**ANALYSIS
SPECTRAL SHAPES FROM
CALIFORNIA AND
CENTRAL UNITED STATES
GROUND MOTION**

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INTRODUCTION

The objective of this study is to analyze the spectral shapes from earthquake records with magnitudes and distances comparable to those that dominate seismic hazard at Oak Ridge, in order to provide guidance for the selection of site-specific design-spectrum shapes for use in Oak Ridge. We rely heavily on California records because the number of relevant records from the central and eastern United States (CEUS) is not large enough for drawing statistically significant conclusions. We focus on the 0.5 to 10-Hz frequency range for two reasons: (1) this is the frequency range of most engineering interest, and (2) we avoid the effect of well-known differences in the high-frequency energy content between California and CEUS ground motions.

BACKGROUND: FACTORS THAT AFFECT SPECTRAL SHAPES

This section describes the main factors that affect the spectral shapes of earthquake ground motions, using generally accepted concepts and results from engineering seismology.

Magnitude

Larger earthquakes generally break a larger portion of the earth's crust and have longer durations. As a result, larger earthquakes are more effective at producing lower-frequency ground motions and have a higher proportion of low-frequency energy than smaller earthquakes. Figure 1 shows the effect of magnitude on spectral shapes.

As an illustration, consider the development of a design spectrum for a 1 Hz structure located in the eastern United States, in a region with maximum magnitude in the range of 6.0 to 6.5. If we use a spectral shape based on California earthquakes with magnitudes near 7.0, we implicitly assume that the ratio $PSV(1\text{ Hz})/PGA$ is the same for the earthquakes affecting the site as for the magnitude 7.0 California earthquakes used to construct the spectral shape. In fact, we know from seismology and observation that this ratio is lower for earthquakes that threaten our structures, due to the effects of magnitude. Thus, using a California spectral shape (with its higher $PSV[1\text{ Hz}]/PGA$ ratios), together with a PGA value appropriate for the hazard at the site, will lead to overestimation of the hazard for the 1 Hz structure.

High-Frequency Energy

Earthquake ground motions at rock sites in the western United States have little energy at frequencies higher than 20 Hz (Hanks, 1982; Anderson and Hough, 1982). In contrast, a number of ground-motion records obtained at hard rock sites in the central and eastern United States (CEUS) have significant energy at frequencies as high as 50 Hz. This high-frequency energy affects the spectral accelerations at high frequencies ($f > 20\text{ Hz}$) as well as the PGA, but it does not affect spectral accelerations at lower frequencies. These differences are generally explained as the result of less damping in the upper crust (e.g., Hanks, 1982), but alternative interpretations have been proposed (e.g., Papageorgiou, 1988). The shape of the power spectrum at high frequency is often parameterized by the frequency f_{max} (Hanks, 1982) or the attenuation time kappa (Anderson and Hough, 1984).

As a result of these differences in high-frequency energy, the high-frequency portion of the response spectrum is very different for these two types of earthquakes, as illustrated in Figure 2.

Considering again the 1 Hz structure in the eastern United States, we note that earthquakes in the east will have higher PGA and similar 1 Hz amplitudes (hence, lower PSV[1 Hz]/PGA ratios) than California earthquakes of the same magnitude. Thus, using a California spectral shape (with its higher PSV[1 Hz]/PGA ratios), together with a proper eastern PGA attenuation function, will lead to overestimation of the hazard for the 1 Hz structure.

Distance also has an effect on high-frequency energy, due to anelastic attenuation (i.e., damping) in the earth's crust. High-frequency waves go through more cycles as they travel a certain distance, so they undergo more damping. As a result, ground motions from distant earthquakes contain a lower proportion of high-frequency energy. This effect becomes important at distances of more than 50 km and has only a minor effect on seismic hazard.

Site Response

Site responses may have a dramatic effect on earthquake ground motions. Thus, the presence of soil beneath the site greatly affects the spectra of the ground motions expected at the site. Figure 3 illustrates the effect of site response on spectral shape by comparing the spectra from records obtained at two nearby stations: one on firm soil, the other on rock.

