Navigating 49 CFR 193 for the SSI analysis of an isolated LNG tank: Challenges and Opportunities

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Project Overview

- Jordan Cove LNG, Oregon
- 7.5 MMTPA export terminal
- Arup contracted to KBJ JV
- 2 x 160,000m3 9% Ni Full containment tanks
- Prepared design for FERC submission
  - Compared isolated and non-isolated tank
  - Final documentation for isolated tank
  - Advanced non-linear DSSI

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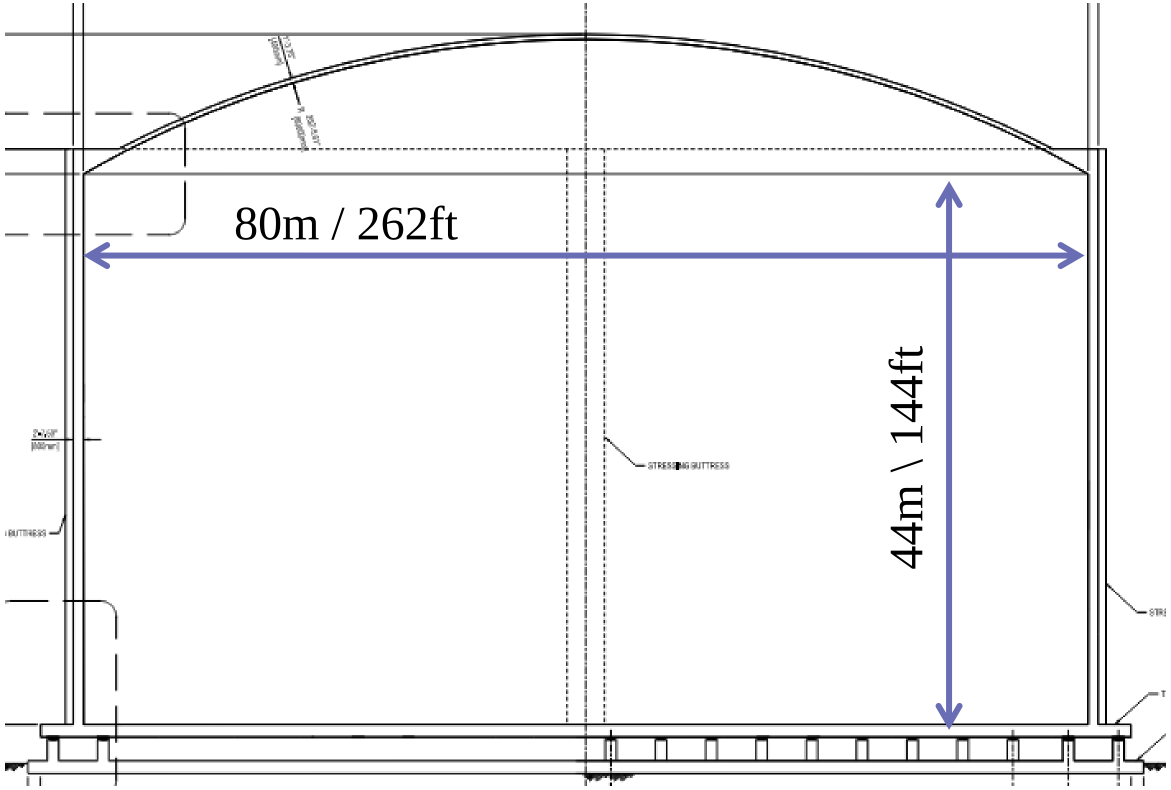
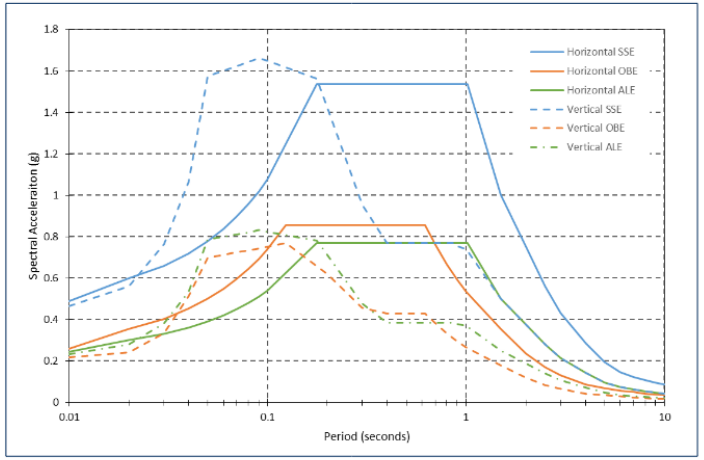
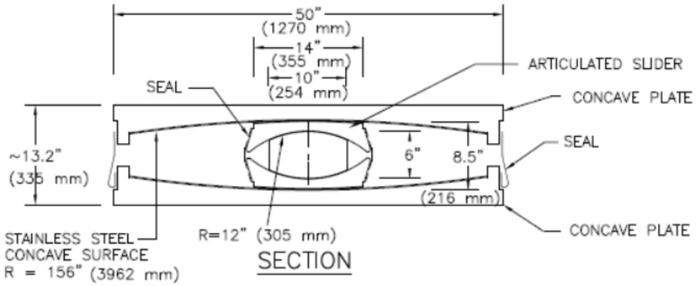
Project Overview

