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UNITED STATES CODE REQUIREMENTS FOR ANALYSIS AND DESIGN OF LIQUIFIED NATURAL GAS TANKS

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ABSTRACT

Liquefied Natural Gas (LNG) storage tanks are massive, tanks, often located near the shoreline with poor soil conditions. The foundation is typically a deep pile foundation system with a large group of piles, under a large concrete basemat (i.e, pile cap). In many cases the in-situ soil may need to be treated to mitigate liquefaction. The combination of the seismic effects of the structure and supporting foundation in high seismic areas lead to significant interaction effects which need to be considered for design.

An example of the Soil-Structure Interaction (SSI) analysis of an LNG tank is outlined in this paper. A description of the applicable federal and/or state regulations, guidelines, codes, standards, and specifications used as basis of design is given. The LNG tank foundation is supported on a large group of piles extending to a competent soil layer at a depth with overlaying soft soil layers. The two-step method of analysis, per ASCE/SEI 4 (2016), is utilized. For the tank structure consisting of the inner and outer walls, two simplified beam-stick models are developed so that the major structural modes of vibration of the tanks are included in the SSI analysis. The foundation response motion is determined from SSI analysis for the subsequent analysis and design of the inner and outer tanks and the pile and basemat foundation. The SSI analysis is performed for three soil cases covering lower bound, best estimate, and upper bound properties. The horizontal and vertical response of the foundation basemat in terms of acceleration response spectra are obtained for a range of spectral damping values.

The resulting foundation response motion is significantly lower than the ground motion, particularly at low periods of excitation of the tank structure. This outlines the importance of considering SSI analysis for LNG tanks, especially those which include pile foundations due to poor soil conditions.

SAFETY-RELATED ASPECTS OF LIQUEFIED NATURAL GAS TANKS

Liquefied Natural Gas (LNG), a fluid in the cryogenic liquid state that is composed predominantly of methane and that can contain minor quantities of ethane, propane, or nitrogen (NFPA, 2006). The U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (DOT PHMSA, 2023) regulates LNG as a hazardous material under 49 Code of Federal Regulations (CFR) part 172 “Hazardous Material Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, Training Requirements, and Security Plans” (49 CFR 172, 2023).

The LNG storage tank contains cryogenic liquid hazardous material, which represents the largest potential hazard if a failure would be realized. In order to protect public safety and prevent damage to the environment due to hazardous material release, the LNG storage tank should be designed adequately.

Typically, LNG storage tanks are massive, often located near the shoreline on poor soil conditions (in many cases liquefaction is of concern). The convective mass of the LNG is a large part of the total structural mass and responds at a very low frequency. The structural frequencies have a wide range (e.g. ~0.1Hz to 25 Hz). Typically, the foundation consists of a large group of deep piles supporting large concrete basemat and the depth of piles varies by site. The piles should be embedded in a competent soil layer.

SEISMIC ANALYSIS REQUIREMENTS FOR LIQUEFIED NATURAL GAS TANKS

The U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) has prescribed the minimum federal safety standards for natural gas pipelines and LNG facilities in compliance with 49 USC 1671 et seq. and 49 USC 60101, respectively. Those standards are codified in 49 CFR Parts 192 and 193 and apply to safety regulations and standards related to the design, construction, operation, and maintenance of natural gas pipelines and the siting, design, construction, operation, maintenance, and security of LNG facilities, respectively. The 2001 edition of National Fire Protection Association (NFPA) Standard 59A, Standard for the Production, Storage, and Handling of Liquefied Natural Gas, is incorporated into 49 CFR Part 193 by reference, with regulatory preemption in the event of conflict.

In accordance with the 1985 Memorandum of Understanding (MOU) on LNG facilities and the 2004 Interagency Agreement on the safety and security review of waterfront import/export LNG facilities, PHMSA participates as a cooperating agency and assists in assessing any mitigation measures that may become conditions of approval for any project. In addition, the August 31, 2018, MOU between Federal Energy Regulatory Commission (FERC) and DOT PHMSA provides guidance and policy on the respective statutory responsibility of each agency to ensure that each agency works in a coordinated and comprehensive manner.

FERC regulations under 18 CFR § 380.12 (h) (5) requires evaluation of earthquake hazards based on whether there is potential seismicity, surface faulting, or liquefaction.

