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NONLINEAR RESPONSE OF A STRUCTURE WITH SIGNIFICANT SOIL-STRUCTURE INTERACTION EFFECTS FOR APPLICATION TO SEISMIC FRAGILITY EVALUATION

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ABSTRACT

An important element of structure seismic fragility evaluation for seismic probabilistic risk assessment is determination of the inelastic energy absorption factor. This factor accounts for a structure's ability to withstand earthquake ground motions in excess of those causing yield through ductile nonlinear response. Methods for determination of the inelastic energy absorption factor have been benchmarked against nonlinear analysis results for fixed-base structures (i.e., structures without significant soil-structure interaction (SSI) effects).

This paper presents a study that investigated nonlinear response of a nuclear structure with significant SSI effects. Nonlinear analyses of an actual nuclear structure founded on soil were performed using a simple nonlinear model. Inelastic energy absorption factors for an ensemble of earthquake acceleration time histories were determined. The method typically used to determine the inelastic energy absorption factor was modified to account for SSI. The modified method obtained a median inelastic energy absorption factor closely matching that obtained by the nonlinear analyses.

INTRODUCTION

EPRI TR-103959 (Electric Power Research Institute, 1994) provides guidance for seismic fragility evaluation of nuclear structures for seismic probabilistic risk assessment (SPRA). An important element of the fragility evaluation procedure is determination of the inelastic energy absorption factor, Fμ, which accounts for a structure's ability to withstand earthquake ground motions in excess of those causing yield through ductile nonlinear response. The Effective Frequency/Effective Damping (EF/ED) Method recommended by EPRI TR-103959 for determination of the inelastic energy absorption factor was benchmarked against nonlinear analysis results for fixed-base structures (i.e., structures without significant soil-structure interaction (SSI) effects).

General guidance on determination of the inelastic energy absorption factor for structures with significant SSI effects is not available. This subject has not been extensively studied. One previous study investigating this subject is documented in Mertz (2002). The objectives of study described below were to investigate how SSI influences structure nonlinear response and to determine if the EF/ED Method can be adapted to account for significant SSI effects.

REPRESENTATIVE STRUCTURE

This study considered a representative structure included in a recent nuclear plant SPRA. The seismic load-resisting system of this structure consists primarily of concrete shear walls and floor diaphragms, with a high bay steel superstructure. Dynamic characteristics of the fixed base structure were obtained by a detailed SAP2000 (Computer & Structures Inc., 2010) finite element model shown in Figure 1. The modes representing overall horizontal response had frequencies of about 5 Hz.

Probabilistic structure seismic response analysis was performed by Latin Hypercube Sampling (LHS) for thirty simulations using computer program CLASSI (Luco and Wong, 1980). Variables in the LHS included the strain-compatible soil profiles, structure stiffness and damping, and the earthquake acceleration time histories. Thirty sets of earthquake acceleration time histories were conditioned to the mean 1.0E-05 uniform hazard spectra (UHS). Figure 2 compares the 5% damped spectra for the time histories in one horizontal direction (excluding horizontal directional variability) with the target UHS. Soil impedances were generated using CLASSI for thirty strain-compatible soil profiles sampled from the probabilistic site response analysis. Median structure stiffness and damping, and associated variabilities were determined following EPRI TR-103959 guidance.

Composite and randomness-only probabilistic in-structure response spectra (ISRS) were generated. The former considers all sources of variability. The latter considers variability only in the earthquake acceleration time histories, with other variables (soil stiffness and damping, structure stiffness and damping) assigned their median values. Figures 3 and 4 show the median composite and randomness-only horizontal ISRS, respectively, at a selected location. The spectral peaks indicated that the fundamental SSI frequency in both directions is about 2.4 Hz. This frequency represents a substantial reduction from the fixed-base frequency of 5 Hz, signifying that SSI effects are significant. The horizontal responses are significantly influenced by horizontal translation and rocking of the foundation on the flexible soil along with some amplification up the height of the structure associated with its flexibility.

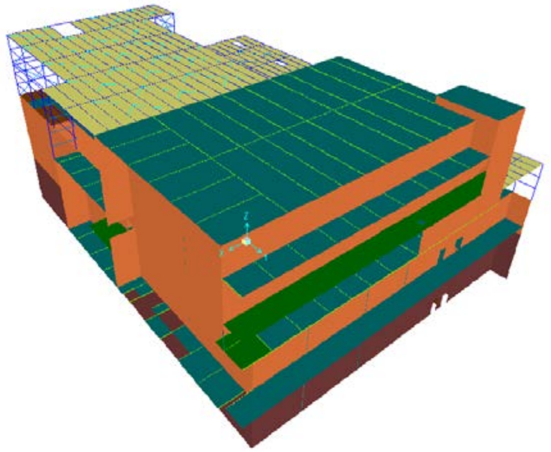

Figure 1. Fixed-base structure finite element model.

