Effects of Reduced Stiffness on Plant Risk and Margin

Roger M. KENNEALLY
U. S. Nuclear Regulatory Commission, Washington,DC USA
Michael P. BOHN, Eric W. KLAMERUS
Sandia National Laboratories, Albuquerque, NM USA

ABSTRACT

Test results sponsored by the USNRC have shown that reinforced concrete shear wall structures may exhibit reduced stiffness and natural frequencies from those calculated in the design process. An evaluation of the effects of the reduced frequencies on several existing seismic PRAs is being performed in order to determine the seismic risk implications inherent in these test results. Also, design-type deterministic calculations of plant response will be made to assess the potential impact of the frequency reduction issue on the design of structures and on the floor spectra used in the equipment qualification process.

1 INTRODUCTION

Since 1983, the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research has been sponsoring the Seismic Category I Structures Program at the Los Alamos National Laboratory (LANL). This program is investigating the static and dynamic response of Category I reinforced concrete shear wall structures (exclusive of containments) subjected to seismic loads beyond their design basis (Endebrock, et al. 1985; Dove and Bennett, 1986; Dove, et al. 1987; Bennett, et al. 1987a, 1987b, 1988; Farrar, et al. 1989, 1990a,). From early tests, measured stiffnesses were found to be as low as 25% of the computed values. Later tests, felt to be more reliable, found measured stiffnesses in the range of 75% to 100% of the computed stiffness. In all tests, when the structures were subjected to increasing shear stress levels, either static or dynamic loads simulating earthquakes, measured stiffnesses and frequencies further decreased.

Differences between calculated and measured stiffnesses and frequencies represents a potentially important issue in the design and safety of nuclear power plants. Safety related equipment is located in structures which typically have predicted fixed base natural frequencies in the 5 Hz to 20 Hz range. Most broad band strong motion earthquake time histories have the majority of their energy in the 2 Hz to 8 Hz range. If the frequency reduction was as large as 50%, then these structures could have actual frequencies in the 2 Hz to 10 Hz range. Both the loads experienced by the structural members and in-structure floor acceleration spectra could be much greater than considered in the original design. Also, safety related equipment could experience greater seismic loads due to a shift in the floor spectra near the equipment natural frequency.

In 1988, the NRC funded Sandia National Laboratories to assess the importance of this "frequency difference" issue. The program is assessing the impact of decreased natural frequencies on both the calculated seismic risk and the deterministic design calculations for several prototypical

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power plants. This paper describes the program's scope and current status.

2 SCOPE OF THE SEISMIC PRA EVALUATION

The general approach chosen to assess the potential impact of the "frequency reduction" issue on power plant risk is as follows:

Step 1:	Choose existing seismic PRAs as base cases.
Step 2:	Re-compute structure response with reduced fixed-base natural frequencies using best-estimate SSI calculations.
Step 3:	Re-evaluate capacity of structures with new median loads and uncertainty distributions.
Step 4:	Re-compute floor spectra for critical components (both median and uncertainty distributions).
Step 5:	Re-evaluate critical component fragilities.
Step 6:	Compute accident sequence probabilities with new structure and component fragilities and compare with original PRA results.

Step 1. Three existing seismic PRAs were selected. The first, Peach Bottom, is a rock site Boiling Water Reactor (BWR). The second, Arkansas Nuclear One Unit-1, is a rock site Pressurized Water Reactor (PWR). The third, Zion, is a soil site PWR.

Step 2. Fixed base models used in the design of important structures are coupled with best estimate soil models. Ten time histories matching the original design spectra are selected and a complete dynamic analysis is performed. This includes variations in structure and soil properties, and in the reduced building natural frequencies. The results are: ten values (each) of story shears, slab accelerations and ten floor spectra for each floor. From these, medians and uncertainties of spectral acceleration at each floor level can be inferred.

Step 3. The acceleration to failure is determined for each shear wall and governing walls are identified. Median loads and uncertainty distributions must be included to accurately determine the median and uncertainty of acceleration at structural failure.

