Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Comparison of design and probabilistic analyses of nuclear power plants

Maslenikov, O.R. [1], Johnson, J.J. [1], Campbell, R.D. [2]
1) EQE International, San Francisco, U.S.A.
2) EQE International, Irvine, U.S.A.

ABSTRACT

A study was made to evaluate the margin of conservatism introduced into design in-structure response spectra by following standard design analysis procedures according to the U.S. Nuclear Regulatory Commission (NRC) Standard Review Plan and Regulatory Guides by comparing spectra produced by such a design analysis to response from median-centered probabilistic analyses. Three typical nuclear plant structures were studied: a PWR reactor building, a PWR auxiliary building, and a BWR reactor building. Each building was assumed to be situated on three idealized sites: a rock site, a medium soil site, and a soft soil site. All buildings were assumed to have embedded foundations. The PWR reactor building was also assumed to have a surface foundation. Each design analysis was performed in accordance with the current SRP criteria. Each probabilistic analysis consisted of 30 earthquake simulations for which the free-field motions and soil and structural properties were varied; the simulated earthquakes were generated such that their mean-plus-one-standard-deviation free-field spectra approximated the Regulatory Guite (RG) 1.60 design spectra. In-structure response spectra from the design analyses were compared with the 84% non-exceedance probability (NEP) spectra from the probabilistic analyses. The comparisons showed that the design method produced conservative results for all cases. The smallest margin was about 10 percent for buildings on rock sites. Softer sites had larger margins of conservatism; the reactor buildings on the soft soil site had margins of as much as 100% (factors of 2). The shorter structures and lower locations in all buildings had smaller margins. The margin of conservatism for the surface founded reactor building was about 20% more than for the embedded reactor building.

1 DESCRIPTION OF ANALYSIS METHODS AND PROCEDURES

The overall technical approach to the analyses used the substructure method of soil-structure interaction (SSI) analysis. The substructure approach is particularly attractive because it separates the SSI problem into a series of simpler problems, solves each independently, and superposes the results. This approach allows one to examine meaningful intermediate results and perform sensitivity studies in a cost-effective fashion. The elements of the substructure approach as applied to structures subjected to earthquake excitations are: specifying the free-field ground motion; developing the soil models (i.e., defining the soil profile and performing site response analysis); calculating the impedance functions and foundation input motion; determining the fixed-base dynamic characteristics of the structure; and performing the SSI analysis (i.e. combining the previous steps to calculate the response of the coupled soil-structure system).

1 *Design Analyses*

The design analyses were performed with the intent that they contain the features of typical design analyses performed in the industry according to the criteria specified in the U.S. NRC Standard Review Plan (U.S. NRC 1989). The free-field design response spectra were defined according to U.S. NRC RG 1.60. The horizontal spectra were anchored to a peak ground acceleration of 0.2g. The free-field motions were synthetic time histories generated such that they satisfy the criteria of the SRP including enveloping the design spectra, meeting the PSD requirement and demonstrating statistical independence. The control point location for the free-field motion was at the ground surface. The response spectra of motion at the basemat level in the free-field was shown to envelope 60% of the design spectrum. SSI analyses were performed for three soil property cases. The first case used best estimate properties based on one-dimensional free-field analyses. The other two cases used strain-dependent properties obtained from free-field analyses of low-strain soil profiles whose shear moduli varied from the best estimate values by factors of 2.0 and 0.5. Modal damping ratios for the structures generally conformed to those specified in RG 1.61 for SSE level excitation. In-structure response spectra at selected locations were obtained from each analysis. Envelope spectra for the three soil property variations were then obtained. The envelope spectra were then broadened 15% to account for uncertainties in structural properties.

