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Probabilistic-Based Approach for Developing Soil Liquefaction Fragilities at Nuclear Power Plant Sites

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ABSTRACT

Recent Seismic Probabilistic Risk Assessments (SPRAs) have been performed at numerous Nuclear Power Plant (NPP) sites in support of NTTF 2.1 recommendations (NRC 2011). Amongst the various aspects of the SPRA is the development of fragility estimates of soil-related failure modes that may affect the structures, systems and components (SSCs) included on the seismic equipment list (SEL).

Liquefaction of soils in and of themselves do not pose risks to NPP SSCs. Rather, the behavior of liquefied soil creates demands that are reflected in the seismic fragility estimates for the SSCs. These behaviors are associated primarily with fluid-induced loss of soil strength with two typical Engineering Demand Parameters (EDP) modes: (1) lateral deformations, including lateral spreading where seismic demands exceed the residual strength of the soil and flow failure where the shear strength of the soil drops below the level needed to maintain static stability; and (2) liquefaction induced settlement caused by volume loss due to dissipation of excess pore pressure in the liquefied soil. These EDP modes can lead to displacements that could result in unacceptable performance of the supported or embedded SSCs. The soil EDP modes evaluated include potential for liquefaction, seismic induced settlements, and seismic induced lateral deformation.

This paper describes an evaluation methodology that implements Logic Tree methods to incorporate uncertainty and Latin Hypercube Sampling (LHS) to incorporate variability in the development of EDP estimates of the soil-related failure modes important to typical NPP SSCs. This approach leads to results that are directly incorporable into a performance-based design or evaluation. A buried piping example is provided that demonstrates the implementation of the methodology.

INTRODUCTION

As summarized in NAS (2016), liquefaction occurs when stresses and deformation in the ground caused by earthquake shaking disturb the soil structure of saturated, geologically unconsolidated soils. Water in the pore spaces between soil particles will resist the natural tendency of the soils to consolidate into a denser and more stable arrangement during shaking. Because the soil cannot change in volume until water is drained from the pore spaces, porewater pressure will rise, soil particles may lose contact with each other, and the soil mass may lose much of its strength. This chain of events is referred to as liquefaction triggering.

Liquefaction-Associated Vertical Settlements

Volume loss due to the dissipation of excess pore pressure in the liquefied soil during and after an earthquake generally results in ground surface settlement. Settlement can cause damage to structures if the settlement is not uniform beneath the structure. Settlement can also leave a gap beneath pile-supported structures, cause distress to utilities buried in the soil, and alter drainage grades at a site. The total volumetric strain (volume loss) following liquefaction is not explained entirely by pore-pressure dissipation and the reconsolidation of the soil. This is because cyclic loading of the soil beyond the liquefaction triggering changes the soil structure such that the soil is more compressible than it was in its original state (NAS (2016)). Settlement of the ground surface can also be associated with lateral soil movement and with the extrusion of soil (ejecta) from beneath the ground surface.

Liquefaction susceptibility refers to the potential for liquefaction to occur in a soil. Grain size and plasticity index are primary factors that determine the liquefaction susceptibility of a soil. Bray and Sancio (2006) developed liquefaction susceptibility criteria that considers plasticity index (PI) and the ratio of water content to liquid limit (w_c/LL), while criterion from Idriss and Boulanger (2008) is based solely on PI. The criteria are used to distinguish between soils that are susceptible to liquefaction triggering (i.e., soils that exhibit "sand-like" behavior) and those that are susceptible to some strength loss due to cyclic loading but are not susceptible to the loss of stiffness and strength and cyclic pore-pressure generation characteristic of what Seed and colleagues (2003) referred to as "classic cyclic liquefaction" (i.e., soils that exhibit "clay-like" behavior). The potential for liquefaction-associated vertical settlements of sand-like and clay-like soils must be considered when developing estimates of settlement at a site.

