Site-Specific Seismic Site Response Model for the Waste Treatment Plant, Hanford, Washington

A.C. Rohay and S.P. Reidel
Pacific Northwest National Laboratory
P.O. Box 999, Richland, Washington 99352
U.S.A.

ABSTRACT

The seismic design basis for the Waste Treatment Plant (WTP) at the Department of Energy's Hanford Site near Richland, Washington, was established in 1999 based on an extensive probabilistic seismic hazard analysis completed in 1996 by Geomatrix Consultants, Inc. In subsequent years, the Defense Nuclear Facilities Safety Board (DNFSB) staff questioned the some of the assumptions used in developing the seismic design basis, particularly the adequacy of the site geotechnical surveys. Existing site-specific shear wave velocity data were considered insufficient to reliably use California earthquake response data to directly predict ground motions at the Hanford Site. To address this concern, the Department of Energy's Office of River Protection (ORP) and Pacific Northwest National Laboratory (PNNL) developed and executed a plan for acquiring site-specific soil data down to approximately 500 feet, and for reanalyzing the effects of deeper layers of sediments interbedded with basalt.

New geophysical data were acquired, analyzed, and interpreted with respect to existing geologic information gathered from other Hanford-related projects in the WTP area. Existing data from deep boreholes were assembled and interpreted to produce a model of the deeper rock layers consisting of interlayered basalts and sedimentary interbeds. These data were analyzed statistically to determine the variability of seismic velocities. The earthquake ground motion response was simulated on a large number of models resulting from a weighted logic tree approach that addressed the geologic and geophysical uncertainties. Weights in the logic tree were chosen by a working group based on the strength or weakness of the available data for each combination of logic tree parameters. Finally, interim design ground motion spectra were developed to envelope the remaining uncertainties.

The results of this study demonstrate that the site-specific soil structure (Hanford and Ringold formations) beneath the WTP is thinner than was assumed in the 1996 Hanford Site-wide model. This thinness produces peaks in the response spectra (relative to those in 1996) near 2 Hz and 5 Hz. The soil geophysical properties, shear wave velocity, and nonlinear response to the earthquake ground motions are known sufficiently, and alternative interpretations consistent with this data did not have a strong influence on the results.

The structure of the upper four basalt flows (Saddle Mountains Basalt), which are interlayered with sedimentary interbeds (Ellensburg Formation), produces strong reductions in the earthquake ground motions that propagate through them to reach the surface. Uncertainty in the strength of velocity contrasts between these basalts and interbeds resulted from an absence of measured

shear wave velocities (Vs) in the interbeds. For this study, Vs in the interbeds was estimated from older, limited compressional wave (Vp) data using estimated ranges for the ratio of the two velocities (Vp/Vs) based on analogues in similar materials. The Vs for the basalts, where Vp/Vs is well defined, still is limited by the quality and quantity of the Vp data. A range of possible Vs for the interbeds and basalts was included in the logic trees that produced additional uncertainty in the resulting response spectra. The uncertainties in these response spectra were enveloped at approximately the 84th percentile (based on the logic tree) to produce conservative design spectra. This conservatism increased the seismic design basis by up to 40% compared to the 1999 values.

Because of the sensitivity of the calculated response spectra to the velocity contrasts between the basalts and interbedded sediments, additional boreholes and direct Vs measurements through these layers are now being planned. The new measurements are expected to reduce the uncertainty in the site response that is caused by the lack of direct knowledge of the Vs contrasts within these layers.

INTRODUCTION

In 1999, the U.S. Department of Energy Office of River Protection (ORP) approved the seismic design basis for the Waste Treatment Plant (WTP) planned for construction in the 200 East Area on the Hanford Site near Richland, Washington. The seismic design is based on an extensive 1996 study by Geomatrix Consultants, Inc. [1]. The Geomatrix study had undergone revalidation reviews by British Nuclear Fuels, Ltd. (BNFL) and independent review by seismologists from the U.S. Army Corps of Engineers and Lawrence Livermore National Laboratory prior to ORP acceptance.

Based on the Geomatrix probabilistic seismic hazard analysis, the seismic design was developed using the methodology described in DOE-STD-1020 [2]. Features include a peak ground acceleration (PGA) of 0.26 g horizontal at 33 Hz and 0.18 g vertical at 50 Hz, with a 2,000-year return period and corresponding site-specific response spectra. These PGA values were adopted from the slightly higher PGA values computed for the 200 West Area—the computed values at the 200 East Area were 0.24 g horizontal and 0.16 g vertical—to provide additional margin. The spectral shape determined for the 200 East Area location was retained and anchored to the higher PGA.

