEL OF THE TANK AND PIPING SYSTEM

The tank is cylindrical with a flat base and conical roof. The base of the tank is anchored to the concrete ring foundation with cast-in-place bolts at multiple locations. The draw-off piping is connected to the tank above the base of the tank and extends into the adjacent pump house. The isometric view of the 3D soil-structure-fluid model of the tank and the piping system is shown in Figure 1. The FE model uses a wide range of FE mesh sizes from less than an inch at the location of the tank and draw-off piping connection to about 10 ft. at the boundaries of the soil model. The refined mesh at the connection of the tank and draw-off piping is needed to capture the local stress concentrations and plastic deformations resulting from interaction of the local fluid, tank wall and piping system. The following subsections discuss the details of the FE modelling approach.

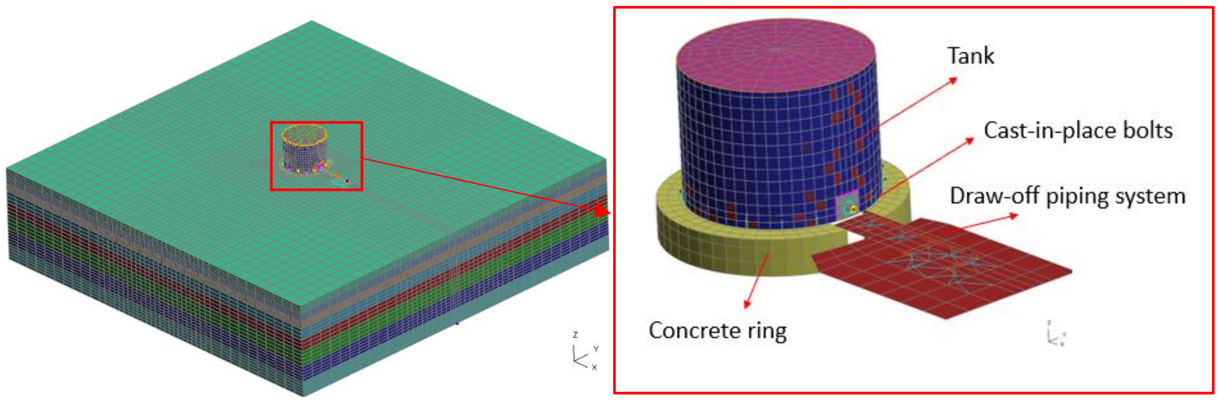

Figure 1. 3D soil-structure-fluid model of the water tank and draw-off piping

Tank and Draw-off Piping Modelling

The tank wall, stiffener plate, and nozzle, as shown in the top panel of Figure 2, are modelled using nonlinear shell elements. An elastic-plastic material model with kinematic hardening is used to capture the post-yield (plastic) strain response of the steel material. The tank shell elements are generally characterized by a mesh size of 1-2 feet except for a refined zone centered around the draw-off piping connection, as shown in the top panel of Figure 2. The refined region of the tank-piping connection model is intended to capture the local stress concentration and plastic deformations of the connection due to relative movements of the tank and the piping system during the seismic loading.

The size of the tank wall mesh in the refined region varies from 0.6 inches at the tank-piping connection to about 2.5 inches at its exterior perimeter, while the stiffener plate and nozzle mesh size is roughly 0.3 inches. These mesh sizes are determined based on a mesh sensitivity study. The responses of the tank fine and coarse meshes are coupled at their common edges using a modelling technique that provides smooth stress fields in the zone centered around the tank-nozzle connection.

Beyond the nozzle, the remaining piping is modelled with linear elastic beam elements, as shown in the top panel of Figure 2.

The nozzle is physically welded to the inner diameter of the stiffener plate and to the tank wall behind the stiffener plate. As shown in the bottom panel of Figure 2, the welds are modelled using solid elements to alleviate the singularity associated with an infinitesimally small, 90-degree connection. Around the exterior edge of the stiffener plate, the weld between the plate and the tank wall is simply modelled using stiff beam elements as the high local stresses and plastic deformations are not expected at that connection. A contact surface is defined between the parallel tank wall and the stiffener plate elements.