Liquefaction-Associated Lateral Deformations

When initial static shear stresses are less than the residual strength of the liquefied soil, but the seismically induced stresses exceed the residual strength, lateral displacement builds up incrementally during the earthquake and ceases when the cyclic loading stops. This displacement is referred to as lateral spreading. When initial static shear stresses are greater than the available strength of the liquefied soil, lateral deformation will not only build up during the earthquake but also continue to accumulate after the shaking stops. This behaviour is referred to as a flow slide which can result in very large soil displacements. If a site is susceptible to liquefaction triggering and assessment indicates that flow sliding is not anticipated, the potential for lateral spreading must still be evaluated.

ANALYSIS METHODOLGY

This section discusses the evaluation methodology used to develop median and 84th percentile estimates of liquefaction-induced vertical settlements and lateral deformations at a site and to assess the impact of the soil movements on embedded piping across the site.

Evaluation of soil failure modes include consideration of liquefaction and cyclic softening (referred to hereafter as liquefaction) and the effect of soil deformation on embedded piping. The methodologies used to evaluate each of the soil failure modes are summarized in this section.

The models used to predict liquefaction triggering, settlement, and lateral spreading require characterization of several soil parameters associated with the site. The variability associated with these parameters is considered to be aleatory and the parameters and their variability are used to develop 31 LHS soil column realizations. The parameters that include aleatory variability are: blow counts and associated corrected values, water content (w_c), plasticity index (PI), liquid limit (LL), ratio of w_c to LL, liquidity index (LI), fines content (FC), recompression index (C_R), void ratio (e_o), and groundwater table (GWT) elevation.

The extent of liquefaction and cyclic softening is estimated by examining the probability of sand-like behavior (susceptibility of liquefaction) of the soil layers of each boring selected as representative of a given region. Susceptibility is computed based on Huang (2008). Probability of liquefaction for sand-like materials is computed based on Idriss and Boulanger (2008, 2010) and Cetin et al. (2009). For clay-like materials, vertical settlements are estimated based on Cetin and Bilge (2014). Soil parameters (i.e. residual shear strength of soils) are estimated using methodologies described by Casey (2014); Kramer and Wang (2015); Weber (2015). Models developed by Rathje and colleagues (Rathje and Saygili (2008), Rathje and Saygili (2009), and Rathje and Antonakos (2011)) are used to develop estimates of lateral deformation. Hereafter, these models are referred to as Rathje and Saygili (2008) since the fundamental model is developed in this reference. The plethora of settlement estimates are treated as epistemic uncertainty in this analysis.

Epistemic uncertainty is included in the evaluations via the use of logic trees. A Latin Hypercube Sampling (LHS) methodology incorporated into event trees is used to evaluate aleatory variability in the liquefaction and cyclic softening estimates. In these evaluations, variability in the soil profiles (soil parameters and depth of profile, amplification of the rock motion to the surface, GWT elevation, and deformation prediction models are used to develop robust estimates of the potential liquefaction and cyclic softening conditions across the site.

Evaluation for Settlement of Sand-Like Materials and Cyclic Softening of Clay-Like Materials

This section describes the methodology used to develop estimates of settlement and lateral deformation of the soils at the NPP site. For given area at the site, 31 soil profiles of varying depth are developed with 1-ft thick layers. These profiles are developed using a LHS sampling process that incorporates correlations between soil properties observed in available geotechnical data across the NPP site.

Multiple analytical models are evaluated to incorporate epistemic uncertainty associated with the various available prediction models, described above, and the site amplification functions. The results from the individual models and SAFs are weighted and used to develop overall estimates of vertical settlement and lateral deformation. Deaggregated PGA values at rock, and their associated weight, are provided in the Probabilistic Seismic Hazard Analysis (PSHA) for ground motion levels having annual frequencies of exceedance (AFE) between 10^{-2} to 10^{-7}. Amplification of the rock motion to the ground surface is provided in terms of median and lognormal standard deviation (β) values representing epistemic variability, for each of six different site amplification functions representing epistemic uncertainty, which consists of three realizations of base case profiles times two different soil degradation models.

