Evaluation of probabilistic seismic FRS including soil-structure interaction effects

Ghiocel, D.M., Wilson, P.R., Stevenson, J.D.
Stevenson & Associates Inc., Ohio, U.S.A.

ABSTRACT: The paper presents some results and issues related to the evaluation of the probabilistic Floor Response Spectra (FRS) for a Seismic Probabilistic Risk Assessment (SPRA) study of a Nuclear Power Plant (NPP) in the Eastern U.S. The SPRA study followed the current practice of the Individual Plant Examination for External Events (IPEEE) program on-going in the U.S. Some limitations of the current IPEEE practice are discussed.

1. INTRODUCTION

A SPRA study of a nuclear power plant requires a sequence of three main evaluation steps: (i) the definition of seismic hazard at the site, (ii) the computation of structure and equipment fragilities and (iii) finally the fault tree analyses of dominant accident sequences leading to core damage. These evaluation steps include large uncertainties generated by the lack of statistical information and the use of simplified mathematical models due to time and budget constraints. Often, the modeling uncertainties are dominant in comparison with the randomness. This situation shows that more funds are needed to obtain a real progress in the accuracy of SPRA studies. Herein the focus is on the step (ii), namely on the computation of probabilistic FRS used for the equipment fragility evaluation.

The major buildings on the NPP site were analyzed. Herein only some results related to the Reactor Building (RB) and Auxiliary Building (AB) are presented. The probabilistic seismic SSI methodology and the probabilistic models used for seismic excitation and soil deposit are described. Some simplifications typical to IPEEE practice were introduced. The most important is related to the seismic input spectral shape variability effect which is introduced directly at the response level (Chen et al., 1991). Monte Carlo simulation was employed to include the random variability of the soil deposit stiffness. Both the low strain shear modulus variation and its dependency with the shear strain were considered random quantities. For other different parameters the random effects on the probabilistic structural response were based on recommended values provided by the SPRA methodology guidelines (Reed and Kennedy, 1994).

The computed FRS for the RB and AB were compared. The results show that the soil stiffness, i.e. shear modulus, random variability affects significantly the FRS of the RB and less significantly the FRS of the AB. Herein it is shown that the use of the SPRA
current rule "median response for median input" leads to unrealistic sharp spectral peaks and valleys in the median FRS especially when the SSI effects are significant.

2. PROBABILISTIC SEISMIC SSI METHODOLOGY

Using Monte Carlo simulation, seismic SSI analyses were repeatedly performed for a sampling set of the random parameters. A set of 20 "calibrated" trials, similar to the hypercube sampling technique, was considered representative to capture the global response random variability due to soil stiffness variations and to determine consistent estimates of the coefficients of variation. Random variability effects of other different parameters were included directly at the response level using the lognormal format and the values recommended by Reed and Kennedy, 1994, for generic situations. It should be noted that the use of the Monte Carlo simulation appropriately includes the nonlinearities due to the material behavior, soil or structure, and/or the frequency dependent nature of structural response (viewed as a superposition of several natural modal responses with different frequencies). The relationship between spectral amplitudes and the input soil or structure stiffness parameters is heavily nonlinear near the resonant frequencies which are of primary interest. Figure 1 explains schematically the nonlinear relationship between resonant spectral amplitudes and soil stiffness. This nonlinearity influences both the median and the coefficient of variation of Floor Response Spectra (FRS). The use of deterministic SSI models to evaluate the median FRS may introduce unrealistic high spectral peaks. Using Monte Carlo sampling appropriate statistical estimations of FRS (including median ones) and also structural forces and moments were computed including the resonant response-stiffness nonlinearity relationship.

The probabilistic seismic SSI analyses were performed using the original 2D stick models developed by the designer. These stick models are considered to model accurately the dynamic behavior of structures up to a frequency of around 33 Hz.

