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soil-structure interaction effects on containment fragilities and floor response spectra statistics

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1 INTRODUCTION

The probability-based method for the reliability evaluation of nuclear structures developed at Brookhaven National Laboratory (BNL) is extended to include soil-structure interaction effects. A reinforced concrete containment is analyzed in order to investigate the soil-structure interaction effects on: structural fragilities; floor response spectra statistics and acceleration response correlations.

To include the effect of soil flexibility on the reliability assessment the following two step approach is used. In the first step, the lumped parameter method for soil-structure interaction analysis is used together with a stick model representation of the structure in order to obtain the motions of the foundation plate. These motions, which include both translations and rotations of the foundation plate, are expressed in terms of the power-spectral density of the free-field ground excitation and the transfer function of the total acceleration response of the foundation. The second step involves a detailed finite element model of the structure subjected to the interaction motions computed from step one. Making use of the structural model and interaction motion the reliability analysis method yields the limit stat probabilities and fragility data for the structure (Pires, Hwang and Reich, 1985, 1986).

2 SUMMARY OF ANALYSIS METHOD

A frequency domain solution for the equations of motion is used. The solution obtained is the transfer function which relates the translational and rotational responses of the foundation plate to the free-field ground motion. Once the transfer function of the foundation motions is obtained, the cross-spectral density matrix of the foundation accleration response can be obtained in terms of the free-rield ground acceleration. This cross-spectral density matrix is then used as input for a detailed finite element model of the fixed-base structure for the calculation of the structural fragilities (Shinozuka et al., 1984, Pires el al., 1985). For the computation of the floor response spectra statistics the simplified stick model is used. In this manner, the two step approach required for the structural fragility evaluation is not needed for the floor response spectra calculations.

The limit state probabilities and fragilities are evaluated considering the randomness and uncertainties in the earthquake load, structural resistance and soil properties. The earthquake loads are random and modeled as a Gaussian process with an appropriate power spectrum. Uncertainties in the strength of concrete and reinforcement, and in the shear modulus and material damping of the soil are included in the reliability assessment using the Latin hypercube rampling technique. Limit states considered in the study where the flexure limit state and tangential shear limit state, which are described elsewhere in greater detail (Shinozuka, 1984, Pepper, Hwang, and Pires, 1985).

3 PROBLEM DESCRIPTION

The reinforced concrete containment structure consists of a circular cylindrical wall, a hemispherical dome and a circular foundation plate. The containment wall is reinforced with hoop and meridional rebars in two layers, one in the vicinity of the internal surface and the other near the external containment surface (Pires et al., 1985). The concrete uniaxial compressive strength is considered to follow a Gaussian distribution with a mean of 6,085.6 psi and a standard deviation of 650.5 psi. The Young's modulus and Poisson's ratio for the concrete are taken as 3.6×10^6 and 0.20, respectively. For the reinforcing steel a lognormal distribution with a mean of 71,100 psi and a standard deviation of 2,570 psi is considered appropriate. The Young's modulus and poisson's ratio for the steel are 29×10^6 psi and 0.3, respectively.

A three-dimensional finite element model of the containment was constructed using thin shell finite elements. Under the dead load the stresses in the containment were calculated using this model. With that same model the first twenty natural frequencies and mode shapes were determined. The frequencies of the first two pairs of bending modes, the significant modes for the containment response to earthquake are 2.97 cps and 8.82 cps, respectively. To account for cracking of the concrete the stiffnesses of the elements in the containment model are taken to be one half of those of the uncracked sections. For the soil-structure interaction analysis, a simplified model of the containment and internal structures is used. The internal structures are: the drywell, the reactor pedestal and the reactor shield wall. The simplifed structural model is the so--called stick model which consists of beam elements. Included in the model are the masses and rotational inertias of the reactor and sump floor. For the internal structures the uncracked stiffnesses were used.

The soil deposit beneath the structural foundation has been idealized as an homogeneous soil deposit. The mean S and P-waves velocities in the soil are 1,100 ft/sec and 5,700 ft/sec, respectively. A lognormal distribution with a mean of 1.0×10^7 ksf and CoV of 0.7 is used for the shear modulus (Pires, 1985, Bohn et al, 1984). For the hysteretic damping ratio a lognormal distribution with a mean of 0.075 and a CoV 1.0 is considered appropriate. The Poisson's ratio for the soil is 0.45, and the dry and wet unit weight are 138 pcf and 150 pcf, respectively. It is well known that the dynamic stress-strain behavoir of soils is highly nonlinear. Instead of performing nonlinear dynamic analysis for the soil-structure interaction, it has been customary to use one--dimensional wave propagation analysis and an equivalent linearization technique (SHAKE analysis[11]), in order to obtain the soil properties to be used in the soil-structure interaction analysis. For the reliability anaysis this would have to be done for several levels of earthquake intensity since all ground shaking intensities that are likely to occur at the site must be included in the reliability evaluation. Since consideration of nonlinear effects is beyond the scope of this study, only one set of soil properties are used in the analysis. A mean value of the soil stiffness that corresponds to one half of the initial tangent stiffness is chosen, as well as the corresponding mean damping ratio.