- Ground Conditions
  - Peat overlying sands and silts
  - Peat removal and ground improvement
- Pad foundation
- 352 TFP Isolators
- Post tensioned insitu concrete outer tank





Short period
OBE = 0.85g
SSE = 1.55g
ALE = 50% SSE



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Seismic Analysis Philosophy Objectives

An analysis philosophy was prepared for FERC submission:

- Present the regulatory framework in which the LNG tank will be designed
- Define the analysis model with reference to applicable and relevant codes and standards for SSI of a structure supported on friction pendulum (FP) isolators
- Define how the analysis results will be interpreted to provide recommended design values for LNG tank inner and outer tank design

Basis for Seismic Analysis – Key Issues

The seismic analysis methodology proposed for the Jordan Cove LNG tank addressed and incorporated a number of key characteristics and issues specifically related to the tank:

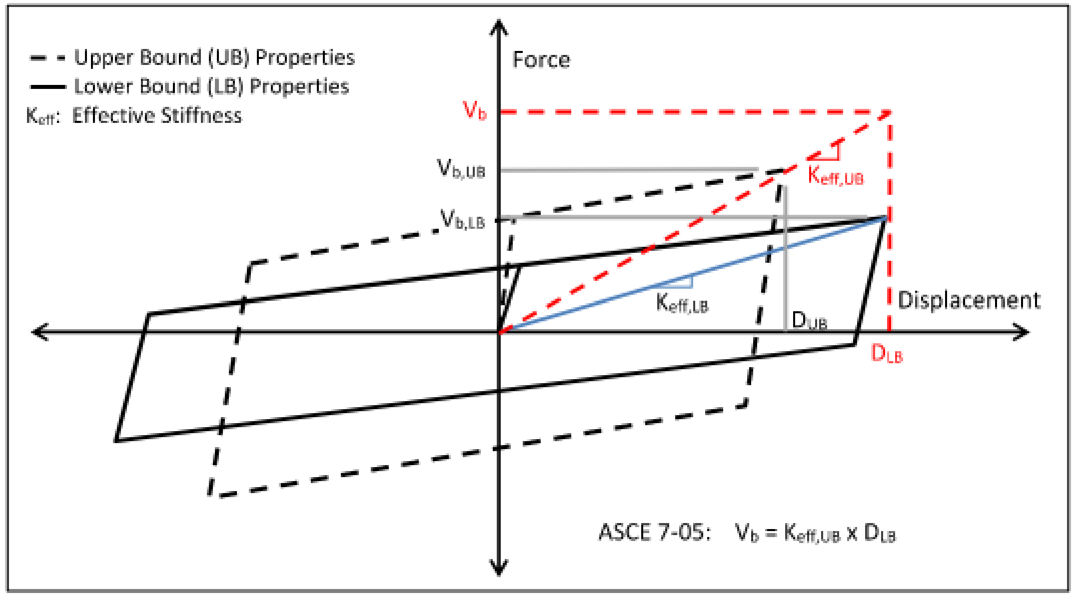
- Compliance with the Incorporated by Reference (IBR) codes;
- Foundation stiffness and damping which will exhibit nonlinear response due to the anticipated levels of ground motion and resulting soil strains; and
- Friction pendulum isolators, which exhibit a nonlinear response to seismic ground motions.