The Defense Nuclear Facilities Safety Board (DNSFB), an independent federal agency established by Congress in 1988, subsequently initiated a review of the seismic design basis of the WTP. In March 2002, the DNFSB staff questioned the assumptions used in developing the seismic design basis, particularly the adequacy of the site geotechnical surveys. These questions were resolved, but in additional meetings and discussions through July 2002, new questions were raised about the local probability of earthquakes and the adequacy of the "attenuation relationships" that describe how ground motion changes as it moves from its source in the earth to the site. The ORP responded in August 2002 with a comprehensive review of the probability of earthquakes and the adequacy of the attenuation relationships. The results of that review resolved most of the DNFSB concerns. In January 2003, a second DNFSB letter stated that one issue still remained—"the Hanford ground motion criteria do not appear to be appropriately conservative" because of large uncertainty in the extrapolation of soil response data from California to the Hanford Site.

Through late 2003 and the first half of 2004, the ORP developed a plan to acquire additional site data and analysis to address the three remaining key aspects of this concern:

- The original 1996 Hanford analysis used California earthquake response data rather than data based on Hanford earthquake response characteristics.
- The physical properties of Hanford soil and rock used in the analysis of response characteristics were broad averages rather than three-dimensional detailed data specific to the WTP site.
- The modeling methods used in 1996 were not consistent with current practice, in particular the randomization of profile velocities.

In response to a specific request in July 2004 for clarification of this plan, the ORP provided a detailed plan in August 2004 to address these remaining concerns. The key features of this plan were acquiring new soil data down to about 500 ft, reanalyzing the effects of deeper layers of sediments interbedded with basalt (down to about 2,000 ft) that may affect the attenuation of earthquakes more than previously assumed, and applying new models for ground motions as a function of magnitude and distance at the Hanford Site.

A PNNL report [3] completed in 2005 documented the collection of site-specific geologic and geophysical characteristics of the WTP site and the modeling of the WTP site-specific ground motion response. New geophysical data were acquired, analyzed, and interpreted with respect to existing geologic information gathered from other Hanford-related projects in the WTP area. Information from deep boreholes was collected and interpreted to produce a realistic model of the deeper rock layers consisting of interlayered basalts and sedimentary interbeds. The earthquake ground motion response was modeled, and a series of sensitivity studies was conducted to address areas in which the geologic and geophysical information has significant remaining uncertainties.

This paper summarizes the PNNL report. The geologic history of the Hanford Site is described first. Next, new and existing data on physical properties are assembled and statistical variability is measured. These data led to construction of a base case model and an extensive series of perturbations that were then used to simulate the earthquake ground motion response at the WTP site. The model and the resulting estimates of response, accounting for uncertainties in the physical data, are finally described.

SUMMARY OF GEOLOGIC SETTING

The Hanford Site lies within the Columbia Basin of Washington State (Figure 1). The Columbia River Basalt Group forms the main structural framework of the area (Figure 2). These rocks have been folded and faulted over the past 17 million years, creating broad structural and topographic basins separated by anticlinal ridges called the Yakima Fold Belt. Sediment of the late Tertiary has accumulated in some of these basins. The Hanford Site lies within one of the larger basins, the Pasco Basin. The Pasco Basin is bounded on the north by the Saddle Mountains and on the south by Rattlesnake Mountain and the Rattlesnake Hills (Figure 1). Yakima Ridge and Umtanum Ridge trend into the basin and subdivide it into a series of anticlinal ridges and synclinal basins. The largest syncline, the Cold Creek syncline, lies between Umtanum Ridge and Yakima Ridge and is the principal structure containing the DOE waste management areas and the WTP.

The site for the WTP is in a sequence of sediments (Figure 2) that overlie the Columbia River Basalt Group on the north limb of the Cold Creek syncline. These sediments include the Miocene to Pliocene Ringold Formation; Pleistocene cataclysmic flood gravels, sands, and silt of the Hanford formation; and Holocene eolian deposits.

The WTP site is underlain by about 4 to 5 km of Columbia River Basalt Group (Figure 2), which overlies accreted terrane rocks and early Tertiary sediment. The Columbia River Basalt Group forms the main bedrock of the Hanford Site and the WTP. The basalt consists of more than 200,000 km^3 of flood-basalt flows that were erupted between 17 and 6 Ma and now cover approximately 230,000 km^2 of eastern Washington and Oregon, and western Idaho. Eruptions have volumes as great as 10,000 km^3, with the greatest amounts being erupted between 16.5 and 14.5 million years before present. These flows are the structural framework of the Columbia Basin, and their distribution pattern reflects the tectonic history of the area over the past 16 million years.