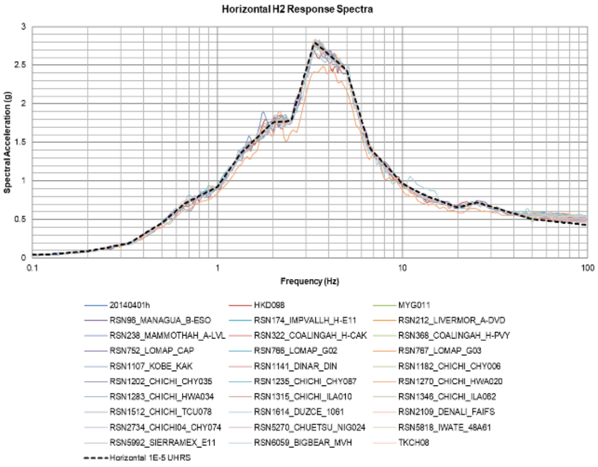

Figure 2. Spectrum-compatible time history response spectra.

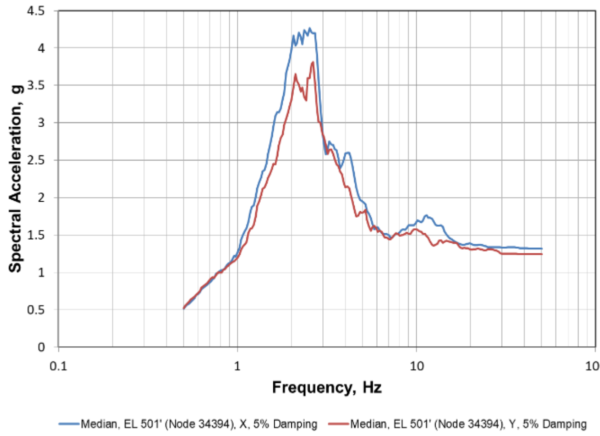

Figure 3. Composite ISRS.

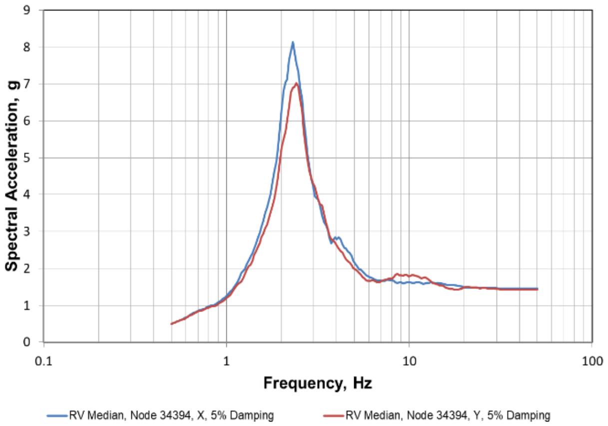

Figure 4. Randomness-only ISRS.

SIMPLE SSI MODEL

A simple two-dimensional SSI model of the representative structure shown in Figure 5 was first developed using computer program SAP2000. Features of the model consisted of the following:

- The foundation was represented by a lumped mass and mass moment of inertia located at the bottom of the structure base mat.

- The structure was represented by a lumped mass and mass moment of inertia located at an effective height about the foundation. Eighty percent of the total structure mass was used to represent the fraction of mass responding in the fundamental SSI mode. The effective height was estimated based upon the ratios of base overturning moments to base shears from the probabilistic response analysis.

- A frame element connecting the foundation and structure masses was used to represent the structure flexibility. The linear shear stiffness of this element was tuned to match the fixed-base structure median frequency of 5 Hz. The element was assigned a very high flexural stiffness so that all deformation is due to shear consistent with the actual structure. Nonlinear properties are described later.

- The soil was modeled by horizontal and rotational soil springs and dashpots attached to the foundation mass. Properties of the springs and dashpots were based on impedances calculated by CLASSI for the median soil properties in the detailed SSI analysis (e.g., randomness-only SSI analysis). The rotational springs and dashpots were modeled as frequency-independent but based on impedance values at the fundamental frequency of 2.4 Hz.