Analysis Options

- ASCE 4-16: Analysis Options
  - Linear response history (4.2)
  - Linear response spectrum (4.3)
  - Frequency domain (4.4)
  - Equivalent static (4.5)
  - Multistep (4.6)
  - Nonlinear response history (4.7)
  - Approx inelastic response spectrum (4.8)
  - Nonlinear static (4.9)
- ASCE 7-05: Analysis Options
  - Equivalent lateral force (12.8)
  - Modal response spectrum (12.9)
  - Linear response history (16.1)
  - Nonlinear response history (16.2)

Analysis Selection

- Soil Structure Interaction
  - ASCE 7-05
    - Equivalent lateral force procedure (19.2)
    - Modal analysis procedure (19.3)
    - Not intended for use with response history
    - Reduction limits not strictly applicable
  - ASCE 4-16
    - Direct method (5.3)
    - Substructuring methods (5.4)
    - Probabilistic SSI (5.5)
  - Selected direct method to capture fully coupled response of the whole system
  - Compliant with API 620 L.1
  - Proposed reduction limits
- Seismic Isolation
  - ASCE 7-05
    - Permits use of response history (17.4.2.2)
    - Results shall be scaled (17.3.2)
    - Conservative for min design displacements



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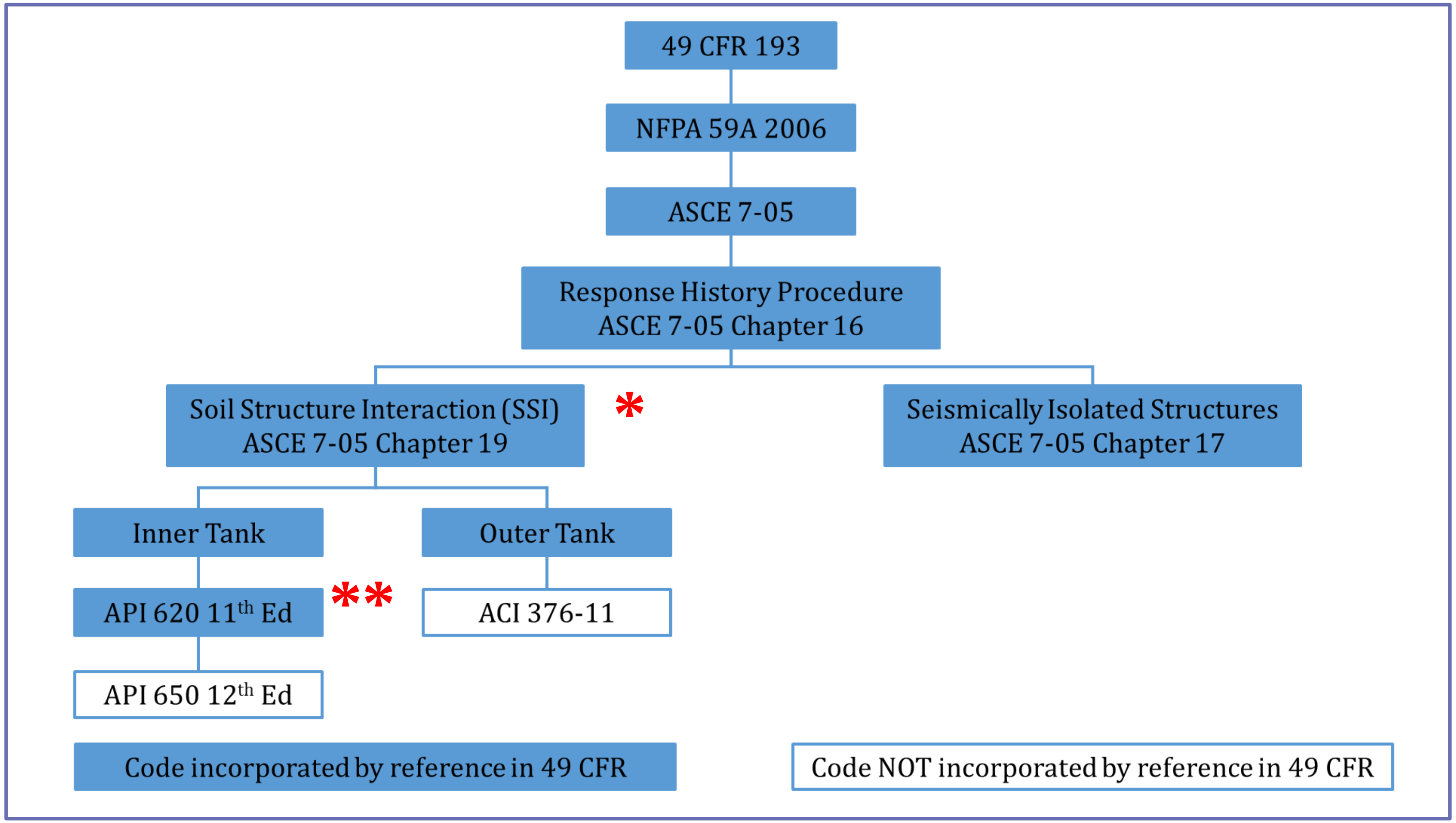
Basis for Seismic Analysis – Code Hierarchy

The code hierarchy adopted for the seismic analysis of the LNG tank is shown below



Note (*)
Not directly applicable for response history analysis

Note (**)
Strictly API 620 8th Ed is IBR, but API 620 11th proposed because

- Recognizes OBE and SSE for FRF and increase in stresses
- Better definition of vertical forces and moments
- SRSS for impulsive and convective forces
- Better definition of load combinations
- More detail and clarity on uplifting checks

