DEVELOPMENT OF EARTHQUAKE GROUND MOTIONS FOR YUCCA MOUNTAIN

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ABSTRACT

Yucca Mountain, Nevada has been selected as the site of the nation's first permanent repository for the disposal of spent nuclear fuel and high-level radioactive waste. The site is located in the southern Basin and Range Province, which is characterized by late-Quaternary normal faulting, a moderate level of historical seismicity, and a paleoseismic record of earthquakes up to moment magnitude (**M**) 7.0 to 7.5. The Yucca Mountain repository will have structures, systems, and components at multiple locations. Using a random vibration theory-based equivalent-linear site response analysis approach, earthquake ground motions were calculated at two locations: at about 330-m depth within the proposed waste emplacement area, and on alluvium at the site of surface facilities. An integrated site characterization program of borehole logging and velocity surveys, spectral-analysis-of-surface-waves surveys, and laboratory dynamic testing was performed to characterize the lithologic, velocity, and dynamic material properties of the repository area for input into the site response analyses. Ground motion parameters were calculated for both preclosure seismic design and for postclosure performance assessment of the repository based on the results of a probabilistic seismic hazard analysis. Variabilities in site properties were quantified and are accommodated in the ground motion estimates. Ground motions for preclosure analyses were calculated for annual frequencies of exceedance (AFE) of 10^{-3}, $5x10^{-4}$, and 10^{-4}. For postclosure analyses, the focus is on ground motion AFEs between 10^{-4} and 10^{-7}. These ground motions are larger than those used for preclosure design and address the regulatory requirement to consider events with a 10^{-4} chance of occurring in 10,000 years in evaluating long-term repository performance.

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Introduction

The Yucca Mountain site (Fig. 1) 160 km northwest of Las Vegas has been designated for development as the nation's first permanent repository for spent nuclear fuel and high-level radioactive waste. This paper describes the development of earthquake ground motion input for preclosure seismic design and postclosure assessment of the repository at Yucca Mountain (Bechtel SAIC 2004). The approach implements a one-dimensional (1D) random-vibration-theory (RVT), equivalent-linear formulation to calculate site response effects on ground motions (e.g., Silva *et al.* 1997). The approach provides ground motions in terms of spectral acceleration and peak ground acceleration, peak ground velocity, and dynamically-induced strains as a function of depth. Time histories were also developed scaled to peak ground velocity or spectrally matched to design acceleration response spectra. A complete description of the analyses is described in Bechtel SAIC (2004).

Yucca Mountain is an irregularly shaped upland, 3 to 8 km wide and about 35 km long (Fig. 1). The crest of Yucca Mountain ranges in elevation from about 1,500 m to 1,930 m. Yucca Mountain consists of stacked layers of tuffs, approximately 7.5 to 15 million years old, that formed by eruptions of volcanic ash from the north. Individual layers of volcanic tuff, therefore, get progressively thinner from north to south. Most of the rocks are welded and nonwelded ash flow tuffs.