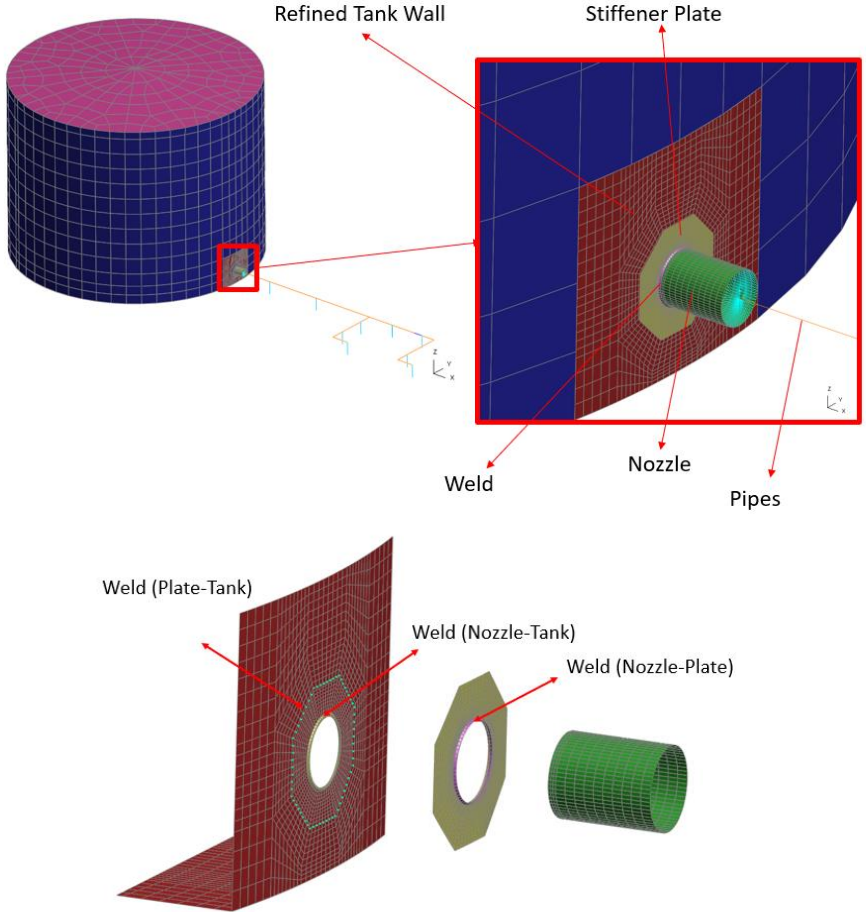

Figure 2. Finite element model of the tank, the nozzle, and the stiffener plate (top) and exploded view of the tank-nozzle connection (bottom)

Anchor Bolts and Foundation Modelling

The tank is anchored to the concrete ring foundation by headed bolts as shown in Figure 3. The ring foundation is modelled using solid elements with a viscoelastic material model. Contact surfaces are defined between the base of the tank and the ring foundation to allow for uplift of the tank. The anchor detail allows for considerable ductility in the anchor bolt given the free length of the bolt. The anchor bolt model is comprised of four components: the anchor chair, tension-only spring, elastic-plastic spring, and the elastic anchor. The anchor chair is modelled as rigid. The anchor bolt yielding, and subsequent softening is modelled using an elastic-perfectly plastic spring. As the anchor chair detailing prevents the tank from loading the anchors in compression, a tension-only spring is included between the elastic-perfectly plastic spring and the anchor chair. The tension-only spring ensures appropriate accumulation of plastic strain in the anchor bolt. The embedded portion of the anchor bolt is modelled using linear elastic beam element.