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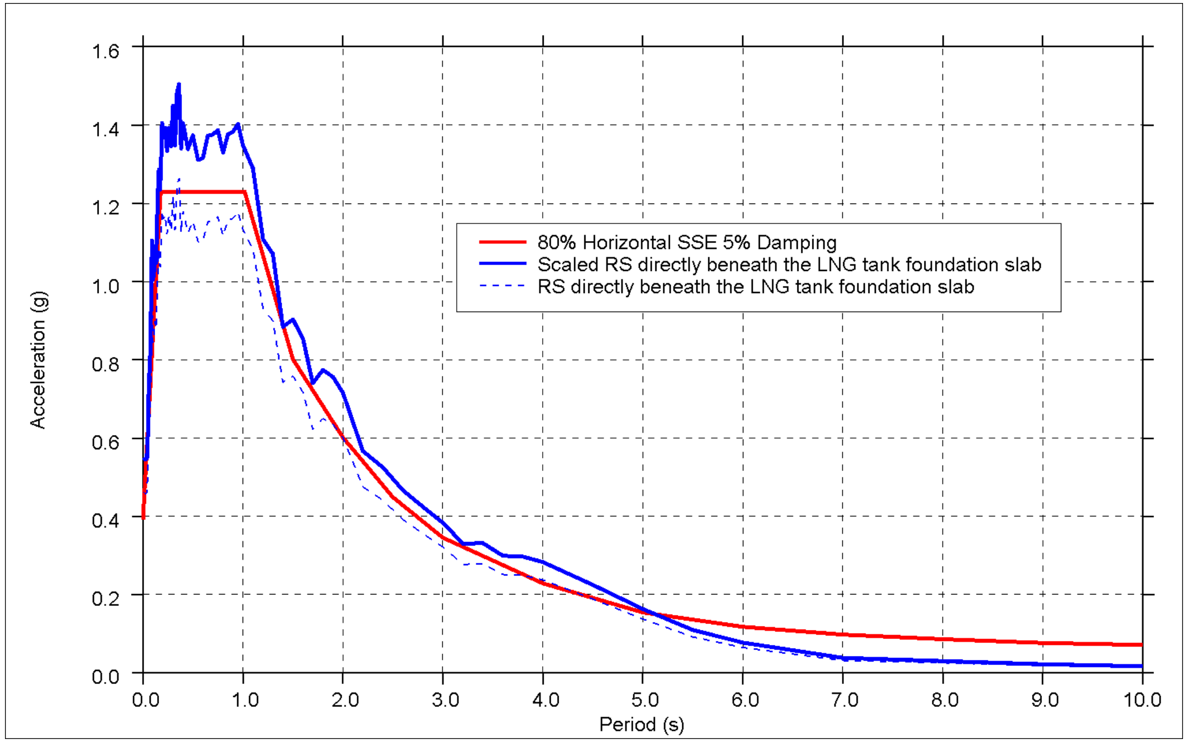
Basis for Seismic Analysis – Summary

1. Time history ground motions will be spectrally matched, in the period range of interest, ensuring compatible free field ground surface response with the Seismic Ground Motion Hazard Study.