The design of LNG storage tanks in the United States is required by the DOT PHMSA 49 CFR Part 193, "Liquefied Natural Gas Facilities: Federal Safety Standards.". Depending on location and use, an LNG facility may be regulated by several federal agencies, primarily the Federal Energy Regulatory Commission (FERC), the U.S. Coast Guard (USCG), and DOT PHMSA, and by state utility regulatory agencies. DOT PHMSA regulations in 49 CFR § 193.2101 under Subpart C require that field-fabricated LNG storage tanks comply with National Fire Protection Association (NFPA) Standard 59A *"Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)"* (2001) and NFPA 59A (2006) for seismic design. Note that FERC regulations do not specify with what edition of NFPA 59A an applicant should demonstrate compliance. In most applications, applicants have interpreted this as the edition(s) incorporated into DOT PHMSA regulations, which for this case would be the 2001 and 2006 editions at the time of application. Others have interpreted this as the NFPA 59A edition published at the time of application or another edition they intend on incorporating in addition to those incorporated into DOT PHMSA regulations. NFPA 59A (2006) requires LNG storage tanks be designed to continue safely operating with earthquake ground motions at the ground surface at the site that have a 10 percent probability of being exceeded in 50 years (475-year mean return interval), termed the Operating Basis Earthquake (OBE). NFPA 59A (2006) also requires that LNG tanks and the associated impounding system be designed to have the ability to safely shutdown when subjected to earthquake ground motions which have a 2 percent probability of being exceeded in 50 years (2,475-year mean return interval), termed the Safe Shutdown Earthquake (SSE). FERC regulations under 18 CFR § 380. 12 (o) (14) require an applicant to demonstrate how they would comply with 49 CFR 193 and NFPA 59A. DOT PHMSA's minimum federal requirements in 49 CFR 193 have specific requirements on design to withstand certain loads from natural hazards and these are incorporated by reference ASCE/SEI 7 (2002) via NFPA 59A (2006) for seismic design of field fabricated LNG storage tanks and ASCE/SEI 7 (unspecified edition) via American Petroleum Institute (API) 620 *"Design and Construction of Large, Welded, Low-Pressure Storage Tanks"* (2008/11th and addendums) for seismic design of all other LNG storage tanks. State and local codes incorporate ASCE/SEI 7 via the International Building Code (IBC) (2021 and earlier editions). FERC regulations under the new rulemaking of 18 CFR § 380.12 (o) (15) (iii) (A) require specific seismic design information for the LNG facility. NFPA 59A (2006 through 2023 editions) requires that Soil-Structure Interaction (SSI) effects shall be considered where the tank system is not founded on bedrock, Site Class A or B per ASCE 7 (2002 through 2016 editions).

In addition, NFPA 59A (2013 through 2023 editions) requires that the storage tank system foundation shall be designed in accordance with American Concrete Institute (ACI) 376 (2010/2011) *"Refrigerated Liquefied Gas Containment for Concrete Structures"*.

Consideration of Soil-Structure Interaction Effects

Consideration of SSI effects on the seismic response of the LNG tank combines the seismic effects of both the structure of the tank and foundation elements along with the seismic effects of the supporting/surrounding site itself. In areas of high seismic activity, consideration of SSI effects leads to significant interaction.

Seismic analysis of LNG tanks is commonly performed using simplified structural analysis methods. Typically, a fixed-base analysis of the LNG tank is conducted using a simplified representation of the foundation, with an input response spectra and higher associated damping. Consideration of the interaction of the soil and structural response through a rigorous SSI analysis can significantly lower seismic demands compared with traditional simplified methods.

SEISMIC ANALYSIS CASE STUDY

Analysis Approach

For the case study conducted herein, the two-step method per ASCE/SEI 4 (2016) is utilized. The first step of the two-step method is to conduct the SSI analysis using a detailed model which includes the foundation piles with a simplified structural model of the inner and outer tanks. The acceleration response spectra at the tank foundation level is exported from the SSI analysis conducted in the first step. In the second step, a fixed-base analysis is conducted using a detailed structural model of the inner and outer tanks using the foundation acceleration response spectra exported from the first step as input to the analysis.

Soil Parameters

The site considered for the case study consists mainly of layers of soft to stiff clay. The profile depth extends to 183' below grade. The low-strain properties corresponding to the site are shown in Table 1. The shear modulus degradation curves used in the site analysis are shown in Figure 1. The damping curves used in the site response analysis are shown in Figure 2.