The Columbia River Basalt Group at the WTP site consists of three major formations—the Grande Ronde Basalt, Wanapum Basalt, and Saddle Mountains Basalt. The Grande Ronde Basalt and Wanapum Basalt are thick sequences of lava flows stacked one upon another with no significant sedimentary layer between. The Saddle Mountains Basalt erupted over a significantly longer time, and sediments of the Ellensburg Formation were able to accumulate between basalt layers.

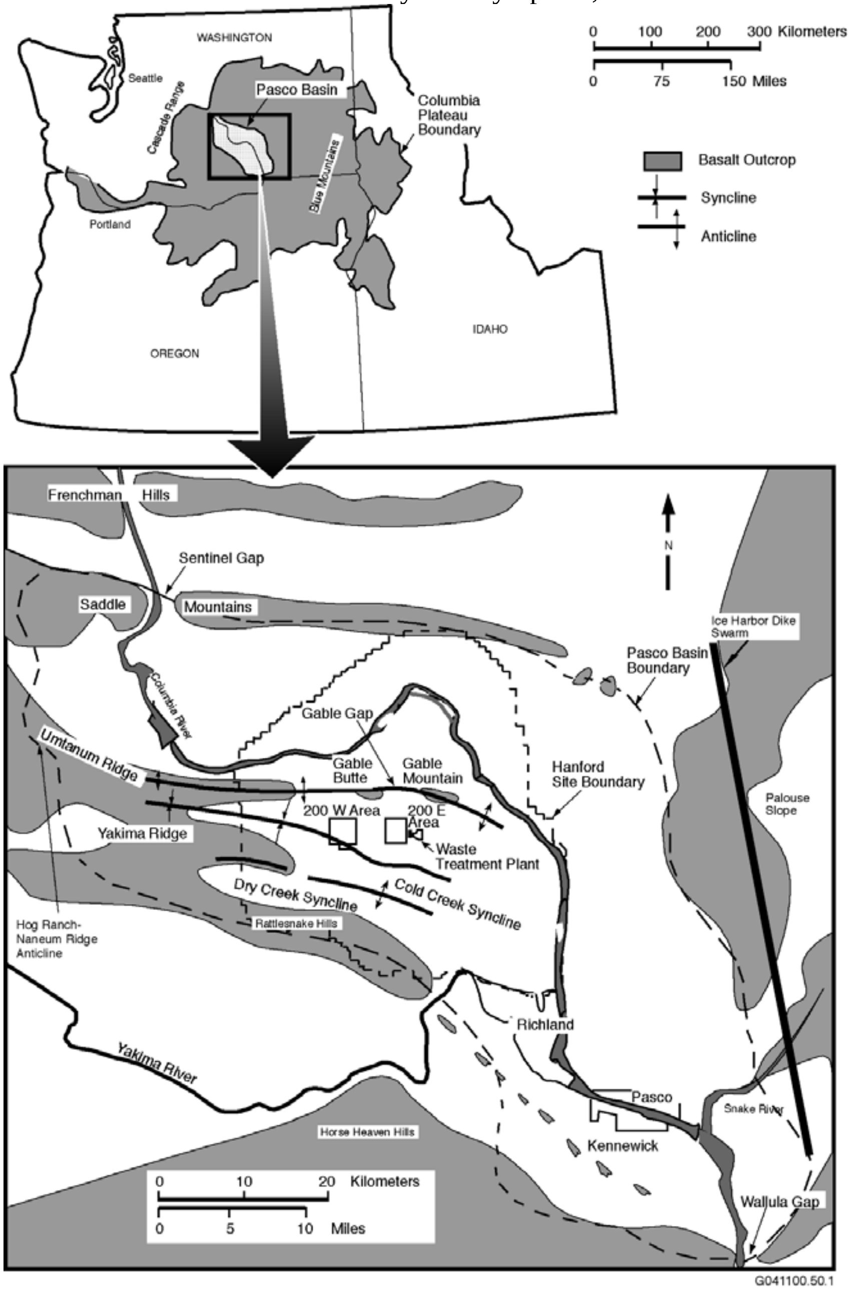

Fig. 1. Geologic setting of the Hanford Site and Waste Treatment Plant

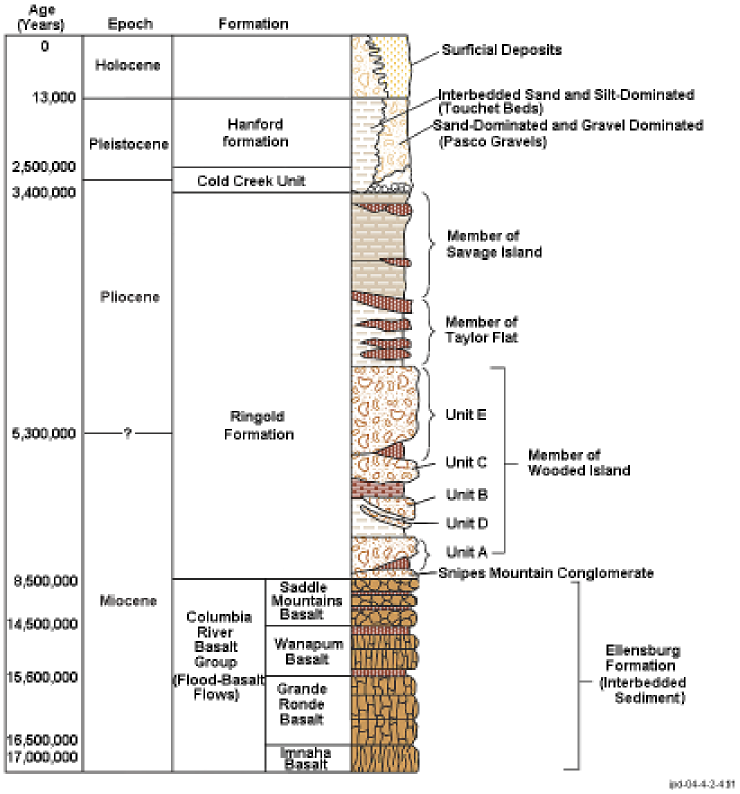

Fig. 2. Generalized stratigraphy of the Hanford Site and Waste Treatment Plant

GEOTECHNICAL DATA COLLECTION AND ASSEMBLY

Geotechnical data from investigations specific to the WTP site were reviewed and reanalyzed [3]. Shear wave velocity (Vs) data were obtained directly beneath the planned location of four major WTP facilities. These data provide a detailed characterization of the upper 270 ft of soils. New data were obtained in 2004 including downhole shear wave logging at five additional locations, suspension logging in one of these boreholes, and the surface geophysical method known as spectral analysis of surface waves (SASW). The new data from four of the boreholes extended to depths of 180 ft to 260 ft, and data from the fifth borehole extended through additional soil layers to 530 ft, the depth of the top surface of the uppermost basalt rock. The SASW data were taken at the surface near the same five boreholes and at four additional locations near the WTP site. A tenth SASW measurement was made at a nearby location where the basalt rock is exposed at the surface.

Existing data from previous geological and geophysical borehole characterizations of the basalts and interbedded sedimentary layers were also assembled and evaluated. Compression wave (Vp) sonic logs and checkshot surveys, taken in the late 1970s and 1980s at Hanford, were assembled and analyzed to obtain velocity data for the basalts and interbedded sedimentary layers. Suspension logging in a borehole 60 miles southwest of the WTP site and cross-borehole data from