2. A nonlinear response history direct method analysis model will be used to determine the response of the LNG tank to OBE, SSE and ALE seismic ground motions.
3. Peak response parameters will be based on the average of 7 tri-directional time history sets.



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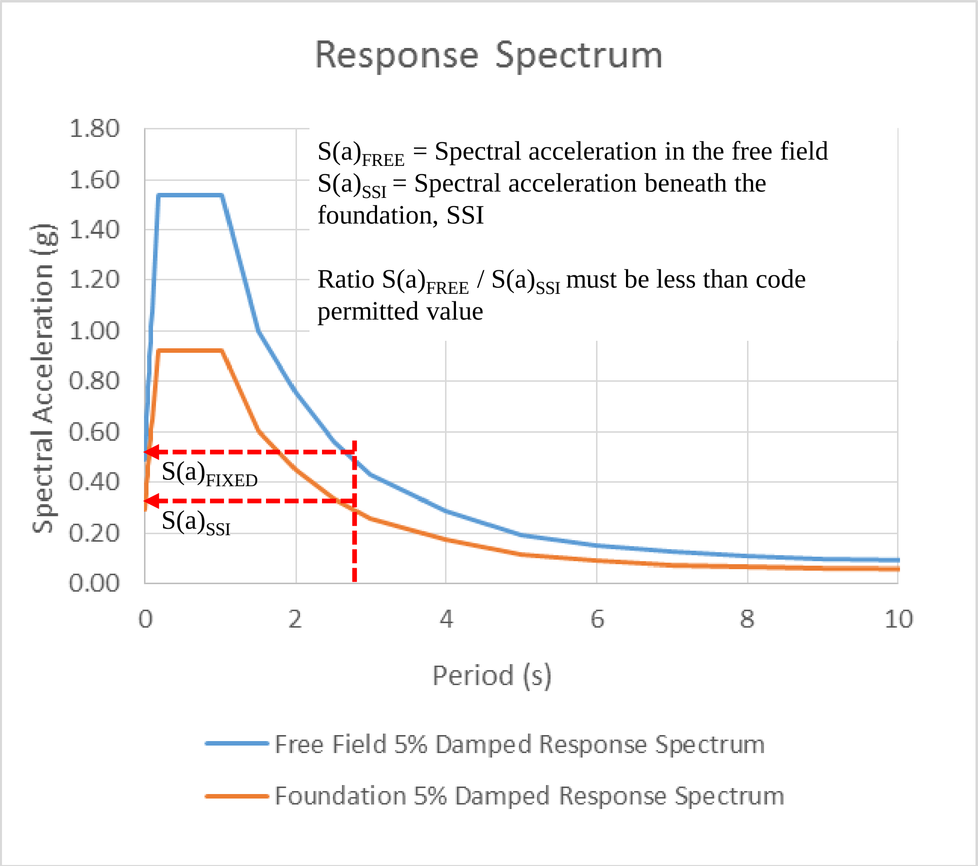
Basis for Seismic Analysis – Summary