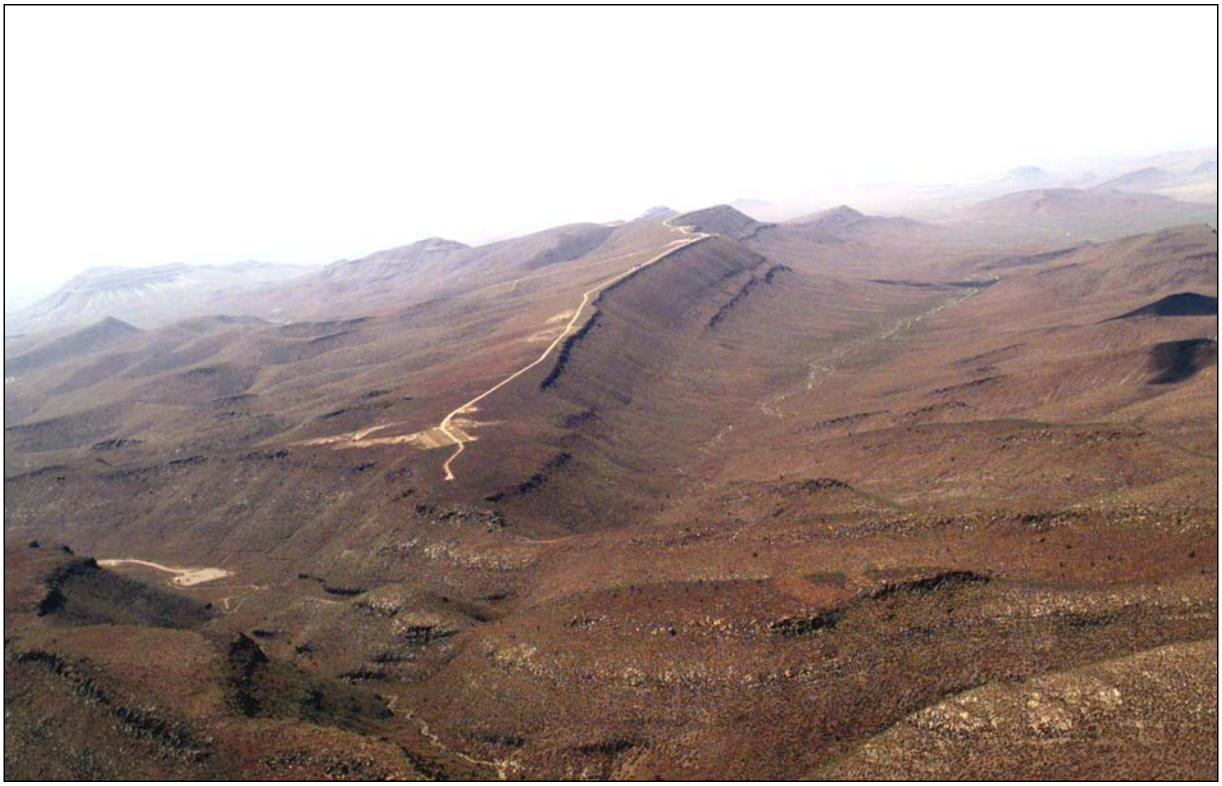

Figure 1. View of Yucca Mountain from the north.

The purpose of the site-response ground motion analyses was to incorporate the effects of the upper approximately 330 m of tuff above the repository waste emplacement areas (Point B,

Fig. 1) and soil beneath the Surface Facilities Area (SFA) (Points D and E, Fig. 2) on earthquake ground motions. The SFA will be the site of the waste handling facilities, which will receive the incoming shipments of nuclear waste. The results of a probabilistic seismic hazard analysis (PSHA) (Stepp *et al.* 2001), which are a basic input into the site response analyses, provides ground motions at a hypothetical reference rock outcrop for the site (Point A, Fig. 2), but those results do not include the response of the approximately 330 m of material above Point B or the soil and rock at Points D and E. Thus, the additional step encompassed in the site-response analyses is required to develop ground motion inputs that are used for preclosure and postclosure purposes. The rock beneath Point A is characterized by a shear-wave velocity (V_S) of 1900 m/sec and a kappa (near-surface attenuation factor) of 0.0186 sec (Stepp *et al.* 2001).

Ground motions (response spectra, time histories) for preclosure seismic design are determined for the planned underground waste emplacement drifts and for the SFA. The waste emplacement drift ground motions are used to evaluate drift stability and to support preclosure waste package design and analyses. The SFA ground motions are used for design of the surface facilities, including soil-structure interaction analyses. For the SFA, two conditions are modeled: a thin layer of alluvium (about 15 ft) covering rock and a thicker layer of alluvium (about 35 ft and 110 ft) covering rock (Points E and D, respectively, Fig. 2). Ground motion inputs (time histories) for postclosure performance assessment are determined for the waste emplacement level only. Ground motions for a rock outcrop at the surface of Yucca Mountain (Point C, Fig. 2) are not required for design or performance assessment analyses at this time.

For preclosure analyses, time histories are developed by spectrally matching appropriate strong ground motion records to target response spectra. For postclosure analyses, peak ground velocity values determined from the site-response analyses for the waste emplacement level are