Table 1: Low-Strain Soil Properties

Soil Layer	Top Elevation (ft)	Thickness (ft)	Total Unit Weight (pcf)	Undrained Poissons ratio	Drained Poisson's ratio	Properties of Darendelli (2001), Shear modulus reduction and Damping curves	Vs (ft/sec)		
							Lower Bound	Best Estimate	Upper Bound
Stabilized Soil	5	3.5	100	0.25	0.25	PI=15, σ'=0.1 atm, OCR=5.0	750	1000	1250
Very Soft Clay	1.5	19.5	100	0.48	0.35	PI=70, σ'=0.2 atm, OCR=1.0	263	350	438
Stiff Clay	-18	45	115	0.49	0.30	PI=25, σ'=1.0 atm, OCR=3.0	450	600	750
Stiff Clay	-63	80	115	0.49	0.30	PI=35, σ'=2.0 atm, OCR=1.9	525	700	875
Stiff Clay	-143	20	115	0.49	0.30	PI=35, σ'=2.5 atm, OCR=1.6	638	850	1063
Dense Sand	-163	20	125	0.30	0.30	PI=0, σ'=3.5 atm, OCR=1.0	750	1000	1250
Stiff Clay	-183	to end	125	0.48	0.30	PI=30, σ'=4.5 atm, OCR=2.0	675	900	1125