4. Compliance with the limits on SSI benefits:
   - This will be demonstrated by comparing free field, no structure, best estimate (BE) 5% damped ground surface response spectrum with the 5% damped ground surface response spectrum directly beneath the LNG tank foundation slab for BE soil conditions.
   - The ratio of the spectral ordinates in the impulsive and convective period ranges will be determined.



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Basis for Seismic Analysis – Summary

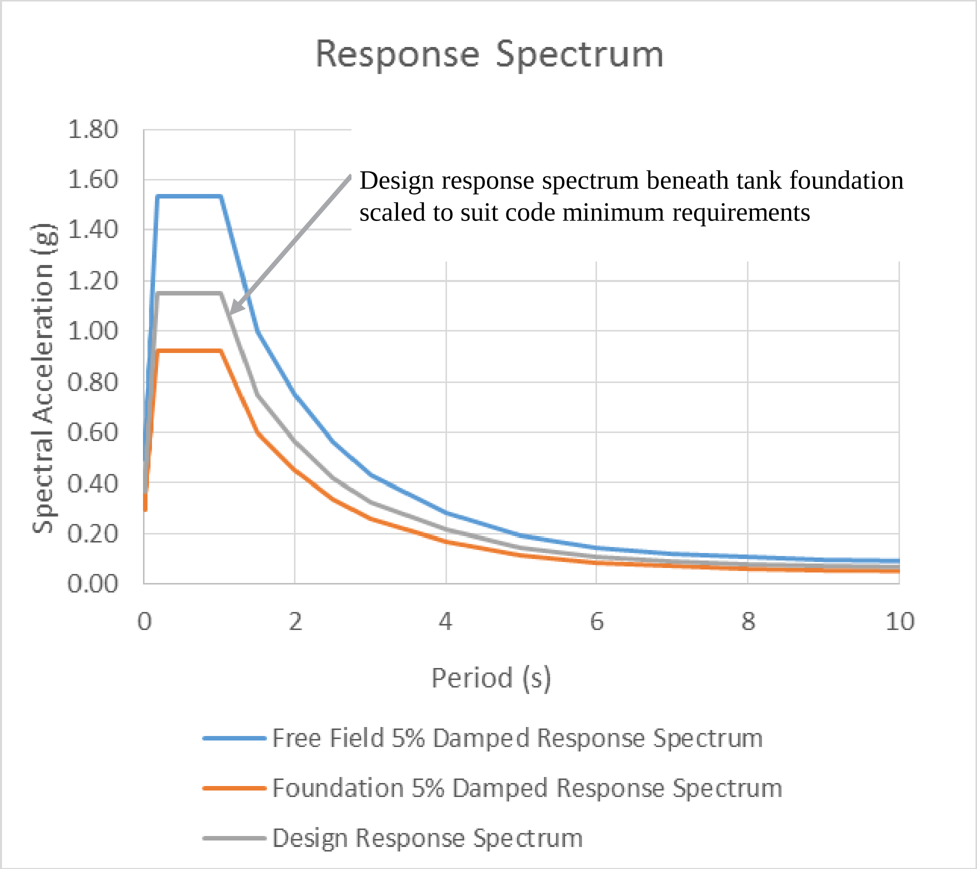
4. Compliance with the limits on SSI benefits (cont):
   - The effective damping will be calculated based on Newmark and Hall
   - For the inner and outer tanks the reduction in spectral acceleration in the period range of interest shall be checked against the limits in Table 1.