The step-by-step process used to develop estimates of vertical settlement and lateral deformation at the site is as follows.

Step 1: Identify ground motion levels considered (AFEs between 10^{-4} to 10^{-7} were considered to be dominate contributors to risk)
Step 2: Loop on site amplification functions d_m = 1 to 6
Step 3: Loop on soil profile realizations j =1 to 31
Step 4: Compute effective static stresses at depth based on density of soil and GWT elevation for realization j
Step 5: Loop on rock motion AFE n
Step 6: Loop on the number of magnitudes (o) for the deaggreagated rock PGA data for AFE n
Step 7: Retrieve seismic amplification of rock motion (SAF) for AFE n, magnitude o, and site amplification d_m
Step 8: Loop on the epistemic SAF variability in - AFE n: p = 1 to 31
Step 9: Compute peak ground acceleration (PGA) and velocity (PGV) at the surface for magnitude o, AFE n, and SAF p

Step 10: Loop on the number of layers (*m*) in realization *j* and perform the following computations. (Steps 11-14 apply to vertical settlements of sands and clays. Steps 15-21 apply to lateral deformation computations.)
Step 11: Compute probability of sand-like behavior (SI) based on Huang (2008)
Step 12: Compute probability of liquefaction (pl_{IB}), vertical settlement (εv_{IB}), and cyclic stress ratio and cyclic resistance ratio (CSR/CRR) based on Idriss and Boulanger (2008) for sand-like soils
Step 13: Compute probability of liquefaction (pl_{Ce}) and vertical settlement (εv_{Ce}) based on Cetin et al. (2009) and Cetin and Bilge (2014) for sand-like soils
Step 14: Compute vertical settlement (εv_{cl}) and its associated β_{cl} based on Cetin and Bilge (2014) for clay-like soils
Step 15: Compute period of ground motion based on magnitude (T_m)
Step 16: Compute median and β of residual shear strength based on Weber (2015), Sur_{weber} and Kramer and Wang (2015), Sur_{kramer}
Step 17: Compute CSR and CRR for clay-like material based on Cetin and Bilge (2014); Cetin et al. (2004)
Step 18: Compute a "slide ratio" for layer *m* that is used to identify the resistance of the layer to lateral sliding based on CSR/CRR of the layer assuming it behaves in a sand-like or clay-like manner based on the probability of susceptibility of liquefaction (SI)
Step 19: Compute a median yield acceleration for layer *m* (k_y) as:

$$k_y = \frac{0.5Sur_{kramer} + 0.5Sur_{weber}}{d_m * \gamma_m} \tag{1}$$

where:
- d_m is the depth and γ_m is the average density of the soil above layer *m*

Step 20: Compute PGA and PGV at the base of the layer with the largest slide ratio (base of sliding mass)
Step 21: Using k_y, PGA and PGV at base of sliding mass, period of soil column above layer *m* (Ts), and T_m, compute lateral deformation assuming layer *m* is the depth of sliding based on Rathje and Saygili (2008)

Upon completion of the above computations, the total vertical settlement for a given realization with *m* layers, a given magnitude, and a given soil amplification case is determined as follows:

$$\varepsilon_v = \sum_{i=1}^{m} \varepsilon v_{IB} \cdot e^{\beta_{IB} Z} \cdot pl_{IB} \cdot SI \cdot \frac{1}{2} + \varepsilon v_{Ce} \cdot e^{\beta_{Ce} Z} \cdot pl_{Ce} \cdot SI \cdot \frac{1}{2} + \varepsilon v_{cl} \cdot e^{\beta_{cl} Z} \cdot (1 - SI) \tag{2}$$

where:
- εv_{IB} and β_{IB} are the median and β settlement terms of layer *i* for sand-like material computed from Idriss and Boulanger (2008, 2010)
- εv_{Ce} and β_{Ce} are the median and β settlement terms of layer i for sand-like material computed from Cetin et al. (2009) and Cetin and Bilge (2014)
- Z = # of std deviations from median associated with equation variability in the LHS methodology
- SI = probability of sand-like behavior for layer *i*
- pl_{IB} and pl_{Ce} = probability of liquefaction for layer *i* based on Idriss and Boulanger (2010) and Cetin and Bilge (2014)
- εv_{cl} and β_{cl} are the median and β settlement terms of layer *i* for clay-like material computed from Cetin and Bilge (2014)