The power spectrum consistent with the site-specific response spectrum at the site (Hwang, Pires and Reich 1985) is shown in figure 1. The duration of the earthquake loading was considered to be 20.0 records.

6 STRUCTURAL FRAGILITIES

Fragility curves are defined as a plot of the conditional limit state probability for a peak ground acceleration $A_1=a$. Fragility curves for both the tangential shear and bending limit states were computed with and without consideration of soil-structure interaction effects. As an example, the fragility curves for the tangential shear limit state with and without soil-structure interaction effects are shown in Figure 2. The median and range of the fragility curves shown in Figure 2 are given in Table 1 below. In Table 1 the upper bound corresponds to a probability of failure of 0.937 and the lower bound to a probability of failure 10^{-11}

Table 1. Median and range of tangential shear fragility (in g's)

Condition	Median	Lower Bound	Upper Bound
Fixed-base	1.60	0.57	2.29
Interaction	1.87	0.56	2.75

As can be seen from Figure 2 and Table 1, the soil-structure interaction increases the median of the fragility curve as well as its dispersion as measured by the fragility range. For the bending limit state the effects of soil-structure interaction were similar to those for the tangential shear limit state (Pires et al., 1985).

7 FLOOR RESPONSE SPECTRA

Floor response spectra statistics were computed for the fixed-base and interaction conditions. In particular, the mean floor response spectra.and the coefficients of variation (CoV) of the floor response spectra ordinates have been computed. The mean and CoV floor response spectra and the top of the containment building are shown in Figures 3 and 4 respectively. The floor response spectra for the interaction and fixed-based condition for frequencies above

1.5 cps, the predominant spectral frequency for the interaction condition, are lower than that for the fixed-base. The CoV's of the floor response spectra ordinates for the interaction condition are much larger than those for the fixed-base, especially for frequencies between 1.5 and 3.0 cps which is the range of interaction frequencies for the various Latin hypercube samples. The correlation matrices for the total acceleration response at four locations are shown in Table 2, below.

Table 2. Acceleration response correlation

(a) fixed-base

Location	1	2	6	14
1	1.0	.9921	.3855	-0.09524
2	.9921	1.0	.4779	-0.07749
6	.3855	.4779	1.0	.3651
14	-0.09524	-0.07749	.3651	1.0

(b) interaction

Location	1	2	6	14
1	1.0	.8980	.2468	-.2349
2	.8980	1.0	.5369	-.1583
6	.2468	.5369	1.0	.4753
14	-.2349	-.1583	.4753	1.0

Locations 1 and 2 are at the bottom of the containment cylinder wall, location 6 is at the cylinder wall mid-height, and location 14 at the top of the containment building.

8 CONCLUDING REMARKS

Structural fragilities for reinforced concrete containment obtained with the method show that the soil-structure interaction increases the median and range of the structural fragility. Computation of floor response spectra statistics for the example structure have shown that the mean and coefficient of variation of the floor response spectra ordinates are markedly affected by the interaction effect.

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NOTICE

This work was performed under the auspices of the U.S. Nuclear Regulatory Commission, Washington, D.C. The findings and opinions expressed in this paper are those of the authors, and do not necessarily reflect the views of the U.S. Nuclear Regulatory Commission or Brookhaven National Laboratory.