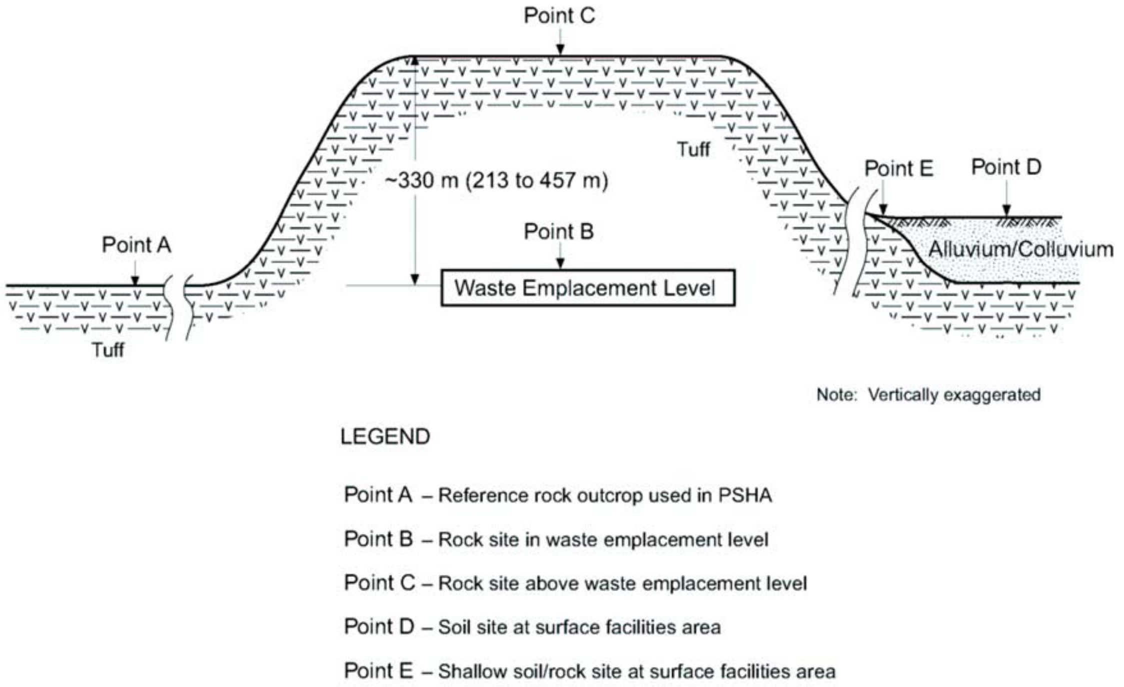

Figure 2. Schematic representation of the locations for which earthquake ground motions are developed.

used to develop time histories that form input to a model of drift degradation under seismic loads producing rockfall. The time histories are also used to carry out kinematic and dynamic structural response calculations of the drip shield and waste package system. For the drip shield, damage from seismically induced rockfall also is considered.

The preclosure seismic design approach for the repository at Yucca Mountain is a risk-informed methodology for establishing design basis hazard levels for systems, structures, and components determined to be important to safety. Two design basis ground motion levels are used. Level 1 has a mean AFE of 1×10^{-3}, while Level 2 has a mean AFE of 5×10^{-4}. Beyond-design-basis ground motion analyses and high-confidence-of-low-probability-of-failure analyses will be carried out, as appropriate. For these analyses, beyond design basis ground motions with a mean AFE of 1×10^{-4} are used. For postclosure analyses, the focus is on ground motions for AFEs between 10^{-4} and 10^{-8}. These ground motions are larger than those used for preclosure design and address the regulatory requirement to consider events with a 10^{-4} chance of occurring in 10,000 years.

Inputs Into Analysis

The starting point for the site response modeling is the output of the PSHA. For a given AFE, the seismic hazard results at Point A (Fig. 3) are used to derive an acceleration response spectrum with a uniform probability of being exceeded, the uniform hazard spectrum (UHS). Results for peak ground velocity are also determined.

Inputs to the site-response ground motion model consist of small-strain seismic velocities, densities, nonlinear dynamic material properties, and the angles of incidence of the control motions. A geotechnical, geological, and geophysical site characterization program was performed to determine these inputs (Bechtel SAIC 2002). Field investigations performed principally in 2000 to 2001 included: (1) borehole logging and downhole and suspension logging of P- and S-wave velocities in 15 new boreholes at the SFA; the boreholes ranged in depth from 100 to 668 ft; (2) caliper and gamma-gamma wireline surveys in selected boreholes; (3) 33 Spectral-Analysis-of-Surface-Wave (SASW) surveys over the repository block area, 37 SASW surveys across the SFA, and 5 SASW surveys underground in the Exploratory Studies Facility (Stokoe *et al.* 2003, 2004); (4) dynamic laboratory testing (resonant column and