Table 1: Code limits on the reduction of response parameter when using SSI

Tank	Seismic Event	Code Requirement	Comment
Inner	OBE (OLE)	API 620 [26] L4.2.4	SSI damping ratio < 10%
		API 650 [28] E6.1.6	Requirements for using SSI
	SSE (CLE)	API 620 [26] L4.3.4	SSI damping ratio < 20%
Outer	ALE (SSEaft)	ACI 376 [30] 8.1.3.1.3	Reduction in forces limited to 40%
		ACI 376 [30] 8.1.3.4.6	Maximum damping in any mode 15%

Basis for Seismic Analysis – Summary

4. Compliance with the limits on SSI benefits (cont):
   - Where the limits are not met the 5% damped ground surface response spectrum directly beneath the LNG tank foundation slab for BE soil condition will be scaled up to satisfy the limit.



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Basis for Seismic Analysis – Summary

5. Minimum design lateral displacements and forces for seismically isolated tank:
   - The scaled 5% damped ground surface response spectrum directly beneath the LNG tank foundation slab for BE soil condition will be the design response spectrum for determining minimum design displacements and forces.
   - The calculation of minimum displacements and forces will **not** be based on a response spectrum in the free field, rather the effects of hysteretic and radiation damping in the soil of the SSI model will be accounted for in estimating the displacements and forces during the applicable seismic events
6. Inner tank design forces for SSE event are reduced by the reduction factor in API 620 Table L-1Q. No force reduction for OBE event