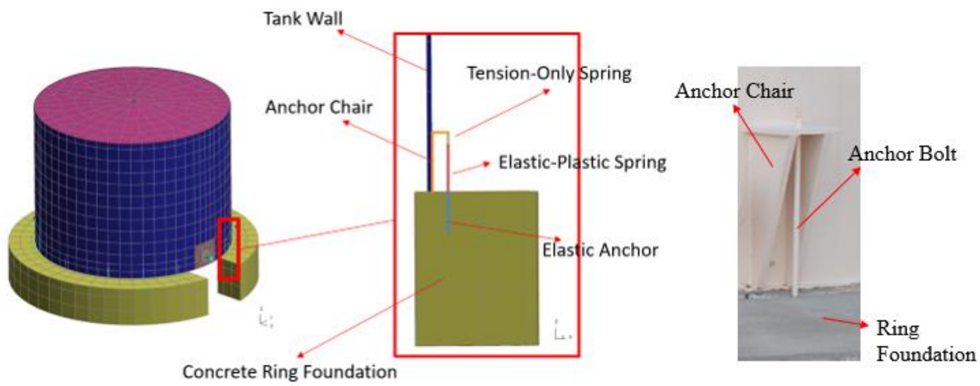

Figure 3. FE model of the foundation and the anchor bolts

The response of a stand-alone anchor model is studied through application of uniaxial vertical tension-compression displacement to the top of the anchor, as shown in the left panel of Figure 4, mimicking the vertical movement of the tank/anchor chair. The force-elongation response of the anchor is shown in the right panel of Figure 4. The anchor response in tension follows the input elastic-plastic force-displacement curve. Beyond the yield point, the anchor does not show any additional resistance and plastic deformations are developed in the anchor. As intended, the presence of the tension-only spring does not allow the anchor to experience any compression force, and therefore the plastic deformation already accumulated in the anchor during the tension load application does not recover due to the application of the compression load.

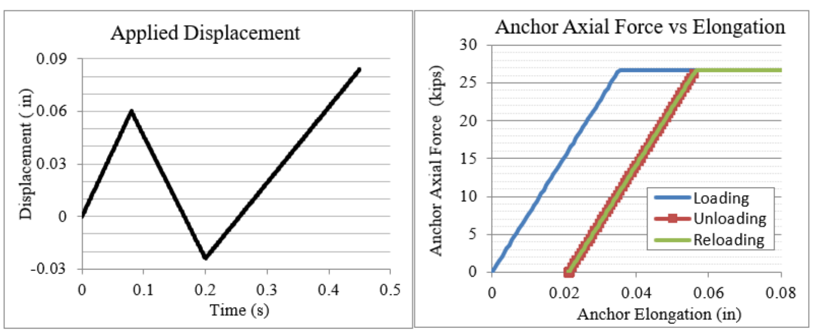

Figure 4. Response of the stand-alone anchor to uniaxial tension-compression load

Fluid Modelling

The fluid modelling approach is selected considering the effects of the local and global responses of the water on the governing failure modes of the tank and tank-nozzle connection. While the proposed approach includes detailed modelling of the FSI effects to capture tank and water coupled behavior, it still maintains the computational efficiency needed to perform multiple dynamic analyses for large integrated SSI models.

Consistent with the design calculation and confirmed by sensitivity analyses, the height of the water inside the tank is equivalent to the tank overflow height, providing a reasonably conservative fluid height for the seismic evaluation. Considering the water height and the tank aspect ratio, contribution of the sloshing response of the water to the global behavior of the tank is expected to be negligible. The global response of the system, namely rocking and uplift of the tank, which contributes to the potential failure of the anchor bolts is primarily governed by the impulsive response of the water. However, the performance of the tank-nozzle connection is affected by the local impulsive pressure of the water that cannot be captured using the conventional discrete fluid modelling techniques such as the one proposed by Housner (1963). Therefore, a continuum modelling approach using Lagrangian fluid elements that is suitable to capture the local and global impulsive responses of the fluid is used to simulate the water contained in the tank. The water behind the tank-nozzle connection and inside the nozzle is modelled using a refined mesh to more accurately capture the water pressure distribution around and inside the connection. The response of the water is coupled with the tank and nozzle shells in the radial direction and the tank base in the vertical direction. The potential separation between the water and the tank is considered through a small tensile capacity for the fluid elements.