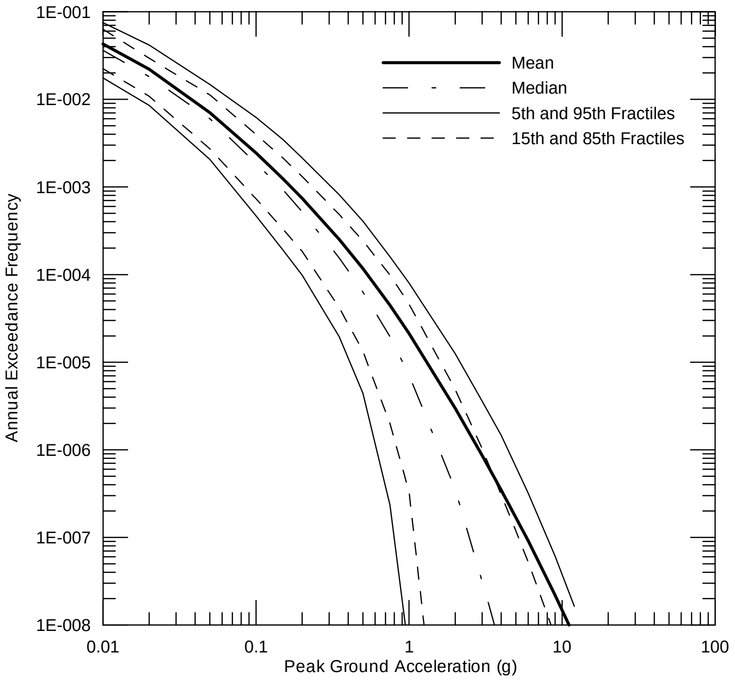

Figure 3. Hazard curve at Point A for peak horizontal ground acceleration.

torsional shear) of tuff and alluvium samples; and (5) test pits and standard static laboratory tests of collected samples from the SFA. For the Repository Block, two base case V_S and compressional-wave velocity (V_P) profiles are used to represent epistemic uncertainty in the mean profile. For the SFA, where uncertainty in the mean profile is less, a single base case profile (for both V_S and V_P) is used (Fig. 4). The base case profiles are used, along with information on the statistical correlation of layer thicknesses and layer velocities, to develop a suite of random velocity profiles that are used as model input. Similarly for the nonlinear dynamic properties of site materials, multiple base case curves of normalized shear modulus reduction and hysteretic damping, as a function of cyclic shear strain, are developed to represent epistemic uncertainty in the mean values of these properties. Two sets of curves (lower mean and upper mean) are developed each for the tuff and alluvium at the site. For input to the site response model, the curves for all materials are randomized to represent random (aleatory) variability in properties within and across the site.

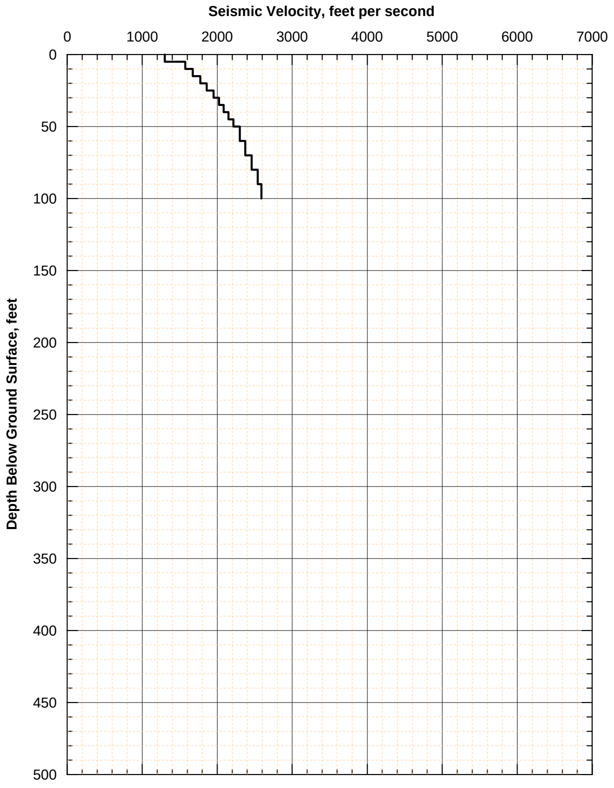

Figure 4a. Base case V_S profile for alluvium in the Surface Facilities Area.

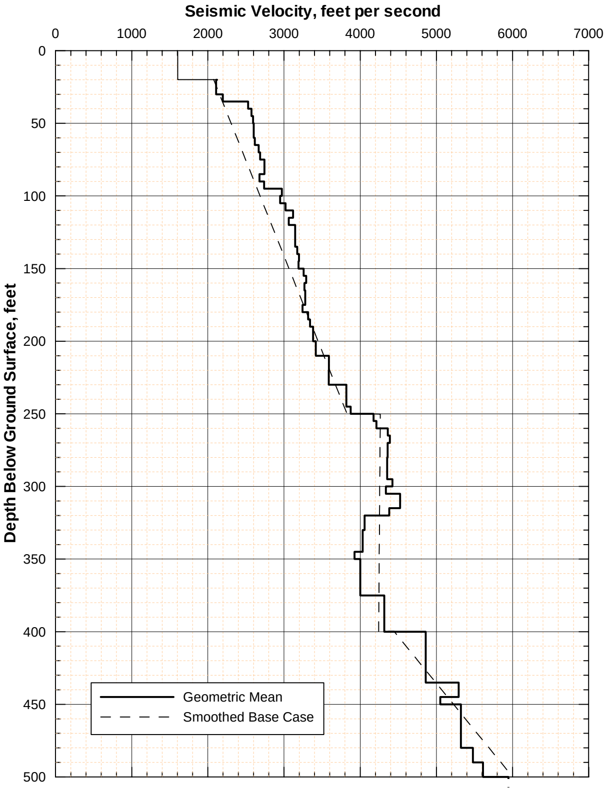

Figure 4b. Base case V_S profile for tuff in the Surface Facilities Area.