Step 4. The floor spectra are recomputed for each floor containing critical components using the model and results from Step 2. The spectral acceleration (Sa) at a given frequency for a specified floor elevation can be determined. When "Sa" is plotted at various safe shutdown earthquake (SSE) levels or peak ground accelerations (PGA), an almost linear representation can usually be fit to correlate the PGA with the spectral acceleration. If a linear fit is not adequate, a polynomial equation can be used to relate "Sa" to PGA.

Step 5. The original seismic PRA fragility derivations will be used, but modified to account for the new floor spectra (Step 4). If the building natural frequency is reduced into the critical frequency range for a component the dynamic loading could be considerably increased. Similarly, some components may remain unchanged or experience even smaller dynamic loads.

Step 6. The dominant accident sequences are re-evaluated using failure frequencies derived from the new fragility estimates (Steps 3 and 5). Uncertainty distributions for each accident sequence and for the total core damage frequency are generated. Comparisons of accident sequence frequencies and core damage frequency (and their distributions) with the original seismic PRA results will be made.

3 SCOPE OF THE DETERMINISTIC "DESIGN CALCULATION" EVALUATION

The effect of the structural frequency reduction on deterministic seismic design will be assessed using the following steps:

Step 1.	Identify time histories, damping, and rules and parameters used in the design.
Step 2.	Calculate floor slab accelerations, floor spectra and net wall loads with <u>no</u> stiffness reduction (SSE level only).
Step 3.	Repeat Step 2 with reduced stiffnesses and compare results.

4 ANALYTICAL MODEL

The amount of stiffness reduction to be used is based on LANL data and the results presented by Professor Meta Sozen (University of Illinois) to the ASCE Working Group on Stiffness of Concrete Shear Wall Structures (Lopez, 1989). From all these results, the stiffness reduction model using an initial reduction of 25% (75% of the original analytical stiffness) was chosen to be used until first cracking. After cracking, based on LANL data, the stiffness was chosen to be 50% of the analytical stiffness. Cracking usually occurred at a shear stress of about 150 psi. At higher stress levels the stiffness continued to decrease until major crushing of the concrete occurred.

The stiffness reduction model is shown in Fig. 1. This model does represent one computational complication. Since the amount of stiffness is not constant with increasing shear stress levels, one must iterate until a reduced stiffness produces a shear stress consistent with the model. However, in the analyses performed thus far, convergence usually occurs after only a few iterations.

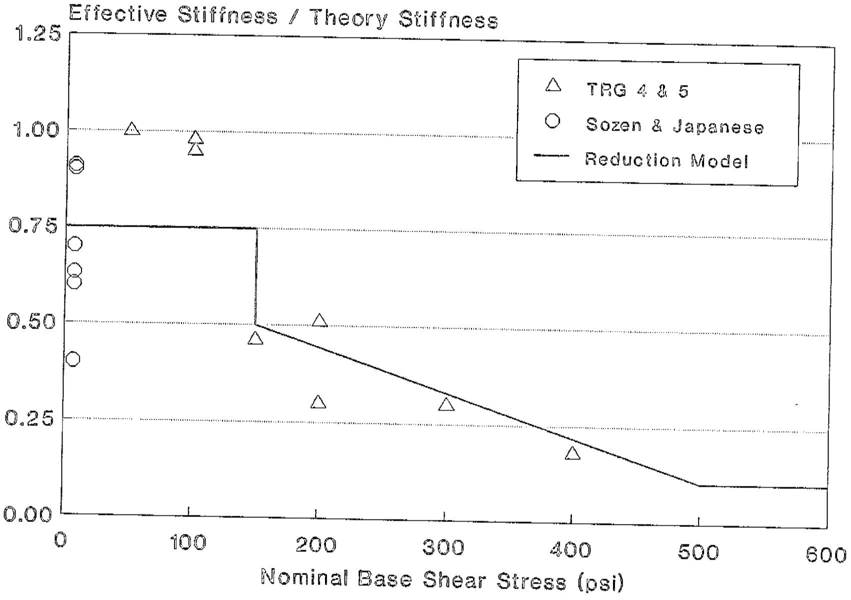


Figure 1. Stiffness Reduction Model With Experimental Test Data.