Hanford were used to determine the ratio Vp/Vs. This ratio was used to convert the Vp profiles into Vs profiles in the basalts. The new downhole and suspension logs in the 530-ft borehole near the WTP site were used to determine Vp/Vs in the lower part of the borehole as an analogue to estimate Vs in the similar sediments in the interbeds between the top four basalt units. The new SASW measurements, which extended into the basalts and interbeds, were shown to provide an average value of Vs without detecting the velocity contrasts between them, providing an additional constraint on the Vs models.

All of the data assembled above are analyzed statistically and were used to quantitatively compare the velocity profiles obtained from the various measurement methods and to assess the accuracy and precision of the final models.

In addition to the geotechnical data collection described above, earthquake records from small local earthquakes at Hanford were used to estimate a ground motion attenuation parameter “kappa.”

LOGIC TREE APPROACH TO HANFORD WASTE TREATMENT PLANT GROUND MOTION AMPLIFICATION FACTORS

Examination of seismic and geologic data collected in the vicinity of the WTP site at Hanford has produced a model of the subsurface physical properties of the site. However, several significant uncertainties in some of the actual properties at the site still exist, due to limited data or inherent variability. A range of values for these properties has been selected to determine the sensitivity of the amplification factors to these properties. The approach uses a conventional logic tree, with branches that define the distribution of site properties and weights that reflect the relative likelihood that the parameters on the individual logic tree branches represent the actual properties at the WTP site (Figure 3). The site response model that results from each path through the logic tree is used to calculate the relative site ground motion response to earthquake ground motions representative of the site hazard. Based on the quality and consistency of the available data, weights for each of the branch points were selected by the working group.

