OVERVIEW OF THE PROBABILISTIC SEISMIC HAZARD ANALYSES OF YUCCA MOUNTAIN

Ivan G. Wong
Seismic Hazards Group
URS Corporation
1333 Broadway, Suite 800
Oakland, CA 94612
ivan_wong@urscorp.com

Probabilistic seismic hazard analysis (PSHA) is now established practice as the basis for determining seismic design ground motions for important nuclear facilities. Consistent with this practice, PSHAs for ground motion and fault displacement have been performed for the Yucca Mountain site (Stepp *et al.*, 2001). The methodology used for the PSHAs incorporated multiple expert evaluations of seismic sources, the potential for fault displacement, and ground motion estimation. The experts provided weighted alternative evaluations to characterize uncertainties in their interpretations. Based on these alternative interpretations, hazards were calculated and expressed as the annual frequency at which levels of ground motion or fault displacement are expected to be exceeded.

The objective of the PSHAs was to provide ground motion and fault displacement hazard results for both determining preclosure (up to 300 years) seismic design requirements and for postclosure (10,000 years or more) assessment for long-term waste containment and isolation performance of the potential repository. The governing regulation requires consideration of two categories of design basis events. Category-1 events are expected to occur 1 or more times during the preclosure operational period of the facility. For ground motion, the target hazard for Category-1 events has been established at 10^{-3} annual frequency of exceedance. For Category-2 events, ground motion will be based on hazard at an annual exceedance frequency of 10^{-4}. For postclosure assessment, annual exceedance frequencies as small as 10^{-7} may need to be considered.

APPROACH

The approach that was implemented to perform the PSHAs for Yucca Mountain is generally consistent with state-of-the-practice guidance for a Level 4 analysis as defined by the Senior Seismic Hazard Analysis Committee (SSHAC, 1997). A Level 4 PSHA involves evaluations of the inputs by multiple experts in a series of workshops and individual elicitation meetings facilitated by a technical facilitator/integrator (TFI). The Level 4 approach was implemented because of the perceived technical complexity of the required evaluations, the first-of-a-kind evaluations of fault displacement potential for probabilistic analysis, the desire to include a sufficiently broad range of diverse technical interpretations to represent the epistemic uncertainty of the scientific community, and the public and regulatory importance of the project. Implementation of the project departed from the recommended Level 4 approach in one respect: throughout the project it was strongly emphasized that primary ownership of the PSHA results rests with the expert evaluators instead of the TFI. This emphasis ensured full compliance with regulatory procedures and practice while implementing the scope of a Level 4 evaluation. The PSHAs were performed in three strongly integrated parallel activities: (1) evaluation and characterization of seismic sources including the potential for fault displacement; (2) evaluation and characterization of ground motion attenuation, including the effects of earthquake source, wave propagation path, and site rock properties; and (3) probabilistic calculations of both fault displacement and ground motion hazards (Stepp *et al.*, 2001).

To capture the state of knowledge of the informed scientific community, epistemic uncertainty was evaluated by six teams of three earth science experts. Each team characterized seismic sources in the Yucca Mountain site region (generally within a distance of about 100 km) and fault displacement potential at the site. Similarly, to capture epistemic uncertainty in ground motion, seven ground motion experts characterized ground motion attenuation in the site region.

Ground motion hazard was computed for a defined reference rock outcrop indicated by Point A in Figure 1. (Points B, D, and E are locations where seismic design ground motions have been calculated through a site response analysis using ground motions derived at Point A as control motions.) Point A is characterized by a shear-wave velocity of 1900 m/sec and a kappa of 0.0186 sec.