For the above mentioned buildings, the seismic SSI analyses were performed using the complex frequency approach via the FLUSH finite element code (Lysmer et al., 1976). Seismic torsional and 3D effects were incorporated in the probabilistic analyses by introducing additional randomness and uncertainty factors. The effect of incoherence motion was included by frequency dependent reduction factors based on the recommended values provided by Reed and Kennedy, 1994. More recently, using the Super SASSI code (Ghoicel, 1995) the incoherence motion effect was analyzed using 3D models. The new results obtained have shown that the recommended values were considerably conservative for the soil conditions of the investigated NPP site. Figure 2 shows the 2D SSI model used for the RB. The steam generators and main piping of the primary loop were included in the RB model. Structural damping was 7% for both steel and concrete elements and 5% for equipment and piping systems. For the SSI analyses a cutoff frequency of 30 Hz was considered to be appropriate.

3. PROBABILISTIC MODELS FOR SEISMIC INPUT AND SOIL DEPOSIT

For the purposes of performing a SPRA for the IPEEE, Chen et al., 1991, recommend the use of the median spectral shape of a 10,000 year return period earthquake as
provided by the NUREG/CR-5250, along with random variability effect estimates. The median Uniform Hazard Spectrum (UHS) at the site was considered. The randomness and uncertainty variabilities were directly introduced at the structural response level in accordance with previous SPRA practice for the IPEEE. The statistical UHS curves defined for the NPP site are shown in Figure 3. For the median UHS curve the maximum spectral amplitude is reached at 25 Hz. Above this frequency the median response decays slowly up to 50 Hz, where the ZPGA of 0.10g was defined. For fragility evaluations a median reference earthquake four times larger than the median UHS earthquake with a ZPGA of 0.40g was defined.

Following the current SPRA practice, the random variability of the seismic excitation spectral shape is included in the probabilistic SSI analysis directly at the response level. The spectral shape effects on the FRS were considered to be lognormally distributed being defined by frequency dependent median safety factors and logarithmic standard deviations, $\beta_r$ for randomness, and $\beta_u$, for uncertainty based on the values recommended by Reed and Kennedy, 1994. For the horizontal direction the following values were used:

<table>
<thead>
<tr>
<th>Freq. (Hz)</th>
<th>Median Factor</th>
<th>$\beta_r$</th>
<th>$\beta_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 1$</td>
<td>1.00</td>
<td>0.20</td>
<td>0.32</td>
</tr>
<tr>
<td>5</td>
<td>1.00</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>10</td>
<td>1.00</td>
<td>0.20</td>
<td>0.16</td>
</tr>
<tr>
<td>16</td>
<td>1.00</td>
<td>0.18</td>
<td>0.15</td>
</tr>
<tr>
<td>25</td>
<td>1.00</td>
<td>0.18</td>
<td>0.15</td>
</tr>
<tr>
<td>50</td>
<td>1.00</td>
<td>0.15</td>
<td>0.00</td>
</tr>
</tbody>
</table>

For the vertical direction slightly larger variabilities were assumed. The random variabilities $\beta_r$ and $\beta_u$ were used together with the median UHS shape to completely define the lognormal model of the reference earthquake effects as usually accepted in the SPRA practice. It should be noted that if the set of three UHS curves defined for the NPP site (including 15 and 85 percentiles) are considered, the computed random variability of spectral shape may be considerably higher than those recommended by the guidelines. This remark is valid for several sites of NPP in the Eastern U.S. and thus there is a real necessity to clarify this issue for other future SPRA.

For the characterization of the soil deposit randomness/uncertainty, two basic variabilities were considered for each soil layer: (i) the value of the shear modulus at low strains, $G_\gamma$, for $\gamma = 10^{-4}\%$, and (ii) the shape of normalized shear modulus-shear strain curve, $G(\gamma)/G_\gamma - \gamma$ describing the nonlinear hysteretic soil behavior. The effect of random variability in the soil hysteretic damping is less significant than that in the soil stiffness (and implicitly radiation damping) and therefore it was not considered. The soil shear modulus random variability was determined based on experimental data. For low strains, the lower and upper bounds of soil stiffness variation used for design calculations were 0.40 and 1.60 times the average stiffness (for the longitudinal elasticity modulus, E, the upper bound is 400,000 psi, the lower bound is 100,000 psi and the average value is 250,000 psi). It should be noted that these bounds differ from the generic ones, thus an additional uncertainty random variability had to be included in the probabilistic SSI analysis.
The symmetry of the extreme bounds suggests that a symmetric probability distribution, such as normal distribution is appropriate. It was considered that the extreme bounds correspond to values defined for a 5% exceedance probability. The coefficient of variation of shear modulus was computed as 0.36. For simulation purposes, the normal deviates representing soil shear moduli were restricted to be not less than 0.30 times the mean value (to limit the softness of the soil for transmitting the high frequency components of seismic waves). The sample of 20 simulated low strain shear moduli is plotted in Figure 4. The random variations of shear modulus values with depth were considered to be perfectly correlated, i.e., the soil layers are considered uniformly soft or uniformly hard. This assumption introduces some conservatism in the probabilistic analysis, with the lower and upper bound for soil stiffness corresponding to a smaller exceedance probability than the assumed probability of 5%.