- Additional frame elements were used to determine structure drift between the foundation and structure mass points excluding horizontal translation due to rocking.

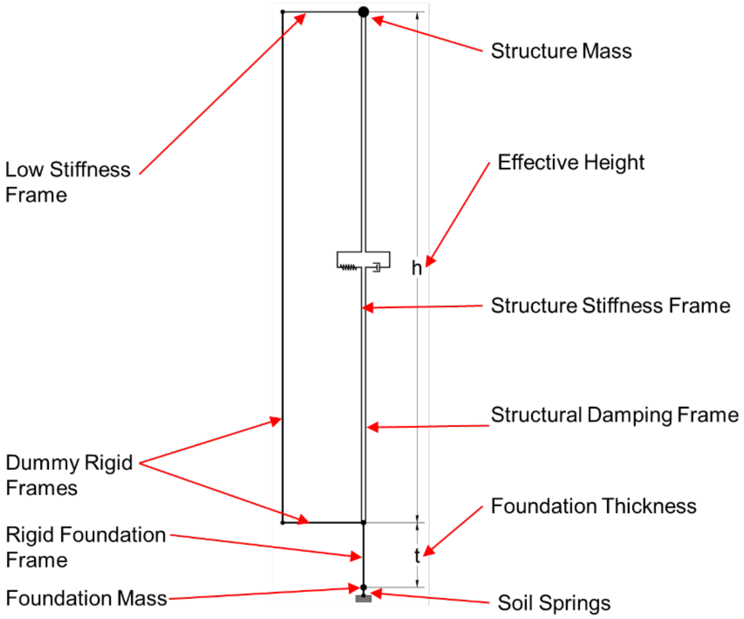

Figure 5. Simple SSI model.

LINEAR VERIFICATION ANALYSIS

Linear analysis was first performed to verify that the simple SSI model adequately replicates seismic response captured by the detailed SSI model. Seven percent damping was assigned to the structure element consistent with the detailed SSI model. Seismic response analysis was performed for the thirty earthquake acceleration time histories in one horizontal direction.

Figures 6 and 7 show the 5% damped ISRS obtained by the simple and the detailed SSI models, respectively. The latter are for a location close in elevation to the structure mass of the simple model. The fundamental SSI frequency, median peak in-structure spectral acceleration, and median structure zero period acceleration obtained by the simple SSI model are reasonably close to values obtained by the detailed SSI model. Table 1 compares median foundation translations, foundation rotations, and structure translations obtained by the two models. Values obtained by the simple SSI model are within about 10% of those obtained by the detailed SSI model. It was concluded that the simple SSI model reasonably replicates the response of the detailed SSI model.

Table 1. Comparison of displacements and rotations.

SSI Model	Fndn. Translation (ft)	Fndn. Rotation (rad)	Structure Translation (ft)
Simple	0.1249	5.251E-04	0.2094
Detailed	0.1142	4.720E-04	0.1872
Difference	9%	11%	12%

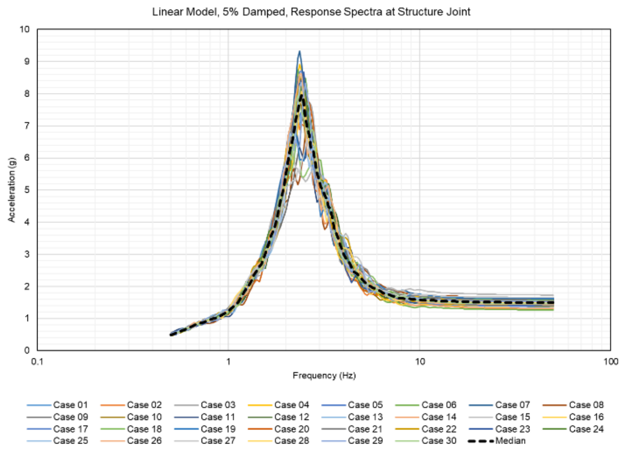

Figure 6. 5% Damped ISRS, simple SSI model.