The fluid response is studied through comparison of the hydrostatic and hydrodynamic pressures from closed-form solutions and a representative 3D seismic analysis, as shown in Figure 5. The numerical hydrostatic pressure is in good agreement with the predictions from the closed-form solution, as shown on the left panel of Figure 5. The FE model hydrodynamic pressure along the height of the tank is compared to the closed-form solution for impulsive pressure based on the equations provided in Tedesco (1982). It should be noted that the closed-form solution provides the impulsive pressure under unidirectional loading. Consistently, the hydrodynamic pressure from the FE model reported in Figure 5 represents the average pressure local to the tank wall from a time instance when the sloshing is minimal and contribution of the ground motion normal to the direction of interest is negligible. The right panel of Figure 5 demonstrates reasonable agreement between the FE and closed-form hydrodynamic responses of the fluid including the one for the zone close to the bottom of the tank where the tank-nozzle connection is located.

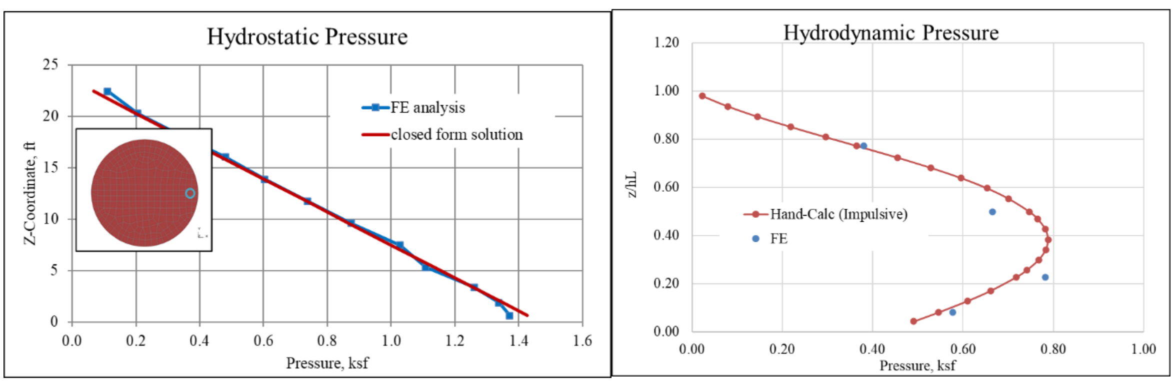

Figure 5. Hydrostatic (left) and hydrodynamic (right) fluid pressure from FE model and closed-form solutions

Soil Modelling and Ground Motion Application

The underlying soil medium is modelled as uniform layers having equivalent-linear strain-compatible properties consistent with the design-level seismic hazard. Figure 6 shows the isometric view of the soil FE model. The depth of the soil model is about 80 feet. The side boundaries of the soil model are roughly 160 feet from the center of the tank in each direction. Solid elements along with a viscoelastic material model are used to simulate the frequency-independent response of the soil to seismic excitation. Three variations of the soil material properties are considered: best estimate (BE) properties, upper bound (UB) properties, and lower bound (LB) properties.

The ground motions are matched to the SDC-3 site-specific design response spectrum at the surface. Site response analysis (SRA) is performed in SHAKE2000 [Ordonez (2012)], without iterations, to deconvolve the surface ground motions and obtain the outcrop motions at the base of the soil domain.

The three components of the outcrop ground motion are applied simultaneously at the base of the site domain. Transmitting boundary conditions are applied at the base of the site domain to prevent the reflection of outgoing seismic waves and efficiently model an "infinite" domain. The seismic waves propagate through the continuum site domain and excite the tank and draw-off piping system through soil-structure interfaces.