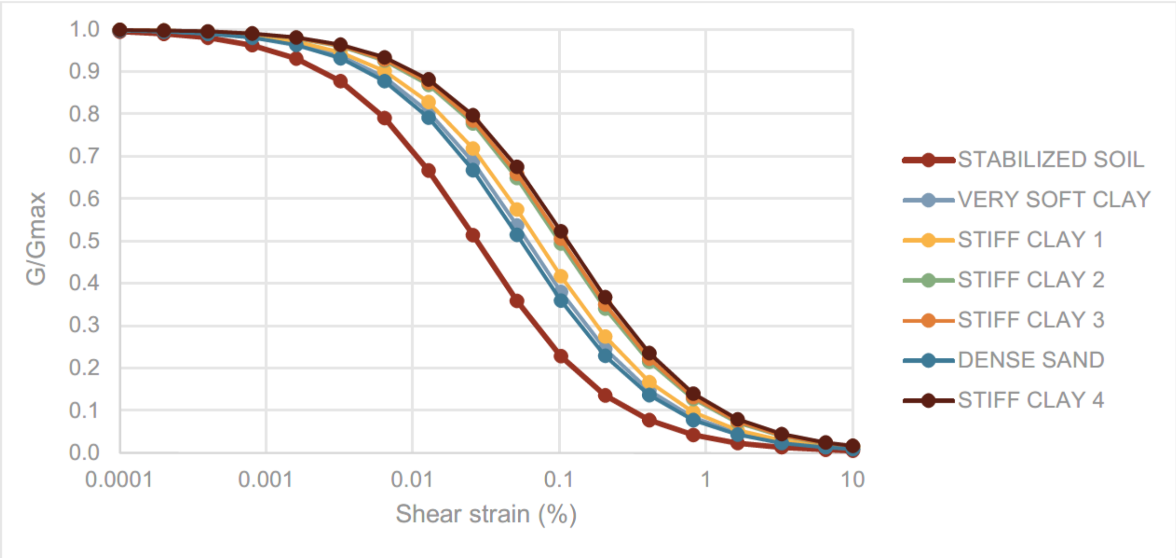

Figure 1: Shear Modulus Degradation Curves

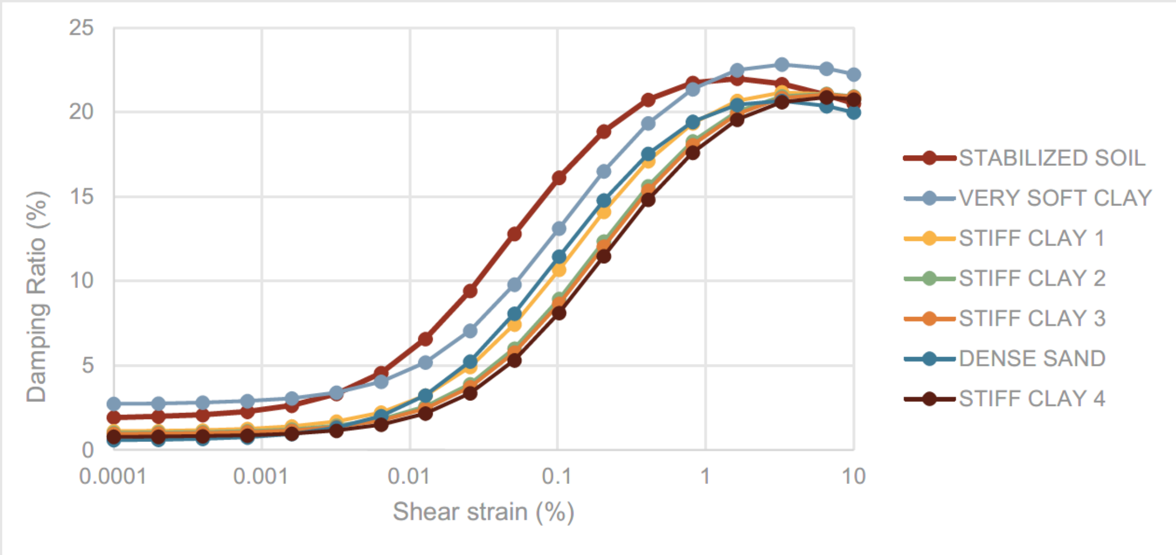

Figure 2: Damping Curves

Foundation Details

The LNG tank used for the case study consists of a pile foundation, with 1150 total piles, extended to a depth of 180’, where competent soil is present in the site properties. The connection of the piles to the basemat is considered to be pinned, allowing moment transfer. A plan view of the tank foundation shown the pile layout is shown in Figure 3.

The basemat foundation is thickened near the location of the tank wall support. The main are of the basemat foundation is 2’ thick and the thickened portion is 3’ thick. A section view is shown in Figure 4.