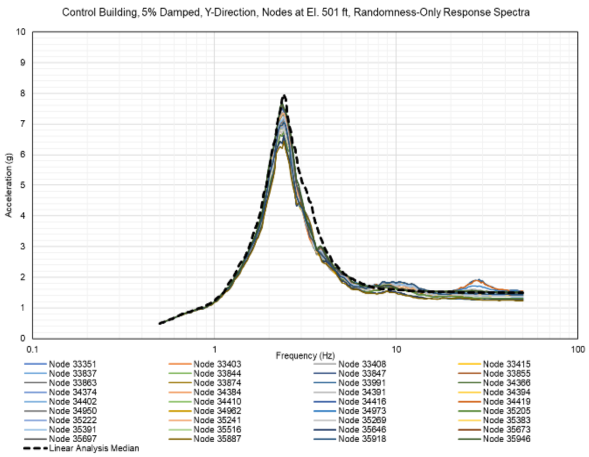

Figure 7. 5% Damped ISRS, detailed SSI model.

NONLINEAR ANALYSIS

The structure element was modified to include nonlinearity representing the hysteretic behavior of a squat reinforced concrete wall. The monotonic yielding behavior of the structure link element was included by defining an elastic-perfectly plastic shear force versus displacement backbone curve. The cyclic loading behaviour included degradation of the unloading and reloading stiffnesses and pinched hysteresis loops. This nonlinear behavior was incorporated using the pivot hysteresis model (Dowell, et al., 1998) available in SAP2000. The pivot model parameters were selected to capture the substantially pinched hysteresis loops characteristic of squat shear critical walls. Figure 8 shows sample hysteresis loops of the structure link element resulting from input motions scaled by factors ranging from 1.0 to 2.0.

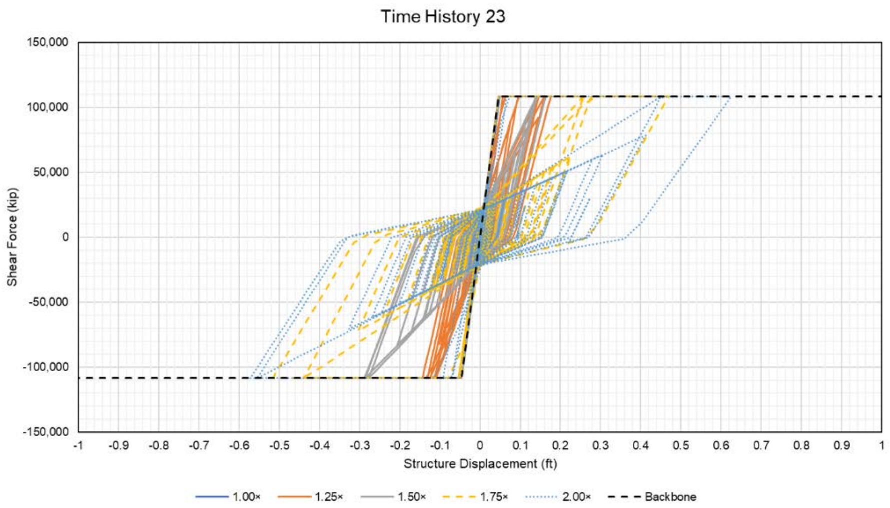

Figure 8. Sample structure hysteresis loops at scaled input motions.

The structure element was assigned 4% damping. This value corresponds to the damping for concrete structures at Response Level 1 permitted by ASCE/SEI 43-18 (American Society of Civil Engineers, 2019). Response Level 1 damping was used to avoid double-counting energy dissipation associated with structure hysteresis.

A different nonlinear model was used for each of the thirty earthquake time histories. For a given time history, the structure yield force was set to the maximum shear force calculated in the linear verification analysis. Each of the thirty structure models yielded when subjected to the unscaled earthquake time history.

Nonlinear analyses were performed for each of the thirty earthquake time histories. Each time history was progressively scaled at factors of 1.0, 1.25, 1.5, etc. The nonlinear shear deformation (excluding structure horizontal translation due to rocking) at each ground motion scale factor was extracted from the analysis.

EPRI TR-103959 recommends that the median shear drift ratio for failure of low-rise concrete shear walls is 0.007, which corresponds to a shear deformation of 0.4424 ft for the structure element of the simple SSI model. For a given earthquake time history, the inelastic energy absorption factor corresponds to the ground motion scale factor at which this shear deformation occurs. Figure 9 shows the probability distribution of inelastic energy absorption factors. The median and lognormal standard deviation were 1.68 and 0.09, respectively. The latter represents variability due only to the earthquake acceleration time histories.