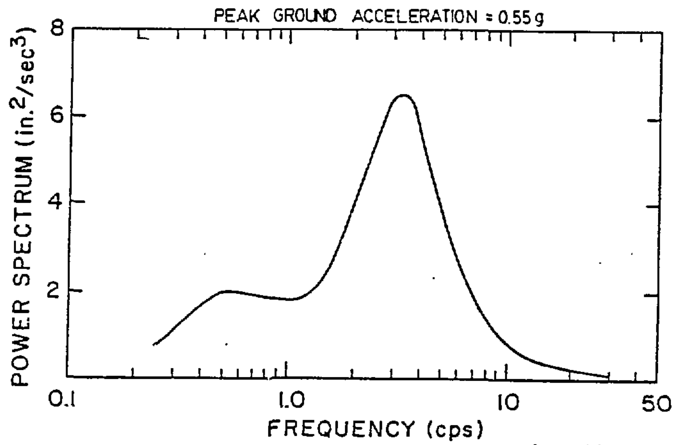

Figure 1 Power Spectrum for the free-field Acceleration

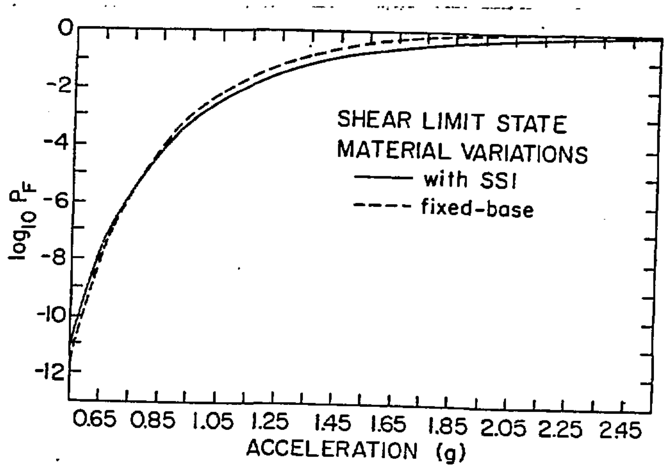

Figure 2 Structural Fragility Curve

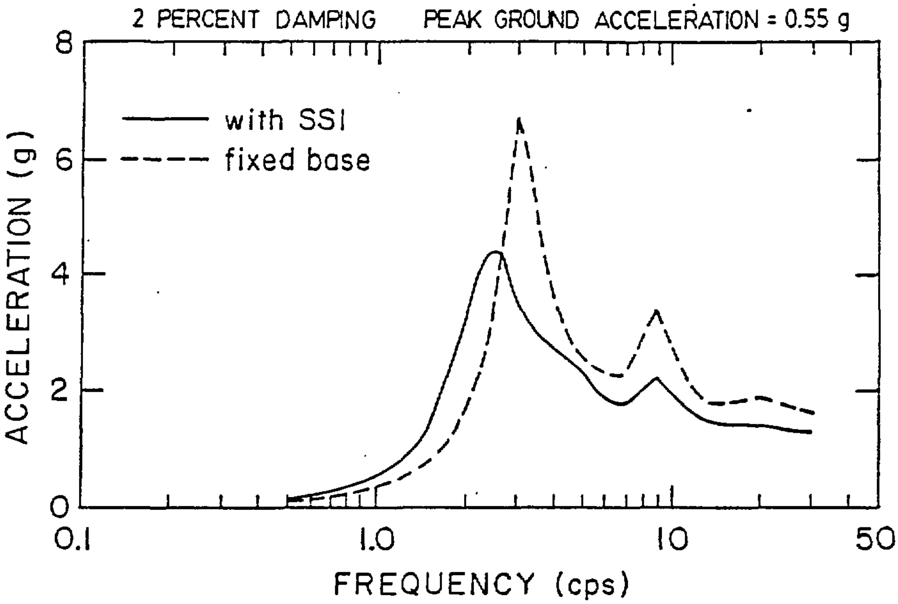

Figure 3 Mean Floor Response Spectrum

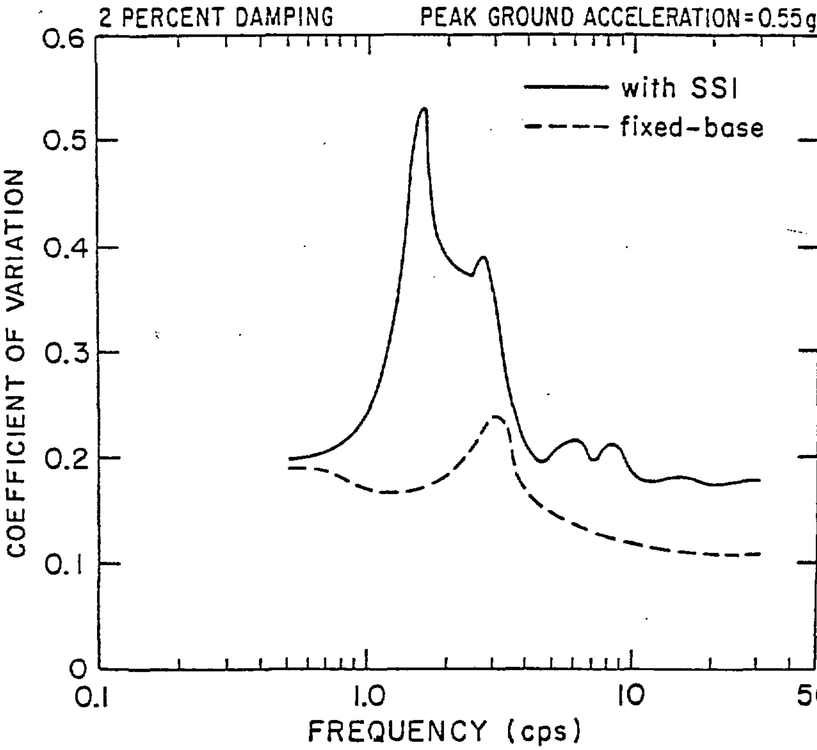

Figure 4 Coefficient of Variation of Floor Response Spectra