Several elements of the model indicate that there are significant amplifications of ground motion response by the WTP Hanford site structure relative to the response of California deep soil sites representative of the ground motion attenuation relationships used to develop the original seismic design. It was also found that ground motion response is sensitive to two poorly known parameters of the model—the crustal attenuation parameter kappa and the Vs in the interbeds within the Saddle Mountains Basalt.

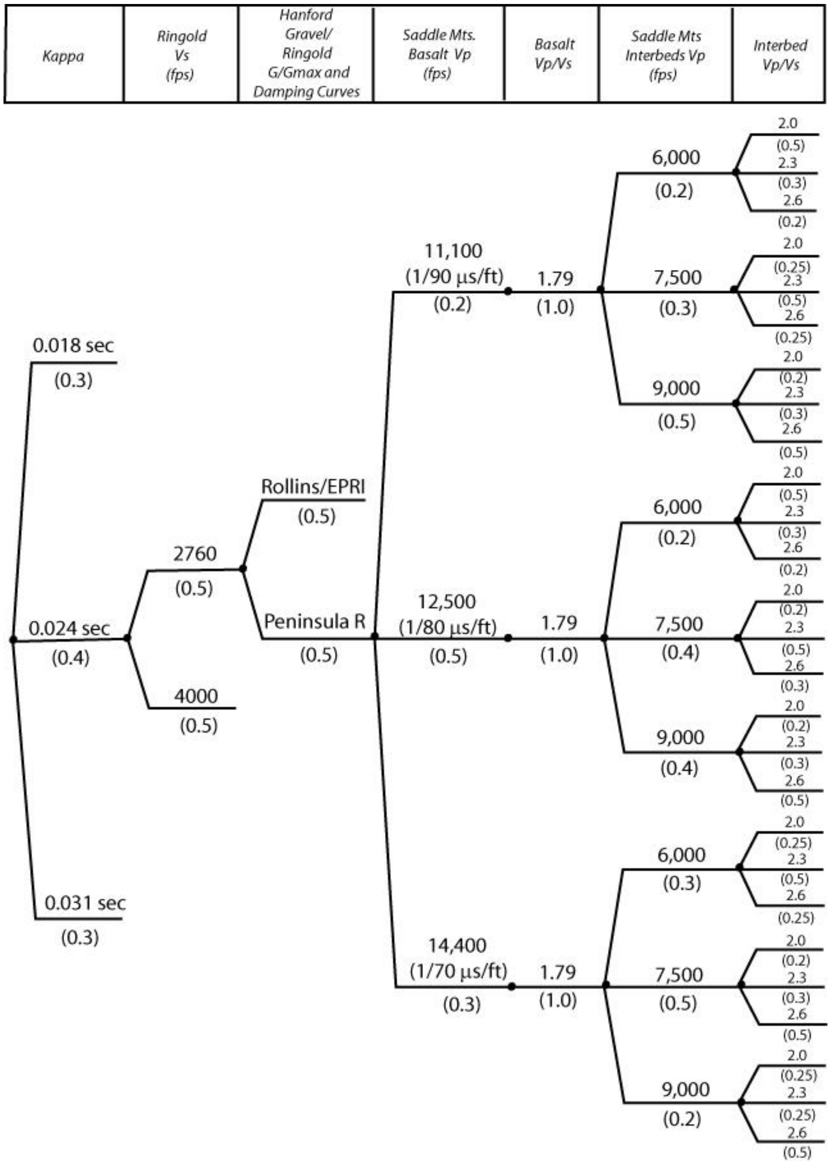

Fig. 3. Logic tree for Hanford Waste Treatment Plant seismic response model

DEVELOPMENT OF RELATIVE AMPLIFICATION FUNCTIONS

Figure 4 compares the median shear wave velocity profile representative of California soil sites to the median shear wave velocity profile developed for the WTP site. The velocity profiles are extended to a depth of 3 km (9,800 ft) where the shear wave velocities at Hanford and California become comparable. The transition from soil to rock in California, shown at 1,000 ft in Figure 4, was randomized to lie between 100 and 1,000 ft in the analysis to reflect the variability in soil depth across the strong motion databases used to develop the empirical attenuation relationships. The velocity in the California soils is somewhat lower than that in the WTP soils. The velocities in the shallow crustal rocks in California begin at about 3,000 fps and show a continuous increase to approximately 10,000 fps at a depth of 10,000 ft. At the WTP site, the upper crustal rocks consist of basalts, with the topmost unit—the Saddle Mountains Basalt sequence—consisting of alternating layers of basalt and interbedded sediments. The rock velocities at the WTP site start out much higher than those in California but show only a small increase with depth. The higher-velocity soils at Hanford produce a somewhat higher response than the California soils. This is offset by the velocity contrasts in the basalt-interbed sequence, which reflects energy downward.