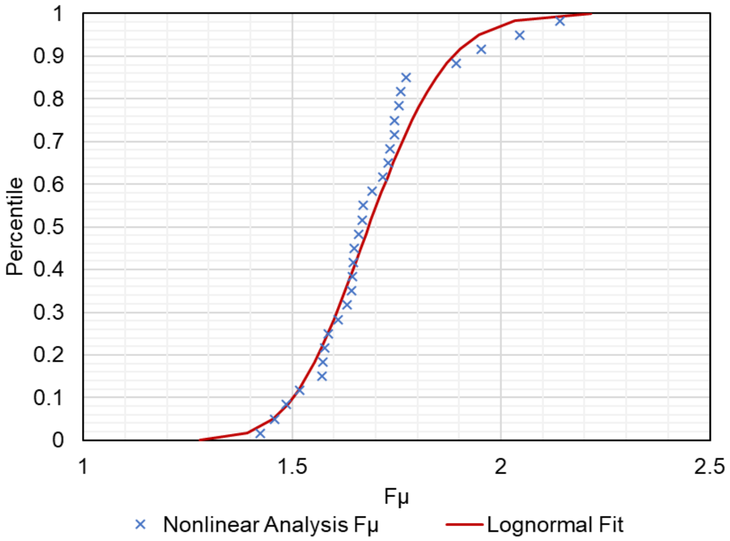

Figure 9. Probability distribution of inelastic energy absorption factors from nonlinear analysis.

MODIFIED EFFECTIVE FREQUENCY / EFFECTIVE DAMPING METHOD

The median inelastic energy absorption factor was then calculated by the EF/ED Method with modifications to account for SSI effects. These modifications included the following:

- The elastic frequency was taken to be the SSI frequency, rather than the fixed-base frequency.

- The damping of the soil-structure system was used instead of the structure damping. The former includes contributions from soil material and radiation damping; CLASSI does not report the damping for the soil-structure system. The soil-structure system damping was consequently back-calculated from the acceleration of the structure mass and the damping-dependent spectral acceleration at the SSI frequency for the given earthquake time history.

- The EF/ED Method uses a mass-weighting approach to determine the system ductility. The system ductility considered displacements of both the structure and foundation mass, rather than just the structure mass alone.

EPRI TR-103959 defines the system ductility, μ_S, as follows:

$$\mu_S = \frac{\sum W_i \Delta_{ui}}{\sum W_i \Delta_{yi}} \tag{1}$$

Where W_i is the weight (or mass) at Floor i, Δ_{yi} is the Displacement at Floor i at initial yield at any location in the structure, and Δ_{ui} is the displacement at Floor i at structure failure.

Table 2 illustrates determination of the system ductility for the Modified EF/ED Method for one simulation.

Table 2. Example system ductility calculation.

Location	W_i (k)	Δ_{yi} (ft)	$W_i\ \Delta_{yi}$ (k-ft)	Δ_{ui} (ft)	$W_i\ \Delta_{ui}$ (k-ft)
Structure	76,950	0.2211	17,010	0.6635	51,060
Foundation	48,300	0.1311	6,332	0.1311	6,332
			23,350		57,390

$$\mu_S = \frac{57{,}390}{23{,}350}$$

$$= 2.46$$

The foundation contributes a significant portion of the total mass. At yielding, the foundation displacement is about 60% of the structure displacement because of soil flexibility. Because the structure force-displacement relationship is modeled as being elastic-perfectly plastic, the foundation displacement does not increase at ground motions greater than yield. The system ductility considering SSI effects is consequently much lower than what would be obtained for a fixed base structure.

Figure 10 shows the probability distribution of inelastic energy absorption factors by the Modified EF/ED Method. The median and lognormal standard deviation are 1.63 and 0.02, respectively.

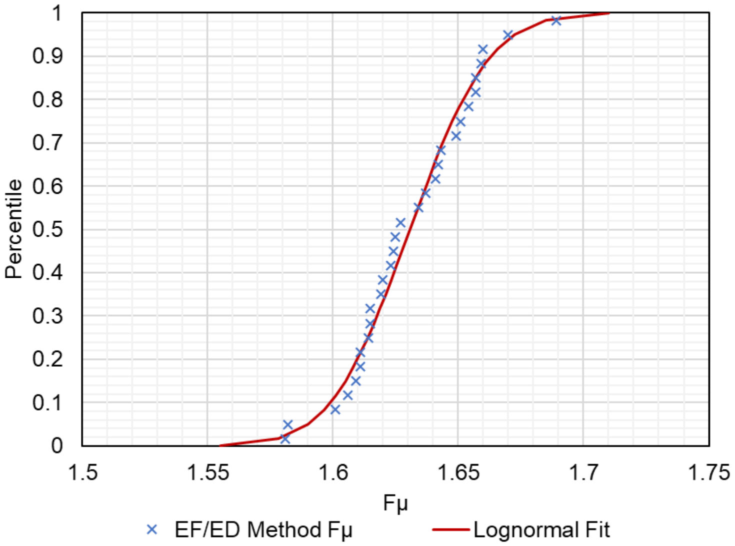

Figure 10. Probability distribution of inelastic energy absorption factors by the modified EF/ED method.