5 RESULTS

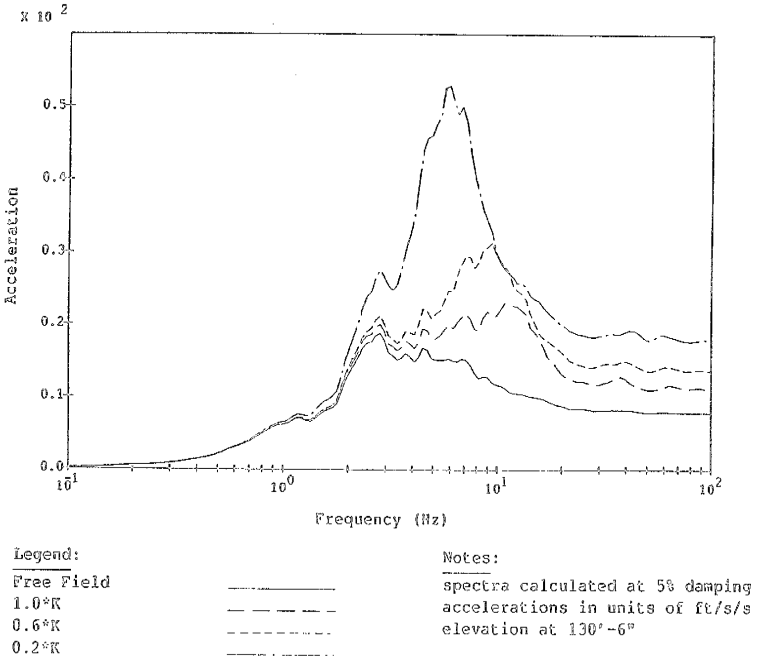
5.1 Peach Bottom Atomic Power Station

A re-evaluation of the original PRA was performed with a preliminary model in which stiffness reduction was a function of PGA, for the critical concrete structures as reported in Bohn, 1989. The stiffness reduction model shown in Fig. 1 was not used.

Peach Bottom is a rock site BWR, the seismic PRA was part of the NRC sponsored NUREG-1150 program (Lambright, 1990). The design basis earthquake level is 0.12g. The seismic hazard curves applied for the PRA were developed by the NRC sponsored Eastern U.S. Seismic Hazard Characterization Program by LLNL (Bernreuter, et al. 1989). A suite of 10 recorded earthquake time histories (chosen to match the site conditions) were used as input for the analysis. Other than building response changes, the re-evaluation of risk follows the original seismic PRA.

The five buildings re-evaluated using the reduced stiffness model were: the Radwaste/Turbine Building, the Diesel Generator Building, Circulating

Water Pump House (Crib House), Emergency Cooling Tower Structure, and Reactor Building. The Crib House and Emergency Cooling Towers showed the most increase in floor responses. For example, the Crib House showed a substantial increase in the 5-10 Hz range for reduced stiffness, as shown in Fig. 2. This is primarily the result of decreasing the natural frequency of the structures (from approxomately 13 - 20 Hz) down into the 6 - 9 Hz range where the ground motion is much higher. These two structures house the three Emergency Service Water pumps and Emergency Cooling Water pumps. Without these pumps, the diesel generators will fail, and in the likely event there ia loss of off-site power during an earthquake, this could result in a station blackout.



Notes:
spectra calculated at 5% damping
accelerations in units of ft/s/s
elevation at 130'-6"

Figure 2. Peach Bottom Crib House Response Spectra for Various Levels of Stiffness Reduction.

When all the accident sequences were re-evaluated using new building responses, the mean core damage frequency was found to increase from 7.66E-05 to 1.24E-04 per year, a 60% increase. Therefore, the inclusion of reductions in stiffness have significantly increased the computed total core damage frequency.

In addition, an evaluation of "design-like" structural dynamic calculations with and without the stiffness reductions was made. In many cases, in-structure floor spectra were significantly amplified due to the stiffness reduction, and spectral peaks were also shifted down. Calculated net wall loads and moments were increased by up to 30% for the safety related structures.