The site response approach used in developing site-specific ground motions follows one (called 2B) recommended in NUREG/CR-6728 (McGuire *et al*. 2001). The PSHA results for a given AFE are deaggregated to identify controlling earthquakes. Two controlling earthquakes are determined from the deaggregated hazard–one representing structural frequencies of 1 to 2 Hz and the other 5 to 10 Hz (Fig. 5). For Yucca Mountain, the controlling earthquakes at 5 to 10 Hz are local events of **M** 5 to 6.5 at distances of less than 15 km. The sources of these earthquakes are the local faults and the background seismicity, with local faults becoming more important at lower AFEs. At lower frequencies, 1 to 2 Hz, a more distant controlling earthquake is determined with **M** 7 to 7.5 at distances of 45 to 60 km. The Death Valley-Furnace Creek faults are the sources for these events. Response spectra for the controlling earthquakes are scaled to match the UHS at 1 to 2 Hz and 5 to 10 Hz and these form the "reference earthquake" response spectra (Fig. 6).

Non-linear site-response may be sensitive to earthquake magnitude (spectral composition of the control motion). Because this sensitivity may not be sufficiently captured by the range of magnitudes for the reference earthquakes, three "deaggregation" earthquakes are defined to account for the range of magnitudes contributing to the hazard in the 1 to 2 Hz and 5 to 10 Hz ranges (Fig. 7). These earthquakes nominally represent the 5th, mean, and 95th fractile magnitudes and associated distances determined from the hazard deaggregation. These deaggregation earthquakes form the input, or control motion, for the site-response ground motion model. Thus, for both horizontal and vertical ground motion modeling, the methodology employs six control motion response spectra as inputs. A weighted average is taken of the model outputs for each set of deaggregation earthquakes with the results for the mean magnitude getting the highest weight.

Site Response Analysis Approach

The RVT-based equivalent-linear site response model involves a computational method (i.e., equivalent-linear) that has been widely employed to evaluate 1D site response using vertically-propagating plane S-waves (Silva and Lee 1987, Silva *et al.* 1997). Both P-SV (vertically polarized S-wave) and SH (horizontally polarized S-wave) waves are

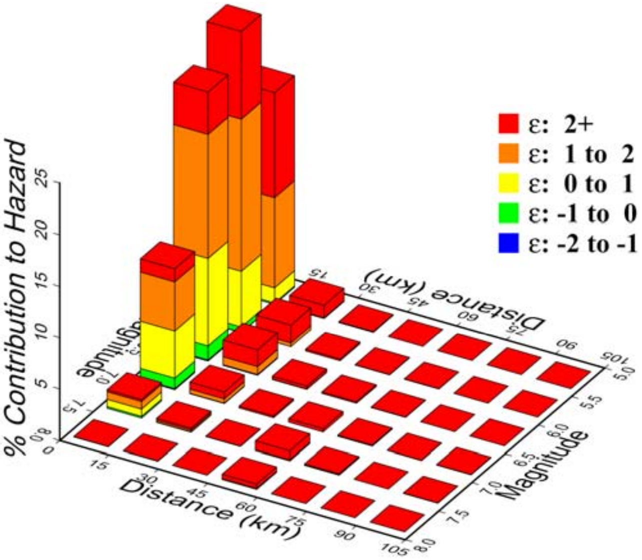

Figure 5. Contribution to mean hazard by magnitude, distance, and epsilon (ε) for the 5 to 10 Hz horizontal ground motions, 10^{-4} AFE.