The above formulation equally weighs the contribution to settlement for sand-like soils from Idriss and Boulanger (2008) and Idriss and Boulanger (2010) and that from Cetin et al. (2009) and Cetin and Bilge (2014), and also incorporates the probability of liquefaction for sand-like soils. To combine the effects from each earthquake magnitude o with an associated weight from the PSHA, ($weight_j$), the total settlement is given by,

$$\varepsilon_{total} = \sum_{j=1}^{o} weight_j \cdot \varepsilon_v \tag{3}$$

This process is repeated for each branch of the logic tree for each ground motion AFE of interest and for each soil profile realization.

Evaluation for Lateral Spreading and Sliding of Soils

Rathje and Saygili (2008) provide equations for estimating lateral displacement of a sliding mass (D) that incorporates period of sliding mass, T_s, mean period of ground motion, T_m, PGA and PGV at the base of the sliding mass, and the yield acceleration of the sliding mass, k_y. The equation is given by

$$\mathrm{Ln}[\mathrm{D}] = a_1 + a_2\left(\frac{k_y}{PGA}\right) + a_3\left(\frac{k_y}{PGA}\right)^2 + a_4\left(\frac{k_y}{PGA}\right)^3 + a_5\left(\frac{k_y}{PGA}\right)^4 + a_6 Ln[PGA] + a_7 Ln[PGV] + \varepsilon\sigma_{LnD} \tag{4}$$

Where $\varepsilon\sigma_{LnD}$ is the standard deviation that varies with k_y/PGA and a_1 through a_7 are empirical coefficients. Rathje and Antonakos (2011) provide modifications to Equation 4 that incorporate the dynamic response of the sliding soil mass into the predication equations.

Effect of Soil Displacement on Embedded Piping

Lateral deformation is generally observed to behave in one of two different mechanisms (O'Rourke and Liu, 2012), which results in either a localized offset, as shown in Figure 1 (after Karamanos et al. (2014)), or in a general region of deformation (after Karamanos et al. (2014)), with larger displacements occurring in the center of the soil mass than at the edges. Strains in piping buried in the soil are computed for the cases corresponding to these two deformation characteristics.

The first condition is evaluated using the methodology developed by Kennedy et al. (1977), as modified by Sarvanis and Karamanos (2016), to estimate the length of piping over which the strains occur. The second condition is evaluated using the methodology described in Karamanos et al. (2014). As discussed in (O'Rourke and Liu, 2012), there is no reliable a priori method to predict the behavior mechanism between localized and distributed behavior. Thus, the maximum strain predicted for the two conditions should be used to evaluate piping fragilities. For the evaluations documented in this paper, the localized deformation case (Figure 1), which combines the effects of both vertical and horizontal deformations, results in the largest strain demands in the piping and the results presented focus on this case only.