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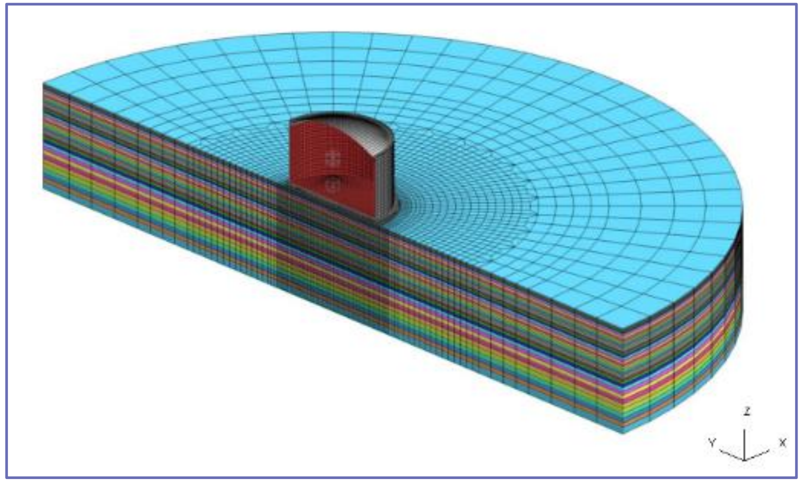
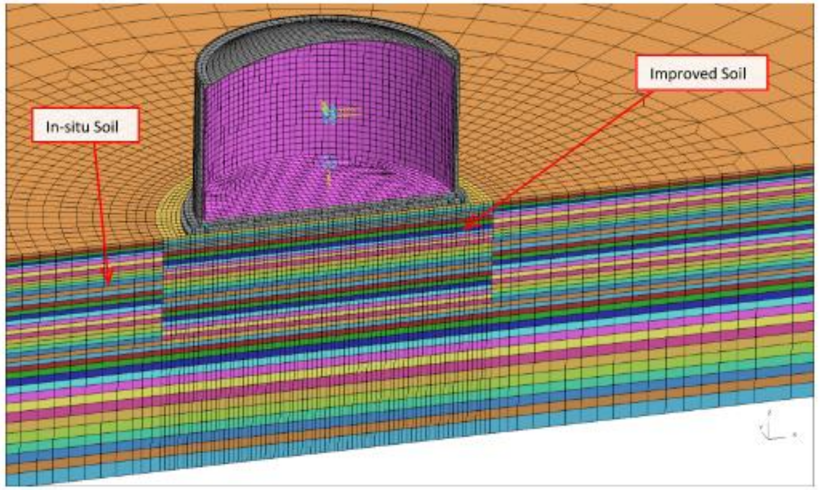
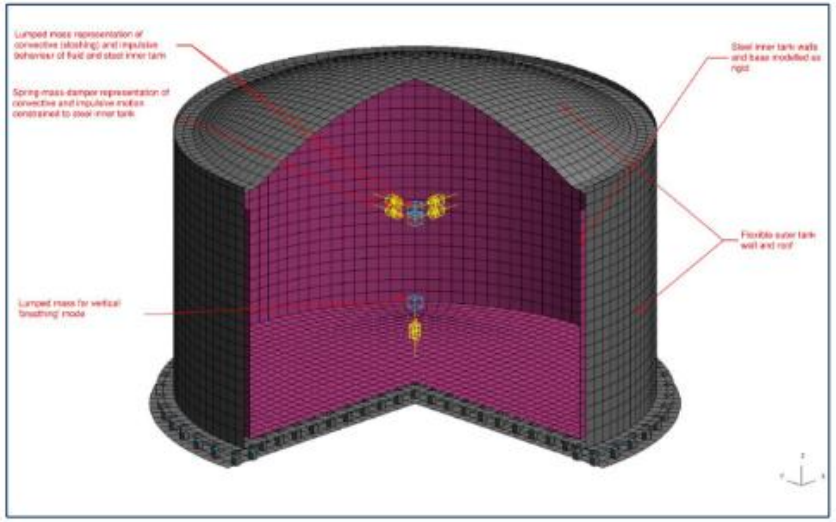
Model Overview







Propagation of earthquake waves from bedrock to ground surface.

The increase in stiffness of the soil due to ground improvement.

The stiffening effect of the structure on the soil.

Degradation of soil due to the ground motions and inertial loading from the tank.

The radiation of energy away from the structure (radiation damping).

Impulsive and convective forces of response to earthquake loading and the interaction with foundation soils.

Explicitly simulate the individual FP isolator bearings.

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Validation of Seismic Analysis Methods

- Impulse load checks on lumped masses to verify period and damper properties.
- Input versus output in order to verify correct application of loading. For example, output the accelerations from the base of the model to compare with original time-history data.
- Comparison with site-response analysis.
- Surface free-field spectra (soil column and soil block without tank) to verify that the analysis method replicates the free-field response. This checks the effects of the soil boundaries used in the SSI model.
- The treatment of nonlinear soil behavior in terms of stiffness and damping at the applicable strain level compatible with the input level excitation, both with and without tank. Comparison with free-field response will include the following:
  - Maximum shear strain profile with depth.
  - Maximum shear strain hysteresis loop.
- FP isolator bearing hysteresis loop.
- Geometry and aspect ratios of finite elements.
- Mass checks of superstructure.
- Verify effect of structural damping in the outer tank wall and roof.

Conclusions

- We implemented the approach……….AND proved the min force levels applied!!
- We need to seek updates to CFR and tank codes to
  - Incorporate latest or more recent API and ACI codes
  - Reflect latest thinking on performance-based design