The shape of the normalized shear modulus-strain curve was modeled as an uniform random variable in the range ± 20% around the mean curve (average design curve) as illustrated in Figure 5. For the evaluation of FRP the effects of other parameters than soil and seismic excitation and modeling uncertainties were included directly in the lognormal format used for structural response as follows:

- The ground motion incoherence was included through frequency dependent "conservative" median reduction factors and standard deviations applied to the structural response:

<table>
<thead>
<tr>
<th>Freq. (Hz)</th>
<th>Median Factor</th>
<th>( \beta_t )</th>
<th>( \beta_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>0.90</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>25</td>
<td>0.80</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>50</td>
<td>0.80</td>
<td>0.06</td>
<td>0.08</td>
</tr>
</tbody>
</table>

The above values are recommended by Reed and Kennedy, 1994, for a 150 ft foundation size. Recent evaluations using the Super SASSI program, developed in-house by Stevenson & Associates (Ghiocel, 1995), show that incoherence motion effects may be larger than those considered above as shown in Figure 6. The incoherent amplitude shape of plane shear waves propagating vertically at the soil - basement interface nodes for different frequencies are plotted in Figure 7. It should be noted that for structures with larger mat sizes than the RB and significant mass eccentricities the incoherence effects are more complex than a simple reduction of structural response in the high frequency range. Significant torsional motions may be induced in such cases.

- The 3D effects, including torsion, and earthquake component combination were included by a unity median response factor and logarithmic standard deviations, \( \beta_t \) and \( \beta_u \), equal to 0.10.

- The random variations and modeling uncertainties for SSI system such as wave propagation (incidence angle and composition), soil layering and nonhomogeneity, foundation flexibility, structure-soil-structure interaction, PGA direction, 2D vs. 3D SSI effects and soil hysteretic behavior based on limited experimental data (mentioned in the previous section) were introduced by an unity median factor and \( \beta_t \) and \( \beta_u \), equal to 0.10 and 0.15, respectively.
The random variation and modeling uncertainties for the structural system such as mass, damping and stiffness were modeled through an unity median factor and $\beta$, and $\beta_u$, equal to 0.15 and 0.10, respectively.

The randomness and uncertainty in the soil effective stiffness and damping due to the Seed-Idrisss equivalent linear model were included by an unity median factor and an additional $\beta_v$ equal to 0.10.

The favorable kinematic SSI effects due to embedment were included using the values provided by Shieh et al., 1985. For the Reactor Building (variable embedment between 23 and 46 ft) a median factor of 0.80 and logarithmic standard deviations, $\beta$, and $\beta_v$, of 0.10 were considered. For other structures a median of 0.90 and logarithmic standard deviation of 0.10 were considered.

For the total floor structural shear forces and bending moments used for structural fragility evaluations slightly reduced random variability effects were considered (Ghiocel, Wilson and Stevenson, 1995).

4. COMPUTED FLOOR RESPONSE SPECTRA (FRS)

Simulated FRSSs computed for 20 random sampled soil stiffnesses (Figure 8) at selected elevations in different buildings are shown in Figures 9 through 13. Simulated FRS for the Reactor Building, at the top of the Containment Shell (Elevation 163.0 ft), top of the Internal Structure (Elevation 87.5 ft) and Basemat (Elevation 8.5 ft) are shown in Figures 9 through 11. Simulated FRS for the Auxiliary Building at the top (Elevation 117.5 ft) and Basemat (Elevation -15.0 ft) are plotted in Figures 12 and 13. From the computed FRS, it should be noted that the random variation of soil stiffness is more significant for the Reactor Building than for the Auxiliary Building.