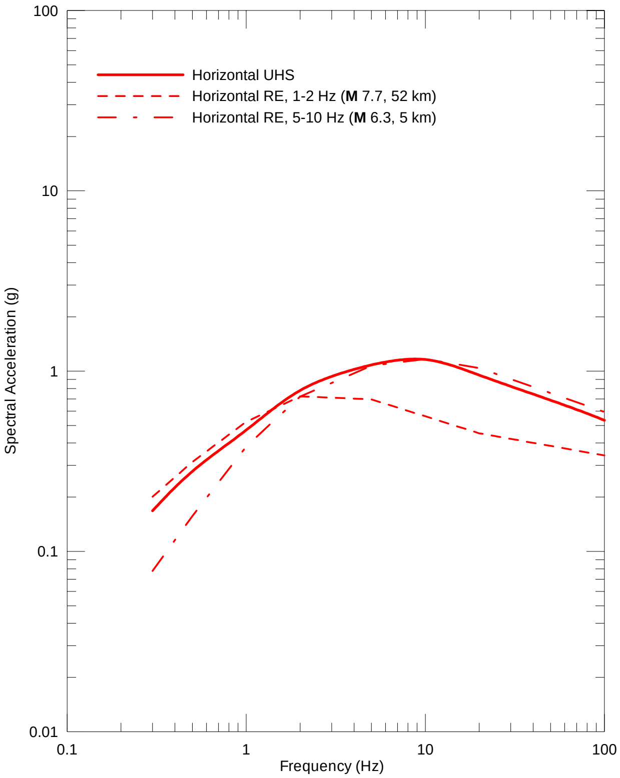

Figure 6. Point A UHS and reference earthquake (RE) spectra at an AFE of 10^{-4}, horizontal component.

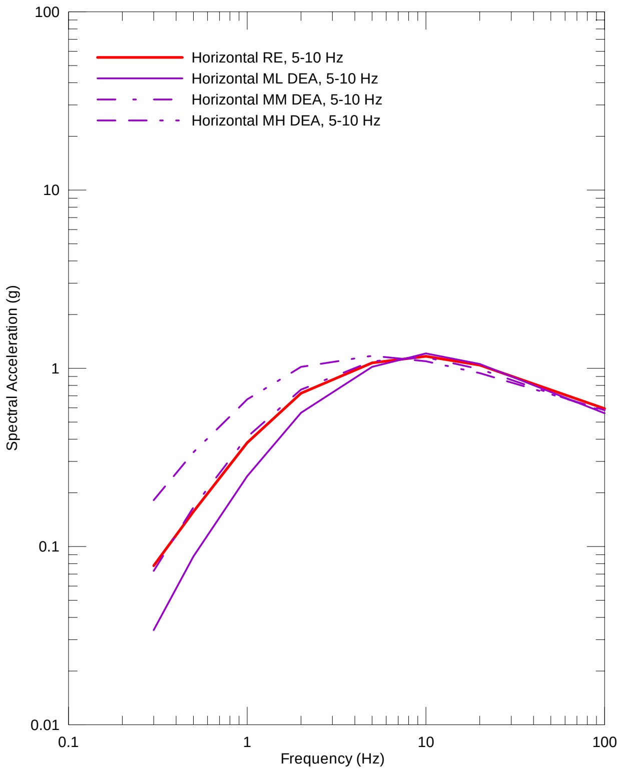

Figure 7. Point A reference earthquake and deaggregation earthquake (DEA) spectra at an AFE of 10^{-4} and 5 to 10 Hz, horizontal component.

incorporated into the analysis and have specified angles of incidence based upon expected seismic source depths and distances.

Comparisons of equivalent-linear site response analyses with fully nonlinear analyses showed equivalent-linear analyses produced 5%-damped response spectra in general agreement with nonlinear analyses as well as recorded motions at several sites and for a wide range of induced cyclic shear strains, with a maximum of about 2% (Bechtel SAIC 2004).

In the analyses for Yucca Mountain, response spectral (5%-damped) and peak particle velocity transfer functions from the PSHA reference rock outcrop (Point A) to repository locations of interest are developed. For each combination of deaggregation earthquake, base case velocity profile, and base case dynamic material properties, multiple runs using the site response model are carried out. In the multiple runs, the velocity profile and dynamic material properties are randomized about their base case values to accommodate parametric aleatory variability across the site. The model results are then appropriately combined to determine the final output (e.g., response spectra, peak ground velocities) for each combination. Next, for horizontal component motions, the transfer function is applied to the envelope of the reference earthquake response spectra and UHS (or peak particle velocities) to determine the final motions for each combination. For vertical motions, the transfer function is applied to a spectrum derived from the horizontal spectrum using vertical-to-horizontal ratios, as a function of frequency, appropriate for the Yucca Mountain site. Finally, the results for each combination of inputs are enveloped to provide the final response (5%-damped) spectra (Fig. 8) or peak particle velocity. Peak ground motions, strains and curvatures, and strain-compatible soil properties, all as a function of depth, are developed in a similar fashion.