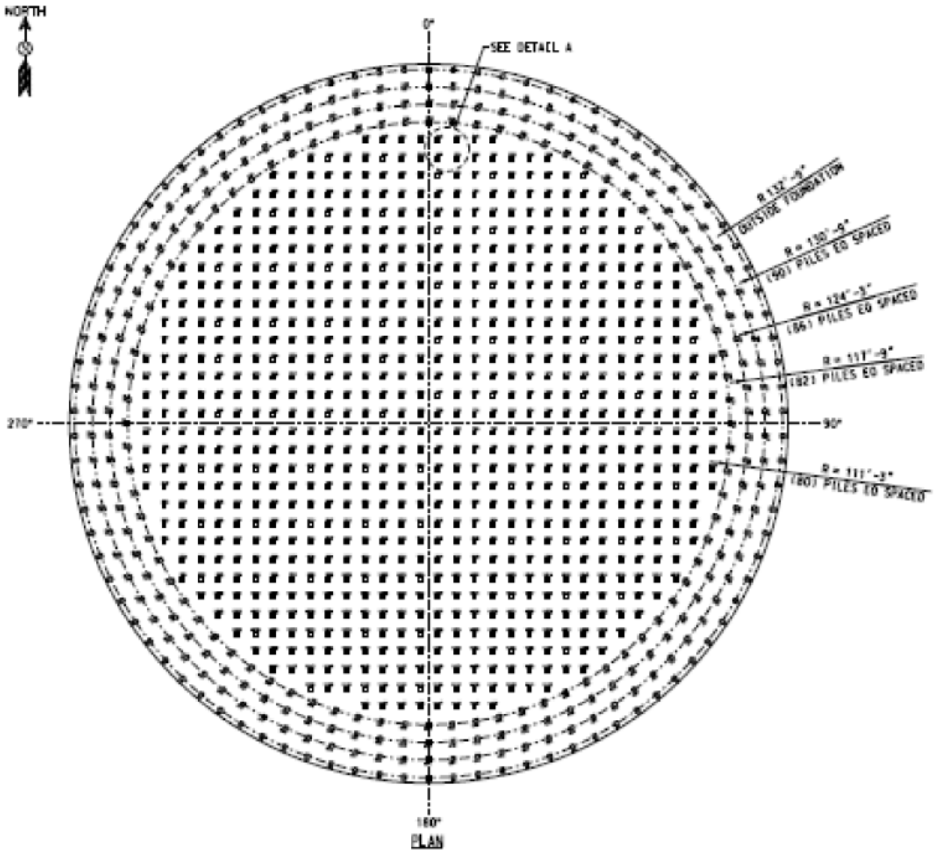

Figure 3: Foundation Plan View

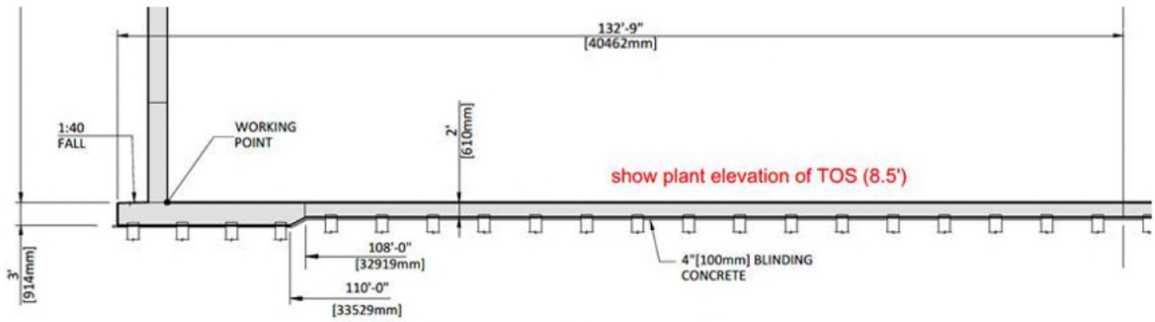

Figure 4: Foundation Section View

Seismic Input Motion

The seismic input motion corresponding to the site has a peak ground acceleration in the low frequency range. The 5% damped horizontal acceleration response spectra for both Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE) are shown in Figure 5. The 5% damped vertical acceleration response spectra for both Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE) are shown in Figure 5.