2 *Probabilistic Analyses*

The probabilistic analysis procedures were based on the SMACS methodology developed for the Seismic Safety Margins Research Program (Johnson et al. 1981) and have been applied in the past to the seismic probabilistic risk assessments of a number of nuclear power plants. The method consists of performing a number of earthquake simulations, varying input parameters for each simulation according to an experimental design, to obtain building and subsystem response. The seismic input motion was comprised of a set of 30 synthetic earthquake free-field ground surface motions, each consisting of three components (two horizontals and a vertical). For each component, the corresponding 30 time histories were generated such that their mean-plus-one-standard-deviation spectral values approximately matched the RG 1.60 design spectra in the frequency range from 0.1 to 33.0 Hz. The variation of the spectral values was about the same as that of the earthquake data that formed the basis for RG 1.60. Probability distributions were assumed for key soil and structural parameters, including soil shear modulus, soil material damping ratio, and modal frequencies and damping ratios of the structure. Lognormal distributions were assumed; they are completely defined by their lognormal means and standard deviations. The mean values to which the distributions were anchored were the best estimates of the parameters identified above which were used for the design analyses. The lognormal coefficients of variation corresponded to those used for the SSMRP Phase 1 study (Johnson et al. 1981); for soil shear modulus the COV was 0.35; for soil damping ratio it was 0.50; for building frequencies it was 0.25; and for building damping ratios it was 0.35. Repeated SSI analyses were then performed for the 30 earthquake simulations. For each simulation, variations of the key parameters were randomly selected based on the Latin Hypercube stratified sampling technique. This sampling method divides each probability distribution into a number of equally probable ranges, the number being equal to the number of simulations. For each simulation, a probability range is randomly selected, with exclusion, for each parameter distribution and a value is randomly selected from that range. In this way, the entire probability space was efficiently spanned by a much smaller the number of simulations than it would for a Monte Carlo simulation. For each of the repeated earthquake simulations, response spectra were calculated at selected locations in the structures. On completion of the repeated simulations, the median and 84% NEP values were calculated. The 84% NEP spectra were then compared with the results from the corresponding design analyses.

2 DISCUSSION OF ANALYSES

Comparative studies were made for three typical nuclear plant structures using data from previous analyses of actual plants. The structures that were selected were a PWR reactor building, an auxiliary building complex and a BWR reactor building. Each structure was analyzed for three different site conditions with idealized properties for uniform halfspaces with different shear wave velocities (V_S): a soft soil site (V_S = 500 ft/sec); a medium soil site (V_S = 1000 ft/sec); and a rock site (V_S = 3500 ft/sec). All buildings were embedded to soil depths of from 36 feet to 50 feet. For the studies, full embedment was assumed for all buildings. Additionally, the PWR reactor building was analyzed assuming it was situated on a halfspace truncated at the bottom of the basemat. Thus, both the design and probabilistic analyses were performed for each of 12 structure/site configurations.

Uniform best estimate high-strain soil properties were assumed for the three site conditions described above. For the two soil cases, one-dimensional free-field analyses were performed to back-fit uniform upper and lower bound high-strain properties for the design analyses that were consistent with the procedures specified in the SRP.

Table 1: Site Condition Cases for Analyses

Analysis	Rock Site		Medium Soil Site		Soft Soil Site	
	S-Wave Velocity	Damping Ratio	S-Wave Velocity	Damping Ratio	S-Wave Velocity	Damping Ratio
Best Estimate	3500 fps	1 %	1000 fps	7 %	500 fps	11 %
Design Upper Bound	-na-	-na-	1620 fps	5 %	820 fps	8 %
Design Lower Bound	-na-	-na-	680 fps	10 %	280 fps	15 %
Probabilistic COV's	0.0	0.0	0.35	0.50	0.35	0.50

The building models (Figures 1 to 3) were fixed-base models obtained from previous work. The PWR reactor and auxiliary building models consisted of beam and shell finite elements and contained considerable detail (the reactor building model included the NSSS piping system). The BWR reactor building model was a lumped mass beam model, more typical of the type used in industry.

The impedance and scattering functions were either generated using simplified methods or were obtained from previous studies; for all cases uniform soil profiles having best estimate properties were used. The PWR reactor building foundation was modeled as an embedded cylinder of radius 78 feet and embedment of 36 feet; The BWR reactor building foundation model was 149 feet square, embedded 50 feet; and the auxiliary building foundation model was simplified from a T-shape to a rectangular shape (452 feet X 243 feet) embedded 42 feet. Variations of properties for both the design and probabilistic analyses were made using the SMACS methodology (Johnson et al. 1981).

The spectra from the design analyses were enveloped over the best estimate, upper and lower bound soil cases and then broadened by +/-15% per the SRP. These were then compared with the median and 84% NEP spectra from the probabilistic analyses to assess the degree of conservatism.

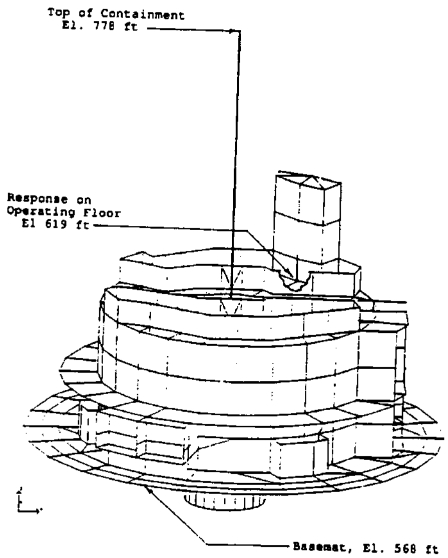

Figure 1: Isometric View of Model of PWR Reactor Building Showing Response Locations