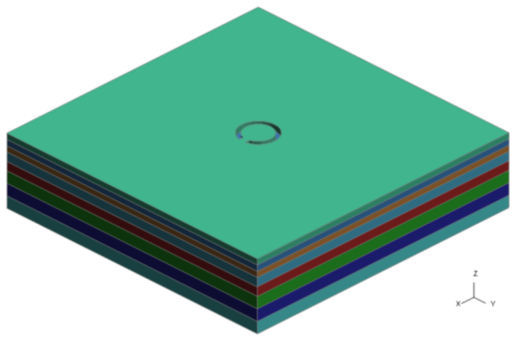

Figure 6. Finite element model of the soil medium

Prior to performing 3D dynamic analysis, a set of SRA is performed to confirm appropriate development and application of the deconvolved ground motion. The outcrop motions generated through the deconvolution process are used as an input to the SRA performed in LS-DYNA and SHAKE2000. As shown in top panel of Figure 7, the horizontal and vertical surface responses from both tools are in good agreement with each other and with the input surface ground motion, confirming that the deconvolution process has generated the desired seismic excitation at the surface. Additionally, the surface response spectrum from the LS-DYNA SRA is compared against the free-field (FF) response of the soil domain in the 3D SSI model, as shown in the bottom panel of Figure 7. The good agreement verifies that the free-field condition has been established away from the structure and the size of the soil domain is adequate.

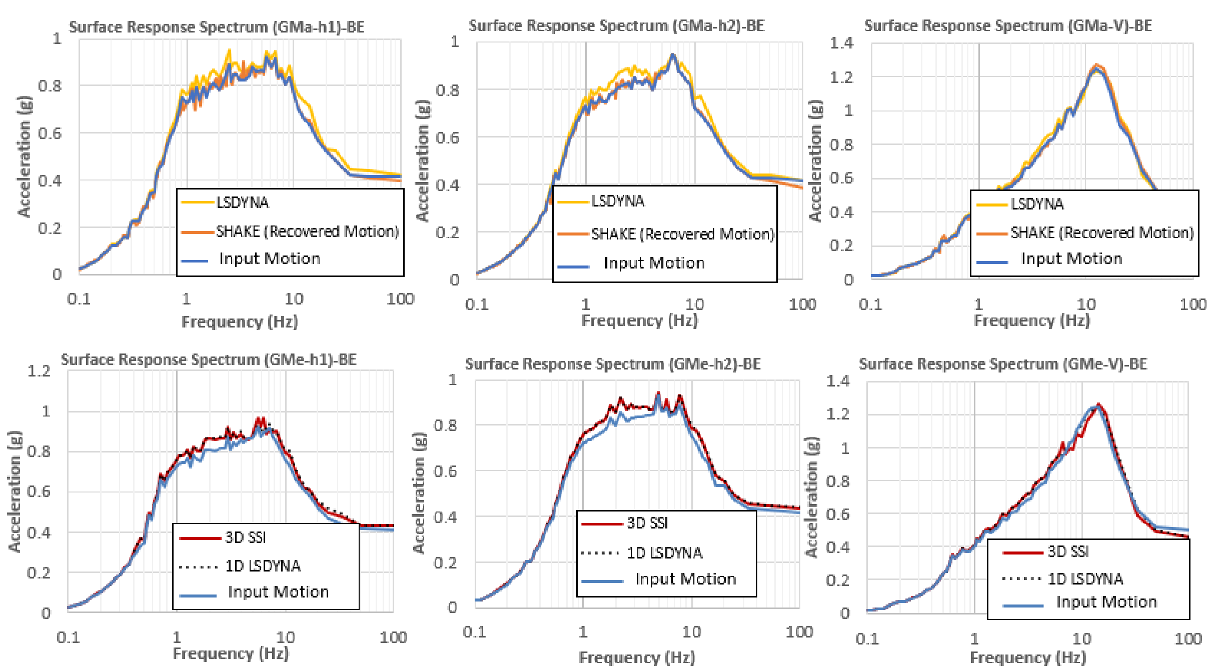

Figure 7. SHAKE2000 vs. LS-DYNA SRA results (top) and LS-DYNA SRA vs. 3D SSI FF response (bottom)