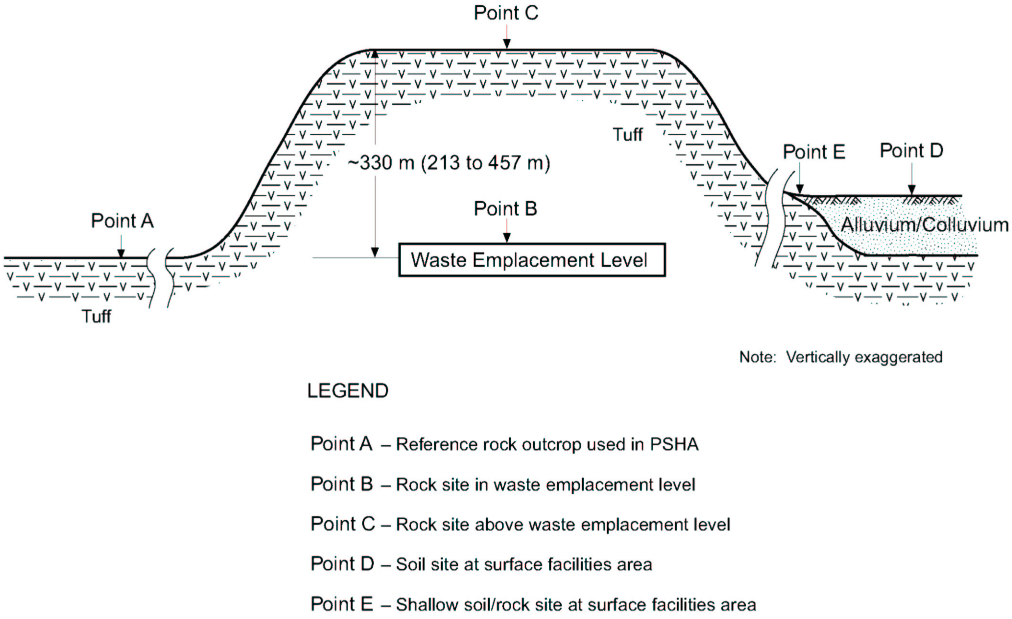

Figure 1. Locations of specified design earthquake ground motions. Point A is a hypothetical site and does not correspond to an actual location at Yucca Mountain.

EVALUATION AND CHARACTERIZATION OF SEISMIC SOURCES

The objective of evaluating and characterizing seismic sources for the ground-shaking PSHA was to describe alternative seismotectonic models of the site region that expressed the seismic source teams' uncertainties in source geometries, earthquake recurrence, and maximum magnitudes. The evaluations involved identifying and characterizing the seismic sources capable of producing earthquakes significant for ground-shaking hazard computation at the site.

The teams used two types of interpretations to express their epistemic uncertainties in seismic sources: fault-specific sources and areal source zones. Faults were characterized when earthquake activity (either through paleoseismic evidence or historical seismicity) could be confidently associated with a specific fault or fault zone. Alternative total fault lengths, alternative fault dips, and possible linkages with other faults express uncertainties in the geometry of fault-specific sources. The approximately 100 faults or fault zones identified as potential seismic sources within the site region were evaluated by the seismic source teams and incorporated into their interpretations (Stepp *et al.*, 2001).

Areal seismic source zones were used to represent distributed seismicity not apparently associated with known specific faults or to model groups of faults interpreted to have the same earthquake potential, at sufficiently large distances from the site such that the details of the individual faults are not significant for hazard calculation. Uncertainties in areal seismic source zones were expressed by weighted alternative interpretations of source boundaries. The teams interpreted the spatial distribution of earthquakes within areal source zones to be either homogeneous or nonhomogeneous.

GROUND MOTION EVALUATION AND CHARACTERIZATION

Strong motion data from the Basin and Range Province, even when combined with the limited data from analog tectonic environments are insufficient to adequately constrain empirical attenuation models for normal faulting earthquakes. Consequently, a key issue with respect to characterizing ground motion attenuation in the Yucca Mountain region was the applicability to the Basin and Range Province of western U.S. empirical attenuation models, which are based on relatively large data sets. Most empirical attenuation relations in the western U.S. are based primarily on recordings in California from strike-slip and reverse-slip earthquakes. Because strong motion recordings of normal faulting earthquakes are sparse, separate style-of-faulting factors typically have not been estimated for normal faulting.