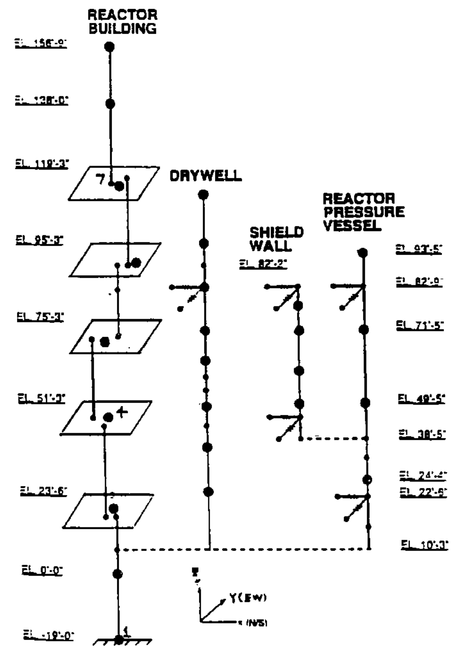

Figure 2: Sketch of Model of BWR Reactor Building Showing Response Locations

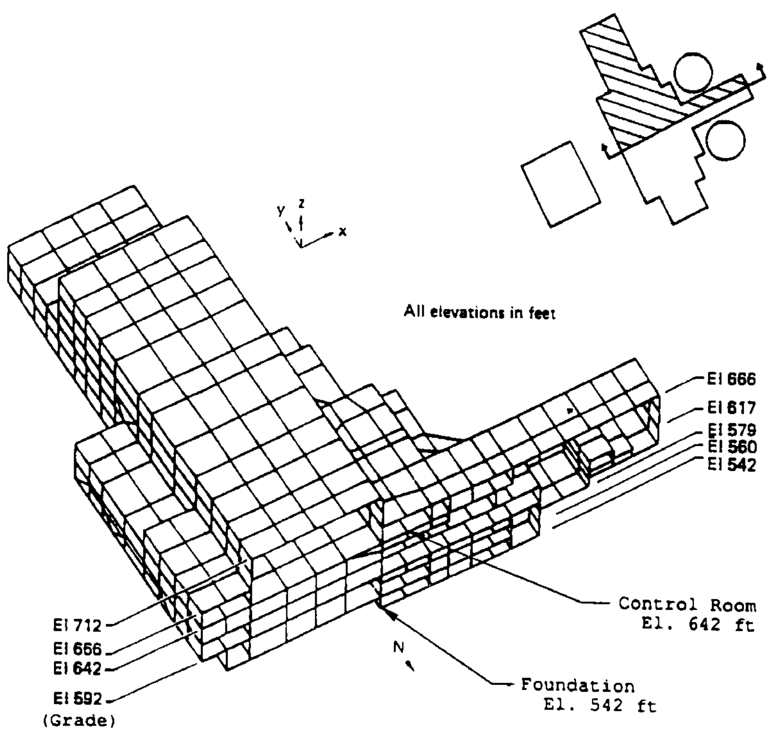

Figure 3: Isometric View of Half-model of PWR Auxiliary Building Showing Response Locations

3 RESULTS AND CONCLUSIONS

Comparisons of the results of the design and probabilistic analyses show that the design procedure generally produced results that were from 10% above the probabilistic results to over twice their values. Figures 4 and 5 show typical examples of results. The general trends observed were the following: for structures on rock sites, the design results tended to be less conservative than for the soil sites. Generally, the softer the site, the greater the conservatism. For locations higher in the structures, the design results tended to be more conservative, varying from factors of about 1.1 to 2.0. For taller, more flexible structures, design results tended to be more conservative. The relatively short, squat auxiliary building was less conservative than either of the reactor buildings. Modeling the PWR reactor building on a flat foundation produced design results that were somewhat more conservative (on the order of 20%) than for the embedded foundation.