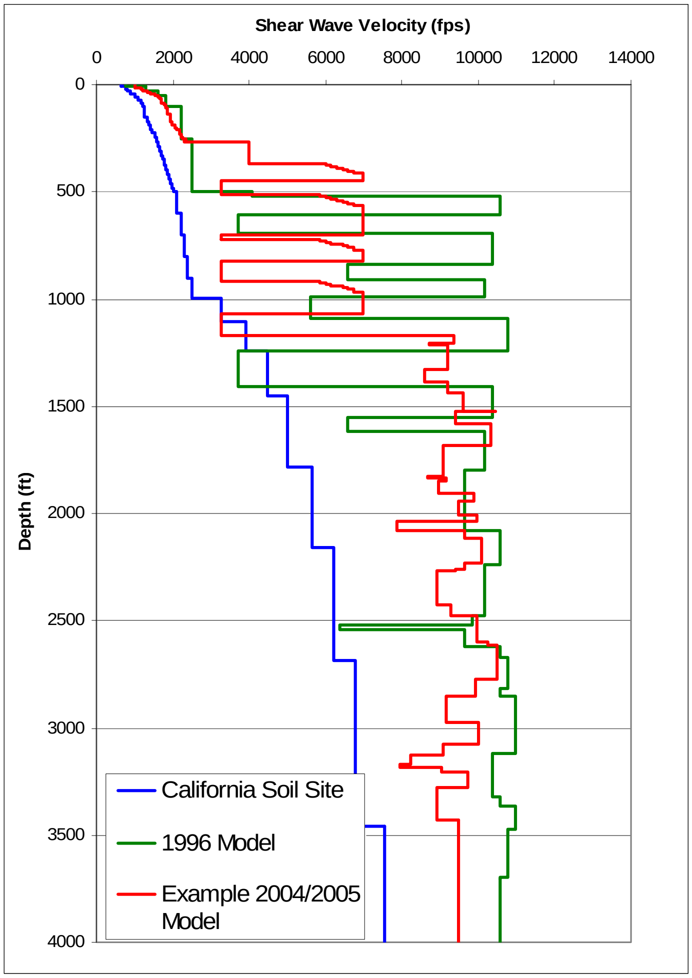

Fig. 4. Comparison of California soil site velocity profile to Hanford profiles used in site-response modeling in 1996 and 2005

Various subsets of logic tree elements also were used in the development of the design recommendation. These combinations generally led to the conclusion that the 84th percentile from the logic tree represented a conservative envelope of the range of the mean results. Therefore, the 84th percentile from the logic tree was chosen to guide the development of the design recommendation. Figure 5 compares the 84th percentile results from the full data set with the means from several subsets of interest that were felt to be conservative indicators of the expected WTP site response. The subsets considered are the RAF maxima from the interbed

Vp/Vs ratio (Vp/Vs of 2.0), the Case 8 mean (Vs of interbeds at 3,913 fps), and the low-kappa case. The 84th percentile from the full data set is somewhat higher than the subset means. This result shows that the 84th percentile RAF from the full logic tree reflects a reasonably conservative estimate of the RAF. The 84th percentile from the logic tree was therefore chosen to guide the development of the design recommendation.