SEISMIC ANALYSIS RESULTS

Dynamic analysis is performed for the developed 3D FE model considering three sets of soil properties (BE, UB and LB) and five sets of input ground motions, resulting in a total of 15 analysis cases. The response of the system, including the performance of the tank-nozzle connection and anchor bolts, is dominated by tank rocking and uplift, with an example of this response presented in Figure 8. The local tank wall deformation primarily caused by the tank uplift and rocking in the X direction (the longitudinal axis of the draw-off piping) induces peak stresses in the tank wall, nozzle, and stiffener plate. The off-axis response is a secondary contributor. The uplift is also directly responsible for anchor elongation.

The performance of the pressure boundary (as measured by the tank-nozzle connection and anchor bolt response) is determined by comparing the governing demands to the corresponding capacities, as discussed in the following subsections. The demands from each of the five input ground motions for a given soil profile are averaged, and the governing demand is calculated as the maximum of the average demands across each of the soil profiles.

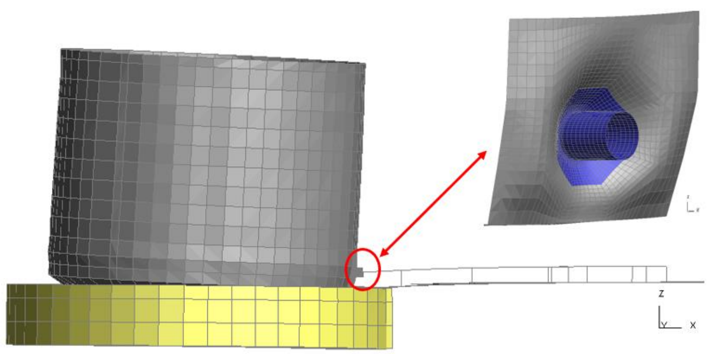

Figure 8. Tank rocking toward draw-off piping, with uplift of the tank opposite of the nozzle location (50x magnification)

Tank Wall and Nozzle Performance

The tank wall and nozzle performance is evaluated based on the level of damage, monitored through cumulative plastic strains, experienced by the nozzle and the local tank shell at the draw-off piping connection. The cumulative plastic strain acceptance criteria—developed based on the ASME Boiler & Pressure Vessel Code (ASME B&PVC Section III, 2019) and WSRC-RP-92-859 (1992)—are designed to prevent through-wall crack formation to assure the ability of the tank to maintain its contents. The cumulative plastic strain acceptance criteria for the nozzle, stiffener plate and the tank wall are given as:

$$\text{Average through-wall thickness: } \left(\varepsilon_{eq}^{p}\right)_{avg} \leq \frac{0.67 \cdot \varepsilon_{uniform}}{Triaxiality\ Factor} \quad (1)$$

$$\text{At the maximum fiber: } \left(\varepsilon_{eq}^{p}\right)_{max} \leq \frac{\varepsilon_{uniform} + 0.25 \cdot \left(\varepsilon_{fracture} - \varepsilon_{uniform}\right)}{Triaxility\ Factor} \quad (2)$$

Where $\varepsilon_{uniform}$ and $\varepsilon_{fracture}$ are the conservative (approximately 98th% exceedance value) of the uniaxial uniform and fracture strain limits of the material, respectively.

Based on the analysis results, the average and maximum through-thickness cumulative plastic strain values for the tank, stiffener plate and the nozzle are less than the limits shown in equations 1 and 2. Thus, the tank-nozzle connection does not challenge the credited safety function of the tank.