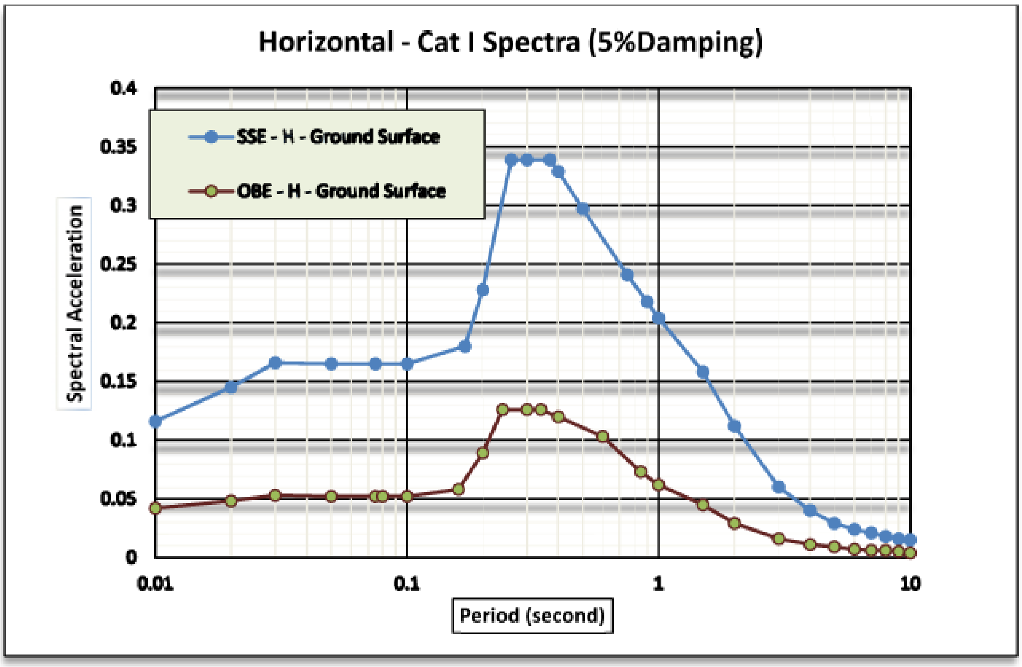

Figure 5: Horizontal Input Acceleration Response Spectra

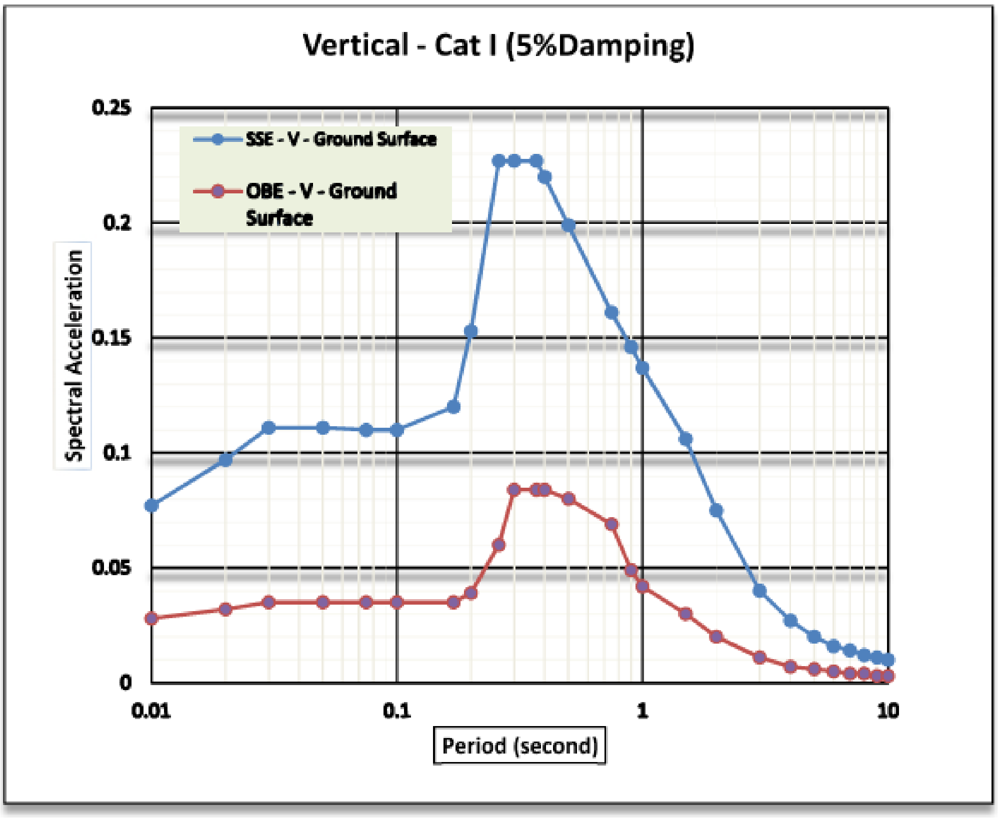

Figure 6: Vertical Input Acceleration Response Spectra

Site Response Analysis

Site response analysis is conducted using the Bechtel Standard Computer Program P-SHAKE (2009), using Random Vibration Theory equivalent linear methodology with iterative variation of shear modulus and damping under seismic strains. Three variations of the soil properties are considered along with SSE and OBE input motions. The results of the site response analysis are strain-compatible soil stiffness and damping values for input to the SSI analysis of the LNG tank.

Soil-Structure Interaction Analysis

SSI analysis is conducted using the Bechtel Standard Computer Program SASSI2010 (2013). The structural model takes advantage of two planes of symmetry as shown in Figure 7. The Inner and Outer tanks are idealized with lumped mass stick models. The tank models include impulsive and convective mass modes. The basemat is modelled using thick shell elements and the piles are modelled using 3-D beam elements with pinned connections to the basemat.