Results

To support preclosure design analyses, ground motions (response spectra, time histories), strain-compatible soil properties, and strains, curvatures, and peak ground motion values as a function of depth are presented for AFEs of 10^{-3}, $5x10^{-4}$, and 10^{-4}. For each suite of base case dynamic material properties, mean ground motions are estimated to accommodate site parametric epistemic uncertainty. Finally, the suite of mean motions is then enveloped to incorporate site epistemic uncertainty into the design ground motions. An example of this process showing the range in site epistemic uncertainty is shown in Fig. 8. To support postclosure analyses, suites of

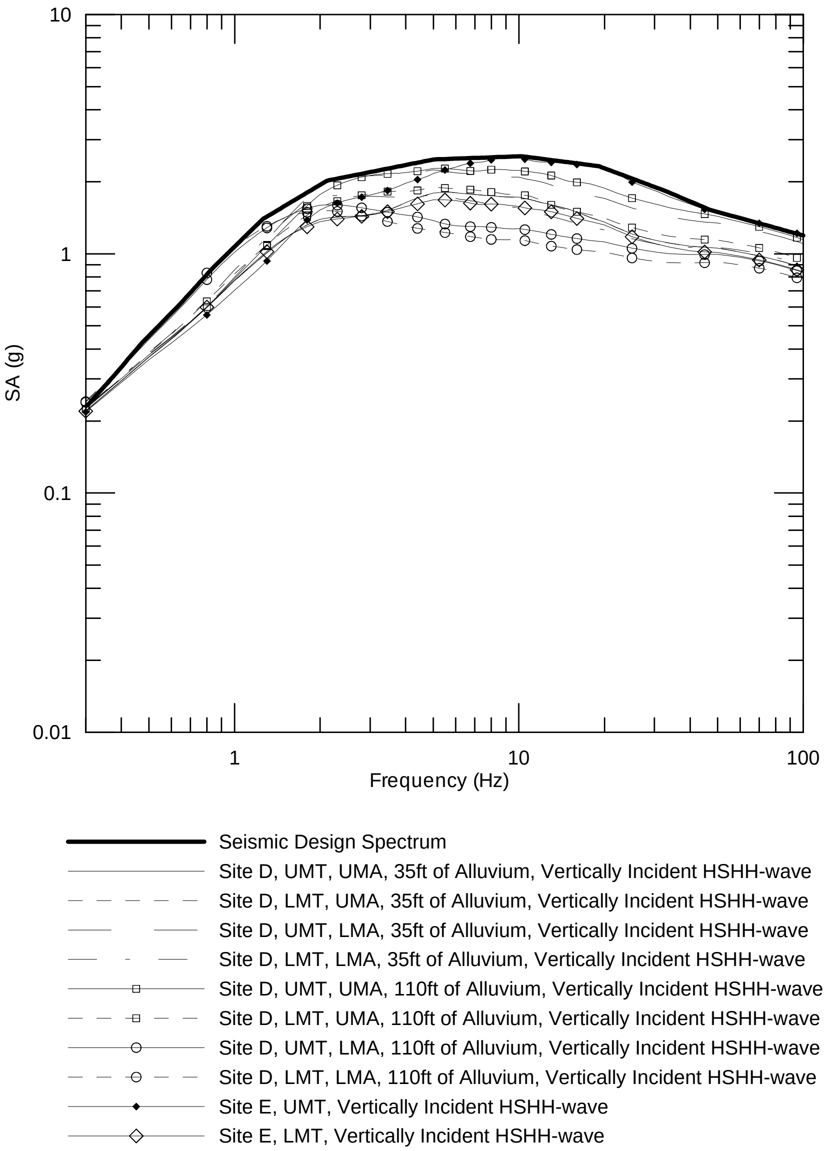

Figure 8. Point D/E horizontal site-specific spectra and seismic response spectrum (5%-damped) at an AFE of 10^{-4}. LMT and UMT refer to the lower mean and upper mean tuff nonlinear dynamic curves. Similarly, LMA and UMA refer to the lower mean alluvium and upper mean alluvium curves. HSHH refers to the horizontal-component of the SH wave.

17 sets of three-component time histories, either scaled to peak ground velocity, spectrally conditioned and scaled to peak ground velocity, or spectrally matched, were developed for mean AFEs of 10^{-5}, 10^{-6}, and 10^{-7}. For most postclosure time history sets developed by scaling to peak ground velocity, one horizontal component is scaled to the target horizontal peak ground velocity and the second horizontal and the vertical component are scaled to maintain the inter-component variability of the original strong ground motion recordings. Thus, the peak ground velocity for the second horizontal and the vertical component can be less than or can exceed the target peak ground velocity. This approach is used so that postclosure analyses reflect the effects of

observed inter-component variability. Table 1 summarizes mean horizontal and vertical peak accelerations and peak velocities.