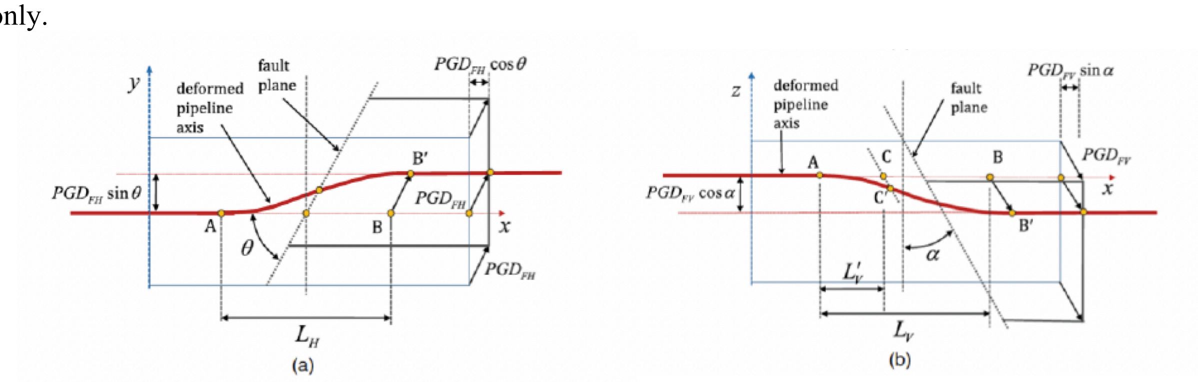


Figure 1. Schematic of Localized Offset Crossing Pipeline: (a) horizontal fault at angle θ (plan view); (b) normal fault at angle α (side view).

Latin Hypercube Sampling

Latin Hypercube Sampling (LHS) is recommended in ASCE 4-16 (2016) for performing probabilistic Soil Structure Interaction (SSI) Analyses. The LHS methodology is adapted for use in representing the aleatory variability incorporated into the soil failure evaluations discussed in this paper.

In the LHS method, the cumulative probability distribution function of each random variable is stratified into N probability bins, in which each bin corresponds to an incremental probability of 1/N. A parameter value is determined for each bin of each random variable. The parameters for a single response simulation are assigned by randomly selecting a value for each of the base parameters, e.g., soil properties, seismic amplification of rock motion, elevation of ground water table, depth to rock of soil profile, variability of analysis methodology, etc. The full set of response simulations is assembled by repeating this sampling process, without replacement, a total of N times until the values in all probability bins are exhausted. The LHS approach has the advantage of being able to capture the parameters defining the probability distribution of the response of interest with fewer simulations than the Monte Carlo method.

The probabilities associated with each bin are developed using midpoint LHS, Voss (1996), as Equation 5,

$$P_{Bin\ I} = \frac{I-0.5}{N} \tag{5}$$

where I is the bin number and $N = 31$ is the total number of bins.

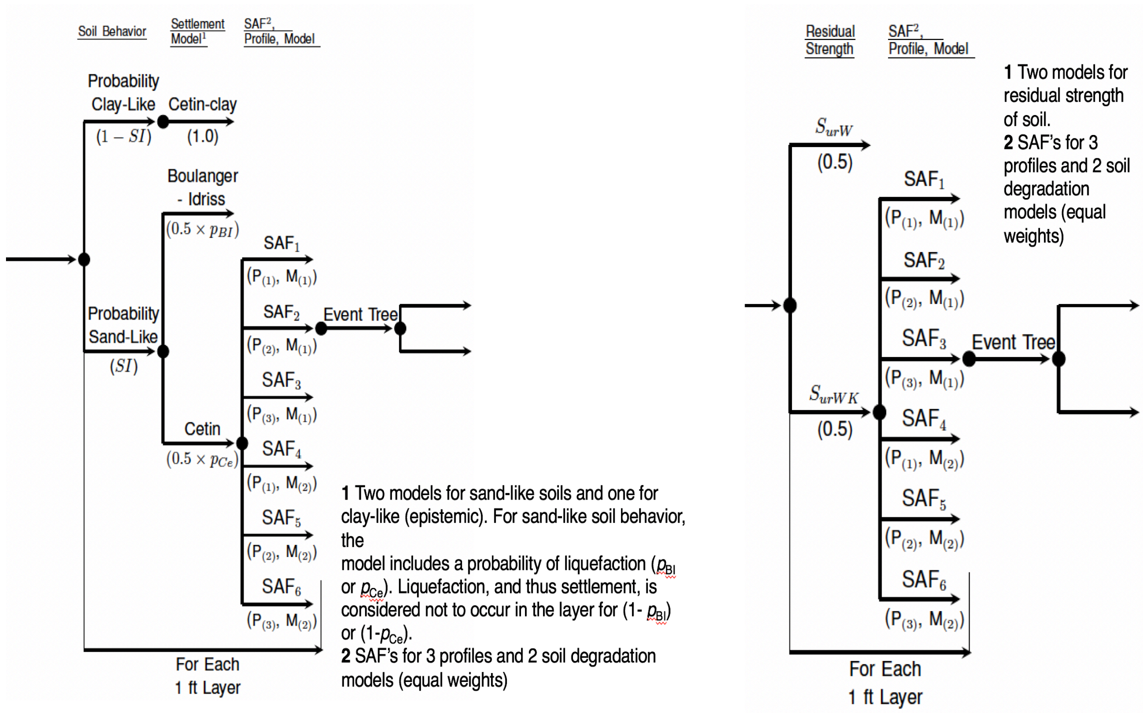
Aleatory random variables are evaluated using LHS within an event tree while epistemic uncertainty are evaluated using logic trees discussed in the following section.