COMPARISON OF INELASTIC ENERGY ABSORPTION FACTORS

Two ratios were used to compare inelastic energy absorption factor obtained by nonlinear analysis, $F\mu_{NL}$, and the inelastic energy absorption factor obtained by the Modified EF/ED Method, $F\mu_{EF/ED}$.

$$R_{F\mu} = F\mu_{EF/ED} / F\mu_{NL} \qquad (2)$$

$$R_{F\mu - 1} = (F\mu_{EF/ED} - 1) / (F\mu_{NL} - 1) \qquad (3)$$

The ratio $R_{F\mu - 1}$ is a better measure of accuracy of the Modified EF/ED Method since it separates out the ground motion level necessary to initiate structure yielding.

Figures 11 and 12 show the probability distributions of the two ratios. Fitting a lognormal distribution of the data, $R_{F\mu}$ has a median and lognormal standard deviation of 0.97 and 0.08, respectively. $R_{F\mu - 1}$ has a median and lognormal standard deviation of 0.94 and 0.20, respectively. Median values for both ratios are slightly less than 1.0, signifying that the Modified EF/ED Method is slightly conservative but provides a reasonable alternative for determining the inelastic energy absorption factor for this representative structure. The variabilities signify that the Modified EF/ED Method has some uncertainty. However, this uncertainty is not considered to be significant from a practical standpoint.

The inelastic energy absorption factor was also calculated by the EF/ED Method using structure fixed-base properties (i.e., fixed-base frequency of 5 Hz and elastic damping of 7%) and ductility. It was determined to be 2.45, which significantly exceeds the median value of 1.68 obtained by nonlinear analysis. This difference signifies the importance of considering SSI effects when determining the inelastic energy absorption factor.

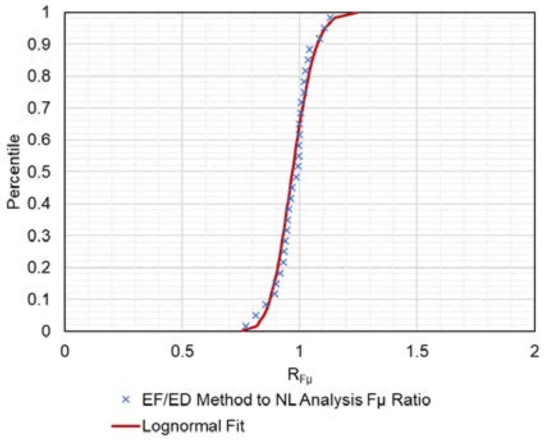

Figure 11. Probability distribution for ratio $R_{F\mu}$.

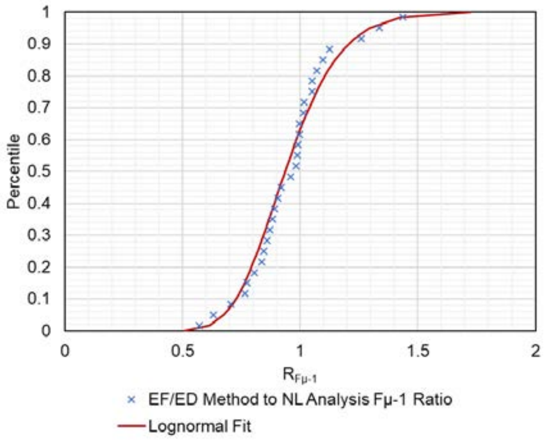

Figure 12. Probability distribution for ratio $R_{F\mu - 1}$.

CONCLUSIONS

Conclusions obtained by this study are summarized as follows:

- SSI effects can significantly influence the inelastic energy absorption factor and should be considered.

- The Modified EF/ED Method accounting for SSI effects obtained a reasonably good match to the inelastic energy absorption factor obtained by nonlinear analysis for this specific application. This method substitutes the frequency and damping for the soil-structure system in place of the fixed base parameters, and the system ductility accounts for the mass and displacement of the foundation.

- Additional analyses should be performed to benchmark the Modified EF/ED Method considering other structure fixed-base frequencies, soil conditions, ground motions, and nonlinear models.

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