The seven ground motion experts estimated median ground motion, aleatory variability (standard deviation), and epistemic uncertainties for a matrix of earthquake magnitudes, source-to-site distances, and faulting styles (normal and strike-slip) and for a suite of spectral frequencies. The ground motions were defined at Point A. These estimates were based on empirical and numerical simulation-based models and on combinations of conversion factors. The experts classified proponent models as empirical attenuation relations, hybrid empirical, point-source numerical simulations, finite-fault numerical simulations, and blast models.

Differences exist in the seismic source, regional crustal path, and shallow site properties for the Yucca Mountain region compared to those properties represented in the western U.S. strong motion data set. Since these attenuation relations are primarily based on California strong motion data, the ground motion experts evaluated the need to modify them (median and/or standard deviation) to account for differences between California and the Yucca Mountain site region. Alternative sets of conversion factors were developed to convert the California attenuation relations to conditions appropriate for the Yucca Mountain site region. The ground motion experts then evaluated which, if any, of the conversion factors should be applied to estimate the ground motion at Yucca Mountain.

A ground motion model estimates the median ground motion as a function of magnitude and distance and the aleatory variability (standard deviation) about the median. Both the median estimate and the standard deviation are uncertain. The experts used logic trees to characterize this epistemic uncertainty in their ground motion evaluations. Each ground motion expert evaluated the alternative models individually and developed his/her own composite model for their best estimates of the median and standard deviation for a given set of earthquake magnitudes and source distances. Thus, the experts' ground motion estimates consisted of four values for each magnitude-distance pair: median, aleatory standard deviation, epistemic uncertainty for the median, and epistemic uncertainty in the aleatory variability.

The ground motion experts' point estimates of the ground motion were parameterized by the ground motion TFI as attenuation equations for use in the hazard calculations. Each ground motion expert defined the distance measure used in the regression analyses for his/her point estimates. In addition, the experts evaluated the degree of ground motion saturation at large magnitude and close distances.

GROUND MOTION HAZARD RESULTS

The ground motion hazard at Yucca Mountain was computed at Point A (Figure 1). The calculation was conducted in three steps. For each seismic source expert team, the calculation was performed for each seismic source for each combination of attenuation and seismic source parameters, resulting in an appropriately weighted aleatory hazard curve for each combination. The total hazard across sources was then aggregated for each team to obtain the teams' mean and fractile hazard curves. The integrated hazard across all seismic source teams was obtained by combining the expert teams' mean and fractile hazard curves giving each team equal weight. A minimum magnitude of **M** 5.0 was used as the lower bound for integrating the earthquake recurrence relationship in the hazard calculations. The aleatory uncertainty (the variability about the ground motion experts' median attenuation) in the ground motion attenuation equations was modeled using the unbounded lognormal distribution (no upper bound was assumed).

Ground motion hazard was calculated for the ground motion measures peak horizontal ground acceleration (PGA), peak horizontal ground velocity, and spectral accelerations at 0.3, 0.5, 1, 2, 5, 10, and 20 Hz structural frequencies. The computations were based on equal weighting of the six seismic source expert teams' interpretations and the seven ground motion experts' interpretations. The results are presented in the form of summary hazard curves, which depict the mean, median, and 15th and 85th fractiles of the calculated aleatory hazard curves. The mean and median convey the central tendency of the hazard results while the separation between the 15th and 85th fractile curves conveys the epistemic uncertainty on the calculated exceedance frequency. Figure 2 shows summary hazard curves for PGA. At small annual exceedance frequencies ($< 10^{-6}$), the mean values exceed 3 g's.

GROUND MOTION HAZARD SENSITIVITY RESULTS

Extensive evaluations to determine the sensitivity of the hazard results to assessed input parameters were performed (Stepp *et al.*, 2001). The largest contributor to uncertainty in ground motion hazard was found to be uncertainty in ground motion attenuation. Specifically, experts' uncertainties about the median ground motion attenuation and the standard deviation of motion about the median, in that order, are the largest contributors. Expert-to-expert epistemic uncertainty is a smaller contributor to total hazard uncertainty.