Soil Movement Estimates Logic and Event Trees

Probabilistic estimates of earthquake-induced soil movements at a NPP site are used in a seismic probabilistic risk assessment (SPRA). In these evaluations, epistemic and aleatory variability are considered.

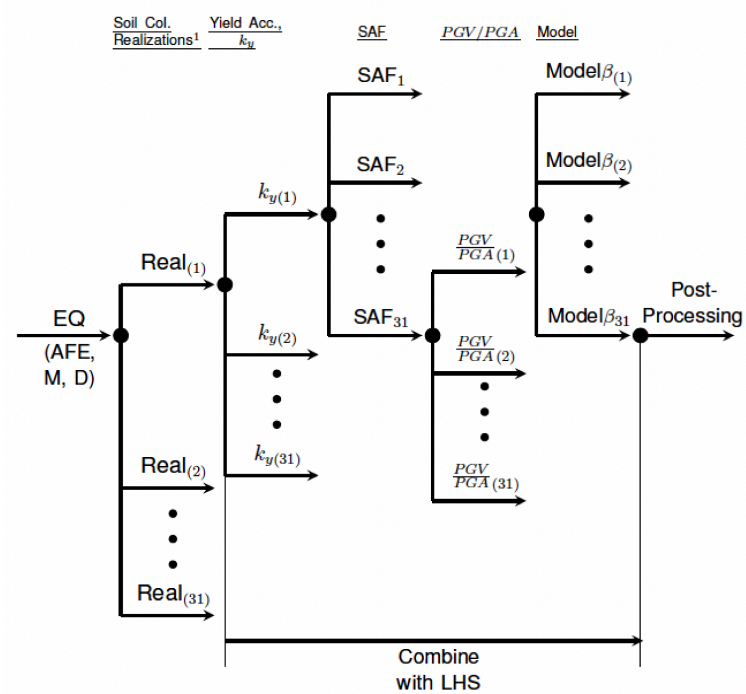
Epistemic uncertainty includes multiple site amplification functions considering varying base case profiles and degradation models (G/G_{max} and damping), the soil behavior models and residual strength models. Aleatory variability includes the deaggregation of the rock motion into Magnitude and Distance Bins, model uncertainty (e.g. variability of the prediction equations for settlement, residual strength (k_y), and lateral spreading), and uncertainty in the site amplification functions (SAF and PGV/PGA).

Logic trees are shown in Figure 2 for settlement and lateral spreading. These figures show, schematically, the process used to incorporate the epistemic uncertainty into the evaluation process. An event tree for lateral spreading is shown in Figure 3. A logic tree similar to Figure 3 can be developed for settlement using parameters associated with settlement in lieu of those associated with lateral spreading. Aleatory variability is represented using a LHS approach while epistemic uncertainty is included as weighted branches in the logic trees.



a) b)

Figure 2. Logic Tree to Consider Uncertainty for Soil Settlement (a) and Lateral Spreading (b).