Table 1. Seismic Design and Postclosure Assessment Ground Motions

	AFE	**Site**	**Mean PGA (g)**		**Mean PGV (cm/sec)**	
			Horizontal	**Vertical**	**Horizontal**	**Vertical**
Preclosure	10^{-3}	SFA	0.37	0.28		
	$5x10^{-4}$	SFA	0.58	0.52		
	10^{-4}	SFA	1.19	1.49		
	10^{-3}	Emplacement Level	0.13	0.12		
	$5x10^{-4}$	Emplacement Level	0.19	0.23		
	10^{-4}	Emplacement Level	0.43	0.61	40	48
Postclosure	10^{-5}	Emplacement Level			105	137
	10^{-6}	Emplacement Level			244	236
	10^{-7}	Emplacement Level			535	625

Control motions used as input to the site response model are based on results of the PSHA (Stepp *et al.* 2001). PSHAs specifically capture variabilities in features, processes, models, and model parameters and express the variabilities in the hazard results. The variabilities in the input parameters are modeled for hazard computation using unbounded distributions and are captured in the hazard results by integrating over all input distributions. The integrated variability in the inputs, which is expressed in the hazard results as a probability distribution, becomes increasingly large and increasingly asymmetric with increasingly low AFE. As a consequence, ground motion values corresponding to very low mean AFEs ($< 10^{-6}$) are larger than can be considered to be physically reasonable or even possible (Table 1). That is, they imply dynamic strains that would exceed the strength of the rock. It is clear for magnitudes near **M** 6.5 and in an extensional faulting environment, ground motions corresponding to the very low AFE are unrealistic. As an example, 10^{-7} AFE ground motions correspond to a Brune point-source dynamic stress drop of about 2500 bars. To characterize extreme ground motions for licensing analyses, incipient deformation of the lithophysal rocks, which has been observed not to occur in the last 12.8 million years and which occurs at shear-strains at about 10^{-1}% is used to assess more realistic exceedance probabilities. Preliminary analyses suggest that for **M** 6.5 ground motions of sufficient amplitude to reach these peak particle velocities of about 250 cm/sec, strain levels are associated with AFE of about 10^{-8}, rather than the AFE of 10^{-6} reflected in the totally unconstrained PSHA.

Summary

Ground motion response spectra and time histories, and strain-compatible soil properties, strains and curvatures, and/or peak ground motions as a function of depth, were computed for the proposed waste emplacement area and the SFA using a RVT-based equivalent-linear site response analysis approach. Inputs into the analyses were derived from an integrated geotechnical, geological, and geophysical site characterization program performed in 2000 and 2001.

Acknowledgments

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References

Bechtel SAIC, 2002. *Geotechnical Data for a Potential Waste Handling Building and for Ground Motion Analyses for the Yucca Mountain Site Characterization Project.* Unpublished report prepared for the U.S. Department of Energy.

Bechtel SAIC, 2004. *Development of Earthquake Ground Motion Input for Preclosure Seismic Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain, NV.* Unpublished report prepared for the U.S. Department of Energy.

Idriss, I.M., and H.B. Seed, 1968. Seismic response of horizontal soil layers, *Journal of the Soil Mechanics and Foundations Division* 94, 1003-1031.

McGuire, R.K., W.J. Silva, and C.J. Costantino, 2001. Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines, NUREG/CR-6728.

Silva, W.J., N.A. Abrahamson, G. Toro, and C. Constantino, 1997. *Description and validation of the stochastic ground motion model*. Unpublished report prepared for the Brookhaven National Laboratory.

Silva, W.J., and K. Lee, 1987. *WES RASCAL Code for Synthesizing Earthquake Ground Motions, State-of-the-Art for Assessing Earthquake Hazards in the United States, Report 24*. U.S. Corps of Engineers Waterways Experiment Station, Miscellaneous Paper S-73-1, 120 p.

Stepp, J.C., I. Wong, J. Whitney, R. Quittmeyer, N. Abrahamson, G. Toro, R. Youngs, K. Coppersmith, J. Savy, and T. Sullivan, 2001. Probabilistic Seismic Hazard Analyses for Ground Motions and Fault Displacement at Yucca Mountain, Nevada, *Earthquake Spectra* 17, 113-151.

Stokoe, K.H. II, B.L. Rosenblad, J.A. Bay, B. Redpath, J.G. Diehl., R. Steller, I.G. Wong, P.A. Thomas, and M. Luebbers, 2003. Comparison of V_S Profiles From Three Seismic Methods at Yucca Mountain. In *Soil and Rock America 2003 Proceedings*, edited by P.J. Culligan, H.H. Einstein, and A.J. Whittle, Verlag Glückauf GMBH 1, 299-306.

Stokoe, K.H., B.L. Rosenblad, I.G. Wong, J.A. Bay, P.A. Thomas, and W.J. Silva, 2004. "Deep V_S Profiling Along the Top of Yucca Mountain Using a Vibroseis Source and Surface Waves." *13th World Conference on Earthquake Engineering Paper No. 538.*