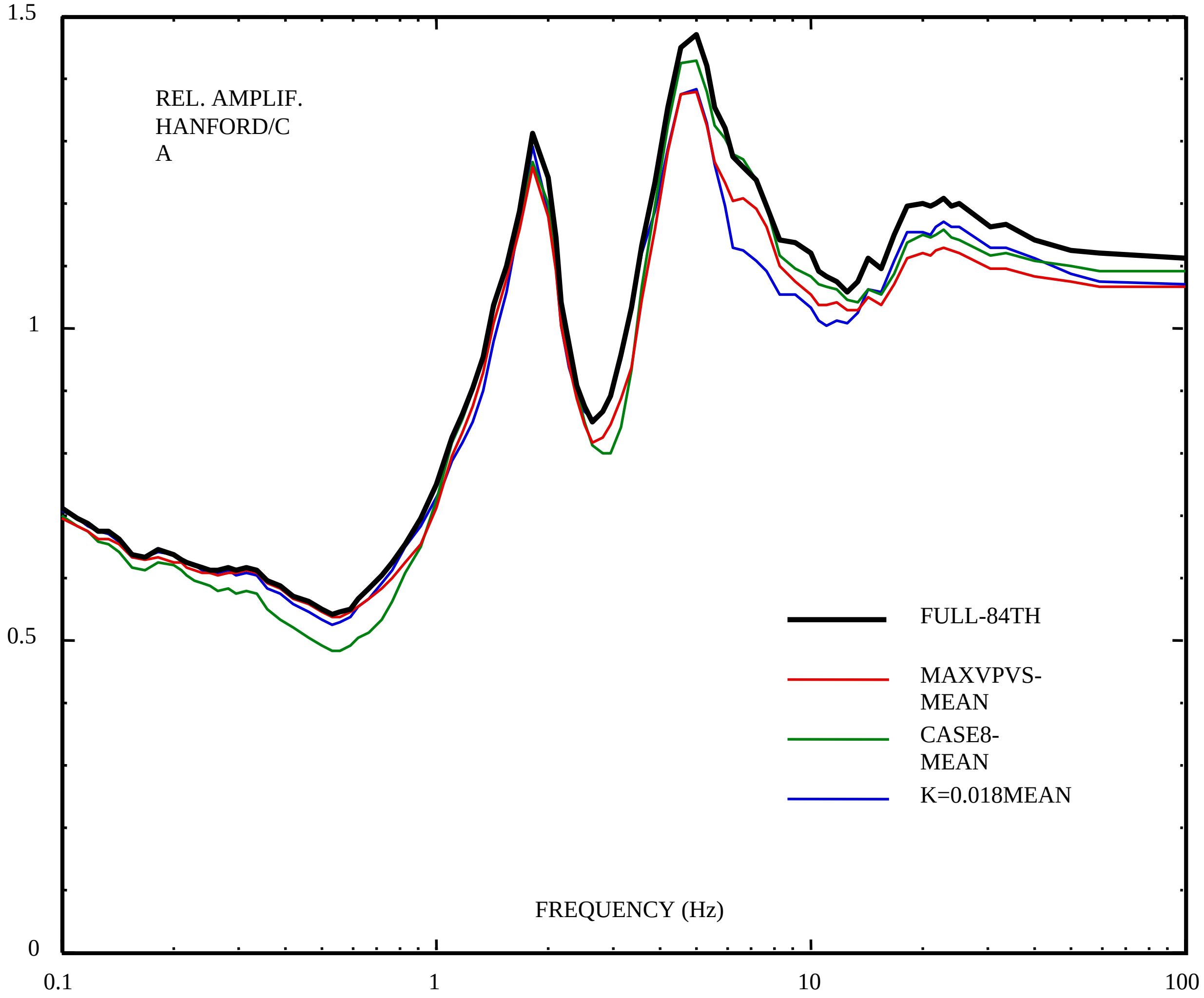

Fig. 5. Comparison of full 84^{th} percentile relative amplification function with subset means

CONCLUSION

Figure 5 shows the original 1996 (black line) 5% damped horizontal design response spectrum. That spectrum was then scaled by the 84th percentile frequency-dependent RAF from the full logic tree result to obtain a conservative estimate of the horizontal response spectrum (red line) appropriate for the WTP site. This spectrum was then broadened (green line) at the peak to arrive at the recommended horizontal design response spectrum for the WTP site that conservatively accounts for the differences between the WTP site and the California deep soil profile associated with the attenuation models used in the original UHS development.

The sharp peak of the recommended spectrum (red curve of Figure 5) is at 5 Hz. The spectral broadening process was accomplished by extending the peak on the low-frequency side about 30% to about 3.85 Hz and about 15% on the high-frequency side to about 5.75 Hz. For higher frequencies, the spectrum was then extended linearly (in log-log space) to a frequency of 12 Hz. The conservatism in the higher frequencies above 12 Hz was found to be significant because the logic tree results indicated that the higher-mode responses of the subsets of the logic tree yielded a dip in the spectra at these frequencies.