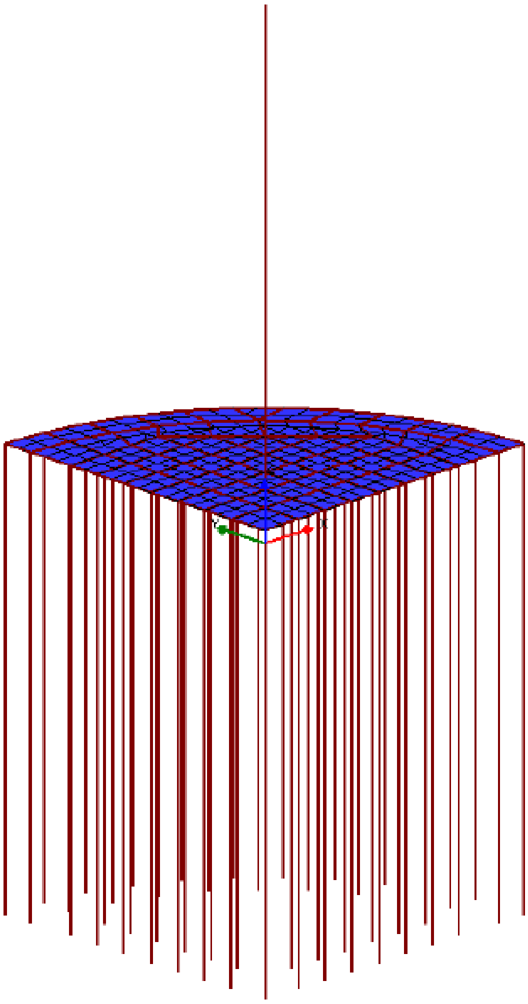

Figure 7: SSI Model

Assessment of Soil-Structure Interaction Effects

The foundation acceleration response spectra resulting from the SSI analysis are compared with the ground motion input response spectra. A comparison in the horizontal direction is shown in Figure 8 and a comparison in the vertical direction is shown in Figure 9.

The SSI results are significantly lower especially at low periods. There is a dip apparent at the frequencies of the foundation acceleration response spectra that correspond to major structural modes of the tank structure. The foundation acceleration response spectra exhibit more realistic seismic demands, due to the explicit modeling of the piles and consideration of radiation damping.