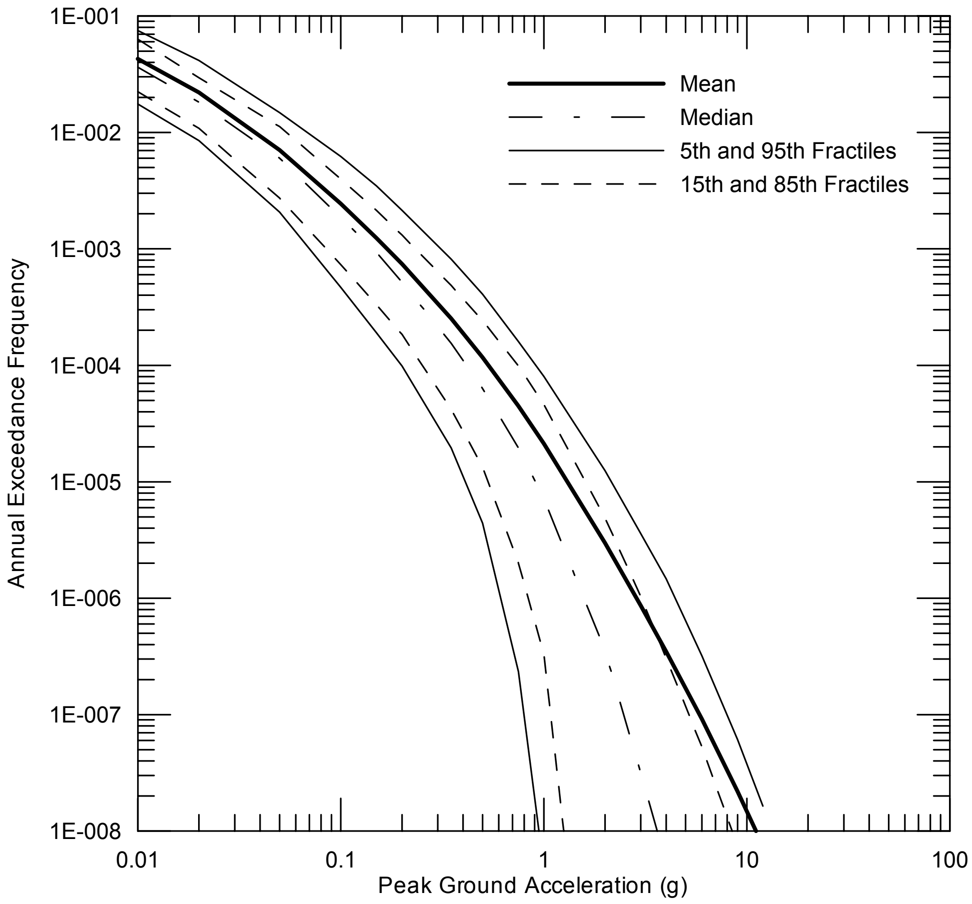

Figure 2. Summary hazard curves for horizontal PGA.

The composite mean hazard was deaggregated on magnitude, distance, and ground motion variability to determine controlling earthquakes and provide engineering insights for development of design basis spectra. Deaggregation of the mean hazard for an annual exceedance frequency of 10^{-7} shows that at intermediate frequencies (5 to 10 Hz), the ground motion hazard is dominated by earthquakes smaller than **M** 7.0 at distances less than 15 km (Figure 3). The sources of these earthquakes are the Paintbrush Canyon – Stagecoach Road and Solitario Canyon faults (or alternative interpretations of coalesced fault systems that include these faults) and the host areal seismic source zone. Dominant earthquake sources for low-frequency ground motions (e.g., 1 to 2 Hz) display a bimodal distribution with significant contributions to the total hazard from large nearby earthquakes, the three sources mentioned above, and from **M** 7 and larger earthquakes beyond distances of 50 km and ground motion variability larger than two standard deviations. The latter contribution is mainly from the comparatively active Death Valley and Furnace Creek faults.