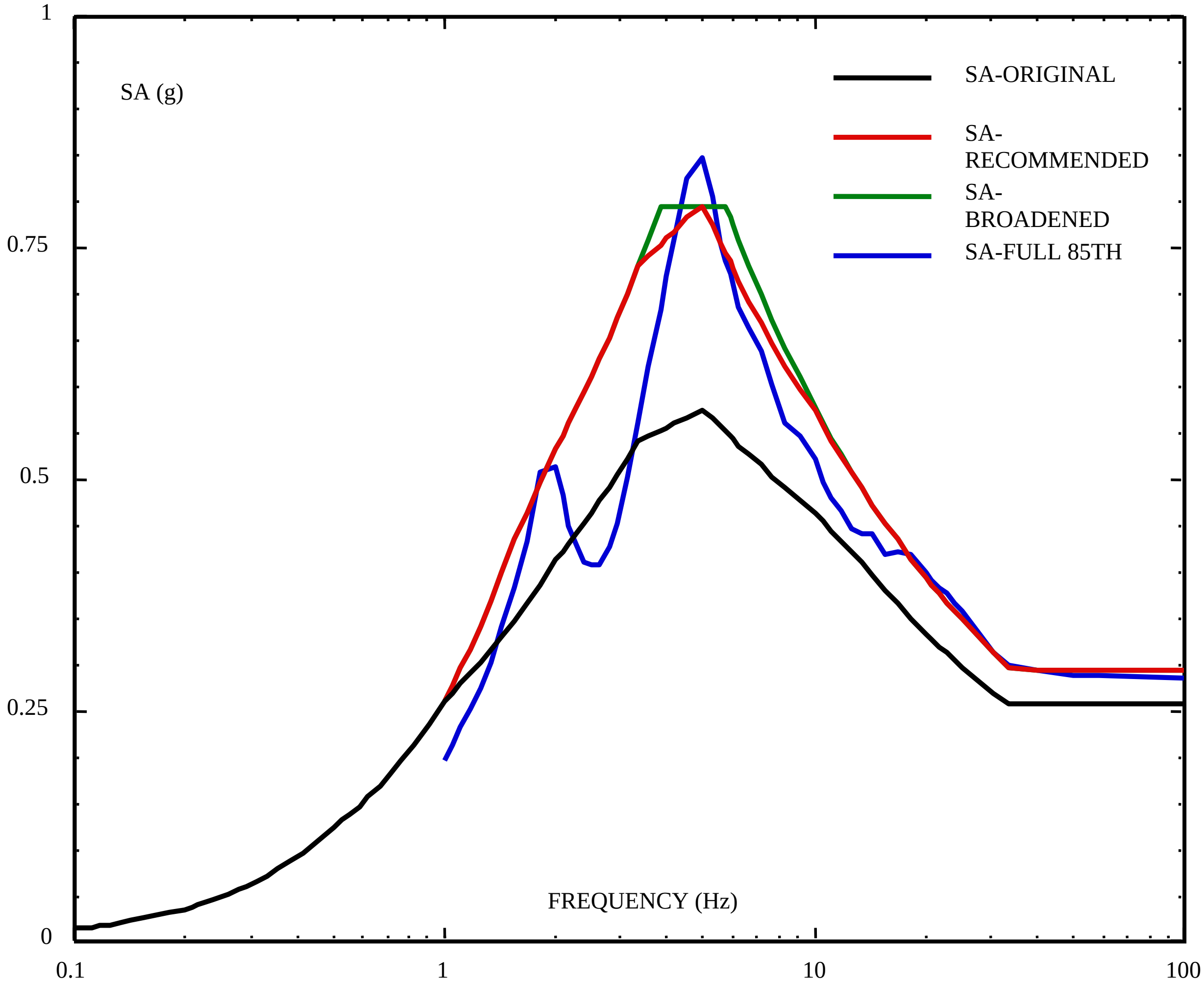

Fig. 6. Enveloping logic model responses and broadening for design response spectrum at 5% damping

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy Office of River Protection under the direction of Lew Miller. The lead authors acknowledge the contributions of Carl Costantino, consultant; Richard Lee of Bechtel Savannah River Site; Jim Cameron, Farhang Ostadan, and Joe Litehiser of Bechtel National; Bob Youngs of Geomatrix Consultants; and Walt Silva of Pacific Engineering and Analysis. These seismologists and engineers provided significant support on developing the scope of the work and contributed to assembling and interpreting the data. They also formed the working group that produced the logic tree and weights for the final model of the Waste Treatment Plant site. Chris Wright of Fluor Hanford directed the construction of the borehole used for the shear wave measurements.

REFERENCES

1. Geomatrix Consultants, Inc. 1996. *Probabilistic Seismic Hazard Analysis, DOE Hanford Site, Washington*. WHC-SD-W236-TI-002, Rev. 1a, Westinghouse Hanford Company, Richland, Washington.
2. U.S. Department of Energy. 1994. *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities.* DOE-STD-1020-94, U.S. Department of Energy, Washington, D.C.
3. Pacific Northwest National Laboratory. 2005. *Site-Specific Seismic Site Response Model for the Waste Treatment Plant, Hanford, Washington*. PNNL-15089, Pacific Northwest National Laboratory, Richland, Washington.