1 31 soil column realizations are assembled using Latin Hypercube Sampling (LHS) method

Figure 3. Event Tree To Consider Parameter Variability (aleatory)

RESULTS

Using the methodologies discussed in the paper, and the LHS approach shown schematically in Figures 2 and 3, 961 estimates of vertical settlement and lateral deformation are computed for the NPP site (31 soil profile realizations with 31 seismic amplifications of the rock motion to surface for each realization). Using rank-order statistics, the median and 84th percentile results are computed for each level of ground motion. Figures 4 and 5 show the median and 84th percentile vertical settlement and lateral deformation at the site.

Using the settlement results in Figures 4 and 5, soil strains in the embedded piping due to localized soil deformation were computed for two conditions: 1) the soil dropping away from the piping (Vertical down) and 2) the embedded piping being pulled upward through the soil (Vertical up). Figure 6 shows median strain levels at which the strain crosses the 5% threshold and where the 84th percentile strain value crosses the 2% threshold. Interpolation in log-log space between the adjacent computed values yields 1.73g for the 5% median strain value (A_m). Similarly, interpolation of the 84th percentile strain value at 2% strain value yields 0.32g (HCLPF) (EPRI NP-6041-SL, 1991). Using the relationship, HCLPF=A_m x Exp[-2.3β], results in a β value on acceleration of 0.73. These values of median capacity and β are used in the SPRA to evaluate failure probabilities for the NPP.

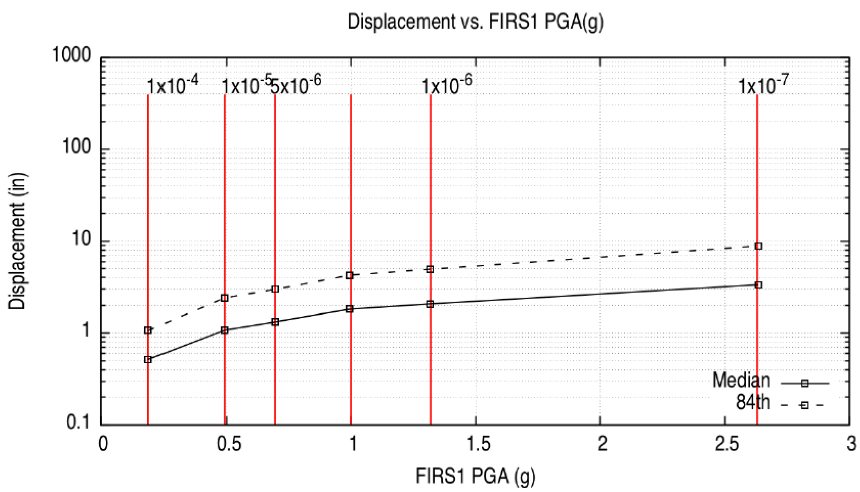


Figure 4. Median and 84th Percentile Liquefaction-Induced Vertical Settlement Estimates at a NPP Site.