1E-7 Hazard, 5-10 Hz Horizontal

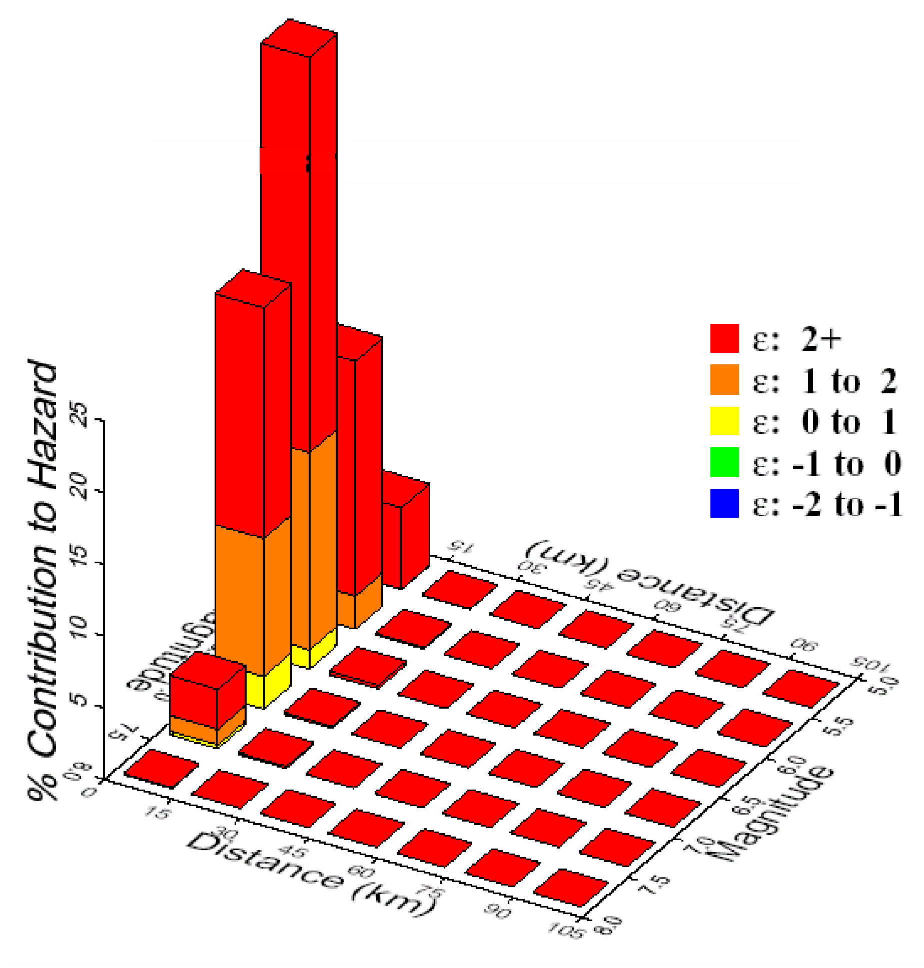

Figure 3. Contribution to mean hazard by magnitude, distance, and epsilon (ε) for the 5-10 Hz horizontal ground motions, 10^{-7} annual exceedance frequency.

REFERENCES

Senior Seismic Hazard Analysis Committee (SSHAC), 1997, Recommendations for probabilistic seismic hazard analysis-guidance on uncertainty and use of experts: U.S. Nuclear Regulatory Commission NUREG/CR-6372, variously paginated.

Stepp, J.C., Wong, I., Whitney, J., Quittmeyer, R., Abrahamson, N., Coppersmith, K., Toro, G., Youngs, R., Savy, J., Sullivan, T., and Yucca Mountain PSHA Project Members, 2001, Probabilistic seismic hazard analyses for ground motions and fault displacement at Yucca Mountain, Nevada: Earthquake Spectra, v. 17, p.113-151.