5.2 Arkansas Nuclear One Unit 1 (ANO-1)

ANO-1 is a rock site PWR. The basemats of all safety related structures are embedded in Pennsylvania McAlester formation shale. Soil properties such as shear modulus and damping were included; however, due to the stiff nature of the soil only a single nominal soil shear modulus was used in the analysis. The design basis earthquake level is 0.20g. The seismic PRA was part of the USNRC sponsored Task Action Plan (TAP) A-45, which only evaluated the decay heat removal (DHR) systems (Cramond, et al. 1987). In this preliminary study only the DHR system seismic PRA will be re-evaluated using reduced stiffnesses in the concrete structures for comparison with the original TAP A-45 results.

Other than building response changes at ANO-1, the re-evaluation of risk follows the original seismic PRA. The seismic hazard curves were those developed by LLNL for the EUS hazards program. Instead of running ten time histories, as was performed in the original PRA, one time history was used in this preliminary re-evaluation.

The Auxiliary and Reactor buildings were modeled in TAP A-45 and that is the only models which were available to re-compute responses using reduced stiffnesses. However, most critical safety related equipment is located in the Auxiliary building, such as the 4KV and 480V buses and emergency turbine drive pumps.

The Auxiliary building is a four story concrete structure. The original fixed-base fundamental frequency was 10.7 Hz. After the structural stiffness was reduced and run through an earthquake time history at the SSE level (0.20g) and a relatively stiff soil base was included, the fundamental frequency of the Auxiliary building dropped to 8.5 Hz. When the model was run at the 3 SSE level (0.60g) and stiffnesses were reduced further, the fundamental frequency dropped to 6.5 Hz.

The Reactor building consists of both an internal structure and an outer containment shell, both are reinforced concrete and are connected only at the foundation. When performing analysis, both must be considered together. The original fixed base fundamental frequency of the internal structure was 9.9 Hz. After the structural stiffness was reduced and run through an earthquake time history at the SSE level (0.20g) and a soil base was included, the fundamental frequency of the internal structure dropped to 8.0 Hz. When the model was run at the 3 SSE level (0.60g) and stiffnesses were reduced further, the fundamental frequency dropped to 6.7 Hz.

When all the accident sequences were re-evaluated using new building responses the mean core damage frequency was found to increase from 8.19E-05 to 8.76E-05 per year, a 7 percent increase. The main reason this increase is so small is due to a very early failure of the 4KV and 480V buses, which are governing most of the core damage probability. Loss of these cabinets will lead directly to station blackout. These cabinets were not adequately anchored down when the original PRA was done and failure was assumed to occur due to sliding and had a median probability of failure of 0.324g. Even though the floor response increased significantly where these cabinets were located, the probability of them failing was already very high and could not increase much further.

If the cabinets were well anchored and failure of the buses was governed by another cause such as relay chatter, the median failure would be about 4.0g. Re-running the accident sequences for this new median failure of the buses,results in a core damage frequency of 4.80E-06 per year with no stiffness reduction. This is significantly lower than the 8.19E-05 computed before, but is believable since the main cause of core damage was reduced by increasing the fragility of the buses considerably. However, the core damage frequency is 8.75E-06 per year when stiffness reduction is considered, an 80 percent increase from using original stiffnesses with the same median bus failure of 4.0g. These cabinets are all located on an upper floor in the Auxiliary building and are sensitive to the 5-10 Hz range, which was shown to increase substantially. Therefore, the inclusion of reductions in stiffness could significantly increase the total core damage frequency estimate.

6 CONCLUSIONS

This paper has presented the project scope and preliminary re-evaluations of core damage frequency for Peach Bottom and Arkansas Nuclear One - Unit 1 (ANO-1). A net increase of approximately 60 percent in core damage frequency was computed for Peach Bottom, and as much as an 80 percent increase is possible at ANO-1. The preliminary results have shown that the stiffness reductions can play a very significant result in the overall risk at the plant. Further, it is shown that these risk increases are likely to be somewhat site specific, and dependent on the presence of structures whose original stiffness is such that further reductions in stiffness reduces their lower natural frequencies down into the amplified acceleration region of the input ground motion.

The final evaluations will be made using the stiffness reduction model shown in Figure 1. Also, recent estimates of the ground motion in the Eastern U.S. will be studied. These estimates typically show less amplified motion in the lower frequency (below 10 Hz) compared to motion used in the preliminary evaluation. The recent ground motion estimates are likely to indicate a much smaller impact on the core damage frequency than that obtained in the initial evaluation.

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