Anchor Bolts Performance

Acceptable anchor bolt performance is defined as no low-cycle fatigue failure (or no unacceptable accumulation of fatigue damage) and cumulative elongation less than the allowable limit of 0.6 inches determined based upon recommendations in EPRI NP-6041-SL (1991) and experience data from similar tanks. The anchor low-cycle fatigue is evaluated by calculating the number of cycles to failure for each strain cycle according to the Manson-Coffin rule (Manson, 1953 and Coffin, 1954), as shown in equation 3, and then summing the damage accumulated in each cycle (given as $1/N_{fi}$) according to Miner's rule (Miner, 1945), as shown in equation 4.

$$\left(N_f\right)_i = \frac{1}{2} \cdot \left[\frac{2\varepsilon'_f}{\Delta\varepsilon_p}\right]^{5/3} \tag{3}$$

$$damage = \sum_{i=1}^{n} \frac{1}{\left(N_f\right)_i} < 1 \tag{4}$$

The fatigue ductility coefficient, ε'_f, is approximately equal to the true fracture strain of the material. Typical values of ε'_f for carbon steels range from 0.4 to 0.6 [Anand and Park (2004)].

The tank maximum governing anchor elongation is found to be less than the limit of 0.6 inches. Similarly, the governing low-cycle fatigue damage is smaller than the allowable damage. Therefore, the tank and draw-off piping pressure boundary is not challenged by anchor elongation or low-cycle fatigue failure under design basis earthquake loads.

CONCLUSION

This paper presents a seismic evaluation framework that uses integrated 3D FE analysis for a performance assessment of complex structures. The proposed framework includes (1) identifying the critical components of the system, (2) determining the acceptance criteria for each component's performance, (3) developing the integrated 3D FE model of the system with sufficient resolution to capture the local and global seismic-induced demands of the critical components and finally, (4) evaluating the seismic performance of each critical component by comparing the demands against the corresponding capacities.

The proposed framework was used for the seismic assessment of a cylindrical flat-base tank and its draw-off piping system. Through preliminary FE analysis, the tank and draw-off piping connection, as well as the anchor bolts had been identified as the critical structural components whose failure may challenge the safety functionality of the tank and draw-off piping.

A strain-based seismic acceptance criteria was proposed for the tank and draw-off piping connection and for the anchor bolts. The proposed criteria eliminate conservatism associated with the conventional stress-based evaluation approaches by allowing material response beyond yielding while maintaining an adequate margin on the required safety function of the tank. The performance acceptance criteria for the connection were defined as unacceptable damage characterized by the cumulative plastic strains in the tank and nozzle. For the anchor bolts, excessive elongation and low-cycle fatigue failure established the performance acceptance criteria.

Different dynamic characteristics of the relatively massive water-filled tank and the light piping system supported by an independent foundation result in complex SSI responses that cannot be captured by decoupled SSI analysis. The local interaction of the tank-piping connection and its contained water may contribute to the failure of the connection highlighting the importance of the detailed FSI analysis.

Therefore, an integrated 3D FE model of the tank and draw-off piping system considering the SSI and FSI effects was developed for the seismic analysis. The seismic analysis accounts for the system components contributing to the local response of the tank-nozzle connection as well as the global response of the tank through development of an integrated FE model of the water, tank, piping system and the supporting soil medium. The analysis focused on the realistic characterization of the tank-nozzle connection and the anchor bolts, and the behaviors governing their response. The seismic analysis considered variability in the supporting soil and in the input ground motion through consideration of three sets of soil properties and five sets of input ground motions, resulting in 15 analysis cases.

Based on the dynamic analysis results, the response of the system including the performance of the pressure boundary (tank-nozzle connection response) is dominated by the tank rocking and uplift. The level of localized damage in the tank-nozzle connection and in the anchor bolts was found to be acceptable. Therefore, the existing tank and draw-off piping system can be credited to maintain functionality when subject to seismic-induced demands due to the design basis earthquake.

The proposed framework can be used to evaluate the seismic performance of similar complex structures where the coupled response of the soil, fluid and structure cannot be captured by decoupled analyses. The proposed integrated FE modeling approach combined with the strain-based acceptance criteria provides the necessary tools for the realistic seismic evaluation of such complex structures.

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