Assuming that the probabilistic FRS have lognormal distributions, the logarithmic standard deviation (coefficient of variation) of FRS including the randomness variabilities, $\beta$, and the total variabilities (both randomness and uncertainties), $\beta_v$, are plotted for the Reactor Building (top and basemat elevations) and Auxiliary Building (top elevation) in Figures 14 through 16.

The FRS logarithmic standard deviation, $\beta_v$, is considerably larger for the Reactor Building showing that the randomness in SSI is more important for the FRS in this building than for the FRS in the Auxiliary Building. For the FRS in the Reactor Building at the upper elevations the standard deviation, $\beta_v$, which is frequency dependent, has spectral peaks with large amplitudes, up to 0.62 near the resonant frequency of the fundamental SSI mode. At the resonant frequency exactly, there is a spectral valley in the variation of $\beta$, due to the highly nonlinear functional relationship between the response amplitude and soil stiffness as described earlier (Figure 1). For a frequency of 1.67 Hz, around the resonant frequency, the amplitude-soil stiffness response function approximated from simulation points is shown in Figure 17.

At lower elevations in the Reactor Building, the logarithmic standard deviation drastically decreases, showing that the SSI effects are less significant for the evaluation of the horizontal FRS near the basemat. The random SSI effects are primarily manifested through the rocking motions and less through the horizontal translation of the structure base.
The Median and 85 Percentile FRS for the Reactor Building at the top elevations are plotted in Figures 18 and 19. These FRS were further used for the equipment and non-structural element fragility evaluation.

5. CONCLUDING REMARKS

The paper shows a practical example of the evaluation of probabilistic FRS based on the current recommendations and guidelines for the IPEEE program (Chen et al., 1991, Reed and Kennedy, 1994). Using Monte Carlo simulation some insights on probabilistic FRS statistics are discussed. Two concerns on the current SPRA practice are reported herein:

(i) The use of the median UHS shape together with random variability estimations given in SPRA methodology guidelines may lead to underevaluation of the probabilistic FRS variability (if the seismic hazard is considered appropriately defined by UHS)

(ii) The rule "median response for median input" is not accurate for evaluating FRSs, especially if the SSI effects are significant, due to the nonlinear relationship between the resonant spectral amplitude and soil stiffness. This effect is less significant for structural forces and moments.

Further investigations of these aspects are needed for improving the SPRAs quality.

6. REFERENCES

Chen et al 1991. Procedural and Submittal Guidance for the Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities, Final Report USNRC, NUREG-1407 F.


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Figure 1. Spectral amplitude-soil stiffness nonlinear relationship

Figure 2. Reactor Building SSI model

Figure 3. UHS curves for the NPP site

Figure 4. Simulated low strain shear modulus

Figure 5. Normalized shear modulus-strain curve randomness
Figure 6. Effect of incoherent motion on the FRS within a typical RB

a) Frequency 3.0 Hz  
b) Frequency 10.0 Hz

c) Frequency 15.0 Hz  
d) Frequency 20.0 Hz

Figure 7. Incoherence effect on shear wave amplitude at the RB soil-basemat interface for different frequencies
Figure 8. Simulated shear modulus shear strain curves

Figure 9. Samples of simulated FRS at the top of the Containment Shell

Figure 10. Samples of simulated FRS at the top of the Internat Structure

Figure 11. Samples of simulated FRS at the Base mat

Figure 12. Samples of simulated FRS at the top of the Auxiliary Building

Figure 13. Samples of simulated FRS at the base of the Auxiliary Building
Figure 14. Logarithmic standard deviations, $\beta_t$ and $\beta_e$ for the FRS at the top of the Containment

Figure 15. Logarithmic standard deviations, $\beta_t$ and $\beta_e$ for the FRS at the RB Basemat

Figure 16. Logarithmic standard deviations, $\beta_t$ and $\beta_e$ for the FRS at the top of Internal Structure

Figure 17. Nonlinear response function of spectral amplitude with respect to soil stiffness

Figure 18. Median and 85 Percentile FRS at the top of the Containment

Figure 19. Median and 85 Percentile FRS at the top of the Internal Structure