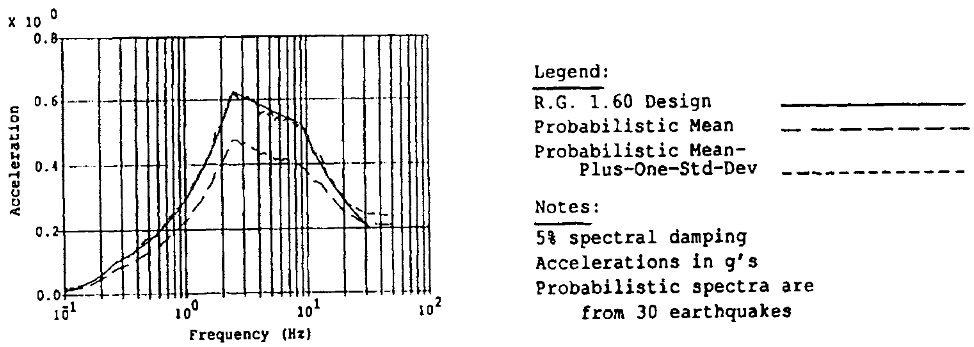

Figure 4: Spectra of Free-field Motions Used for Probabilistic Analyses

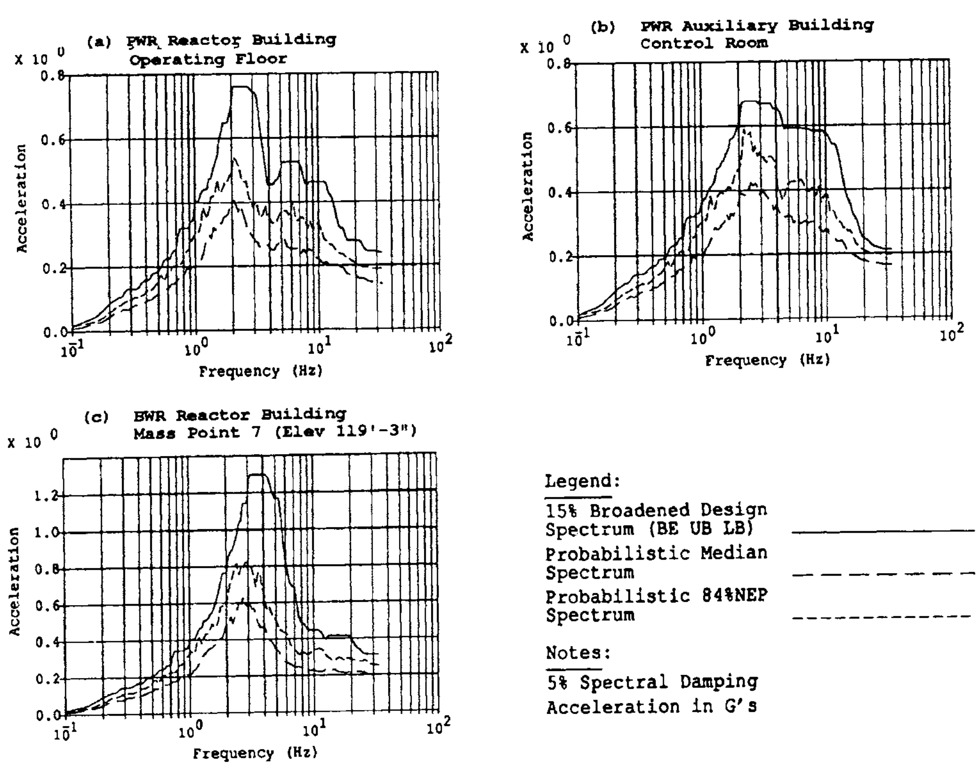

Figure 5: Comparison of In-structure Response Spectra, Medium Soil Site

Based on the observations of the results it appears that the current SRP design procedure produces responses that are conservative relative to 84% NEP responses produced by probabilistic methods. The conservatism appears to be least for rock sites and to increase for softer sites. It also appears to increase for higher elevations in the structures; short, squat structures show less conservatism than taller, more flexible structures. For tall structures on soft sites, the design responses can be as much twice the 84% NEP values. When compared with median probabilistic response, the design procedure increases by another 20% to 50%.

The effect of modeling the PWR reactor building with a flat foundation on a truncated soil profile was to increase the conservatism of the design method by about 20%.

It has been shown that there are varying amounts of conservatism in the development of in-structure response spectra, but in all cases studied, the design spectra were conservative relative to the 84th percentile spectra. The comparison of the 84th percentile spectra to the design spectra is a good measure of the conservatism in design methods of performing structural response analysis and developing in-structure spectra. The comparison of the 50th percentile spectra to design spectra is a measure of the conservatism of the entire process of conservatively specifying the SSE as a mean-plus-one-standard-deviation spectrum and propagating the ground motion through the structure to develop in-structure response spectra.

4 REFERENCES

Johnson, J. J., G. L. Goudreau, S. E. Bumpus and O. R. Maslenikov. September 1981. "Seismic Safety Margins Research Program Phase I Final Report: SMACS - Seismic Methodology Analysis Chain with Statistics (Project VIII)." Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53021, NUREG/CR-2015, Vol 9.

U. S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation. 1989. "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, LWR Edition." NUREG-0800 (formerly NUREG-75/087). Revision 2.

Technical Core Group of First of a Kind Engineering Task E-1, D.F. Landers, Chmn. April 16, 1993. "TCG Report on FOAKE Task E-1: ASME Piping for Advanced Reactor Corporation." Appendix M: Structural Response Margins.