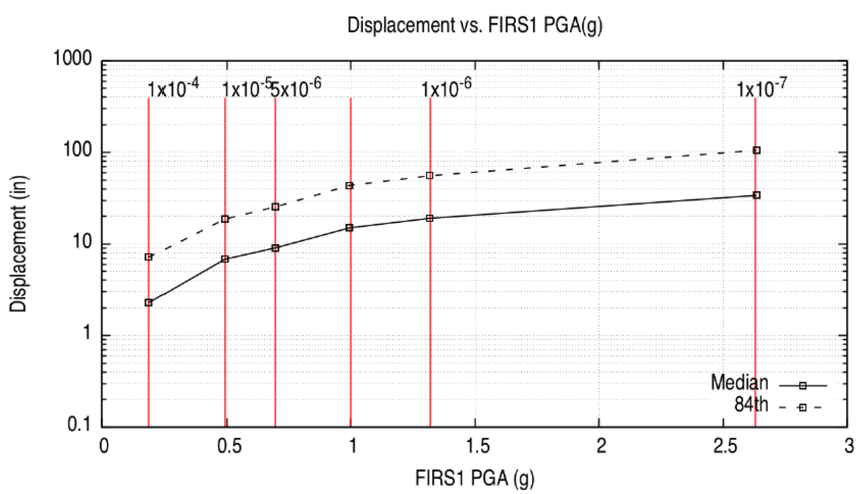


Figure 5. Median and 84th Percentile Liquefaction-Induced Lateral Deformation Estimates at a NPP Site.

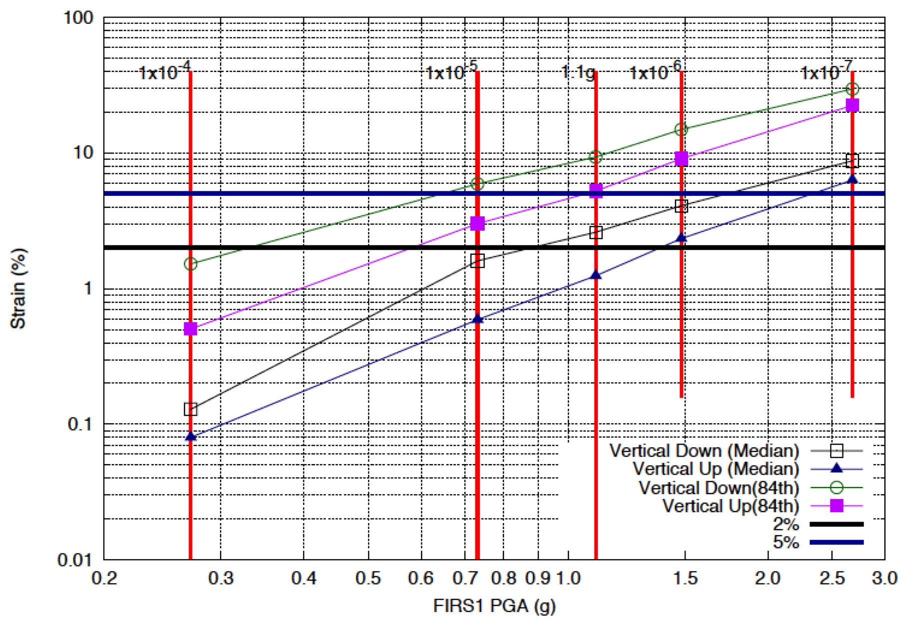


Figure 6. Median and 84th Percentile Liquefaction-Induced Strains in Buried Piping at a NPP Site.

CONCLUSIONS

This paper describes an evaluation methodology that implements Logic Tree methodologies and Latin Hypercube Sampling (LHS) to incorporate uncertainty and variability, respectively, in the development of estimates of the soil-related failure modes important to typical NPP SSCs. This approach leads to results that are directly incorporable into a performance-based design or evaluation. A buried piping example is provided that demonstrates the implementation of the methodology.

As no industry standard is available for use in evaluating liquefaction-induced soil failures and their resulting consequences, the analyses methodologies used to develop fragilities for soil deformation are selected based on the recommendations of the National Academies of Sciences, Engineering, and Medicine (2016). Major sources of uncertainty explicitly considered in these analyse include: 1) variation due to the analysis methodology (model uncertainty); 2) site response variability which influences surface acceleration amplitude; 3) variability of soil properties not captured by site response; 4) variability of soil profile depth. It is judged that variabilities associated with the sources not explicitly considered, such as variability of soil properties not captured within samples taken at existing boring locations, are small compared to sources of variability explicitly considered. By incorporating the significant uncertainties, median and 84th percentile estimates of soil movement and the resulting strain and ground acceleration levels in embedded piping can be developed for use in a SPRA.

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