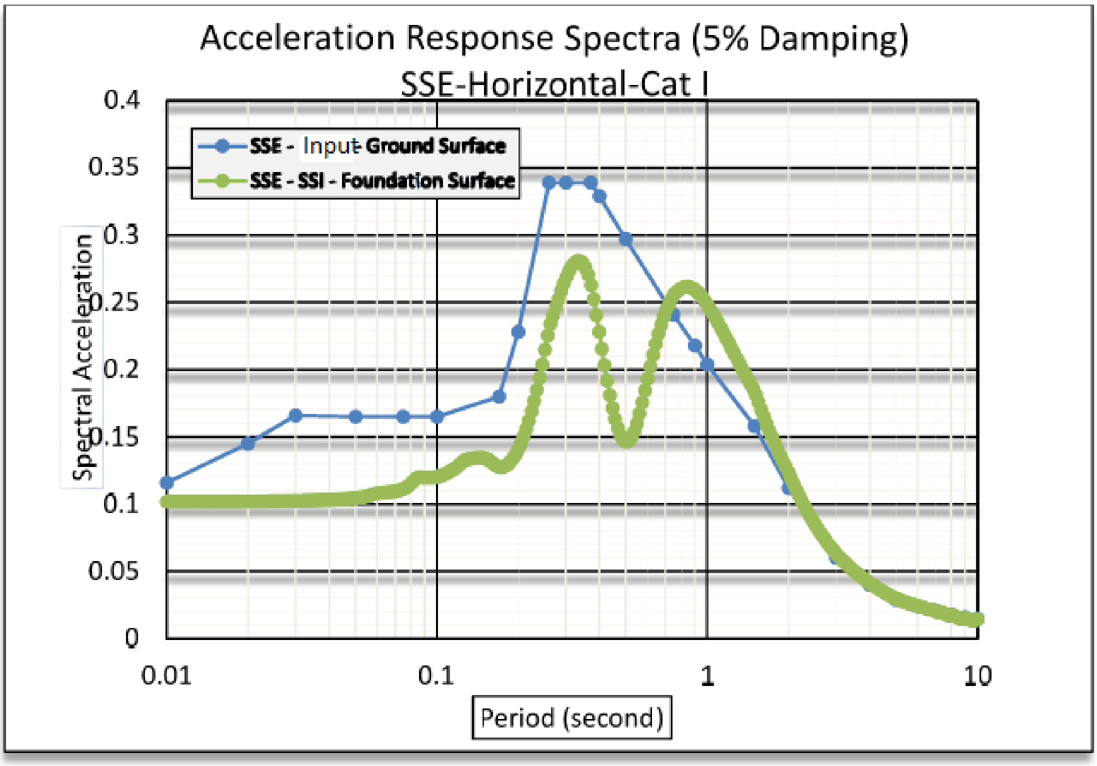

Figure 8: Acceleration Response Spectra Comparison - Horizontal

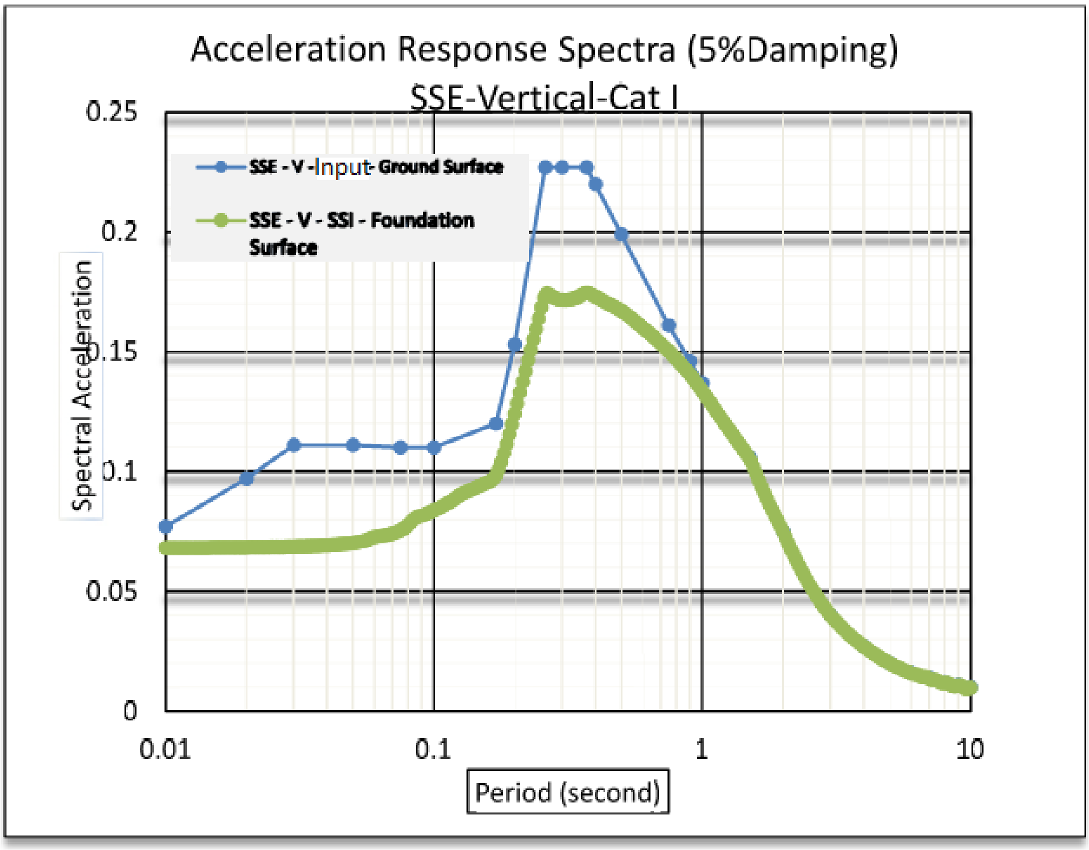

Figure 9: Acceleration Response Spectra Comparison - Vertical

CONCLUSIONS

Soil-Structure Interaction effects are significant for Liquefied Natural Gas tank structures on soft soil sites. It is important to consider the interaction effects of the structure and the foundation with the soil rigorously. In the case presented herein, the resulting seismic input for the design of the tanks was significantly reduced by considering the Soil-Structure Interaction effects, where the foundation response spectra resulting from the Soil-Structure Interaction analysis is used in the 2nd step for detailed analysis and design of the tanks. This produces a more reasonable design and eliminates excessive quantities from overly conservative simplified calculations.

Liquefied Natural Gas storage tanks should be designed in accordance with 49 Code of Federal Regulations 193 Subpart C, National Fire Protection Agency 59A and American Petroleum Institute Standard 620. In addition, the Liquefied Natural Gas storage tank should be designed, fabricated, tested, and inspected in accordance with American Petroleum Institute Standard 625 and American Concrete Institute 376. Other low-pressure storage tanks such as the amine storage tank should be designed, inspected, and maintained in accordance with American Petroleum Institute Standards 650 and 653.

REFERENCES

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