Site characteristics affect ground motions through two basic phenomena: elastic amplification of motions as the waves travel through softer materials and as energy is trapped in the softer layers, and increased energy loss due to damping. Both phenomena are frequency dependent. Both phenomena, particularly damping, are also amplitude-dependent.

Deep-soil sites tend to amplify low-frequency motions (for which amplification effects are dominant) and to dampen high-frequency motions (for which damping effects are dominant). The net effect on peak acceleration is typically small, but the effect on spectral shapes may be dramatic.

Shallow-soil sites have little effect on low-frequency energy and tend to amplify high-frequency energy and PGA (for which elastic resonance effects due to trapped energy are dominant).

More details on the two phenomena described above are contained in McGuire et al. (1988) and EPRI (1993) and references thereof. Other phenomena affecting site response are also discussed in these references.

Use of Spectra Associated with High Fractiles

A common practice in the development of spectral shapes is to select representative records, scale all records to a common PGA, compute their response spectra, and calculate the spectrum associated with the 84 percentile. That is, at each frequency the calculated spectral acceleration is higher than the spectral accelerations in 84 percent of the selected records. This practice was

followed in the development of the NRC Regulatory Guide 1.60 spectrum (NRC, 1973; see also Blume, Newmark and Kapur, 1973).

As one moves to lower frequencies (i.e., away from peak acceleration), the scatter among the selected spectra increases due to the effects of magnitude, high-frequency energy, and site response discussed earlier, in addition to the inherent randomness in spectral shapes (even for sites with similar characteristics). Because of this high scatter at low frequencies, the 84 percentile spectrum deviates substantially at low frequencies from the median value of these same spectra. This difference is not the result of justified conservatism; rather, it is the result of conservatism combined with a sub-optimal, indirect procedure for the estimation of low-frequency spectral accelerations (i.e., an attenuation function for PGA times a constant factor is a much worse predictor of spectral acceleration than an attenuation function for low-frequency spectral acceleration; hence, the indirect estimate will result in higher scatter).

Figure 1: Predicted pseudovelocity response spectra for zero epicentral distance and several values of moment magnitude. Source: Boore and Joyner, 1988.

Figure 2: Comparison of spectral shapes for CEUS and western U.S. (WUS) for moment magnitude 6.5. Source: Silva and Green (1989).

Figure 3: Response spectra (5% damped) recorded at Gilroy 1 (rock: solid line) and Gilroy 2 (soil: dashed line) during the 1979 Loma Prieta earthquake (the log average of two horizontal components is plotted). Source: EPRI, 1993.

DOMINANT MAGNITUDES AND DISTANCES FOR OAK RIDGE

Seismic hazard calculations performed for the Oak Ridge site indicate the following dominant magnitudes and distances for Oak Ridge for 10^{-3} annual exceedance probability (Risk Engineering, 1992, 1993):

Ground Motion Measure	M (m_{Lg})	R (km)
Peak Ground Acceleration (PGA)	5.6	38
2.5-Hz Spectral Velocity	5.9	70
1-Hz Spectral Velocity	6.35	100

These magnitudes and distances were computed using the EPRI methodology and seismological interpretations and considering the normalized contributions of various magnitudes and distances to the mean hazard.

These results indicate that seismic hazard at Oak Ridge is due mainly to earthquakes with intermediate magnitudes, even for low structural frequencies.

SELECTION OF RECORDS FOR THIS STUDY

Based on the dominant magnitudes and distances for PGA and for 1-Hz spectral velocity, we selected ground-motion records from rock sites in California, for earthquakes in the following magnitude-distance intervals:

- a. events that dominate PGA: m_{Lg} 5.25 to 5.75 (moment magnitude M 4.8 to 5.4) at 20 to 60 km;
- b. events that dominate 1-Hz PSV: m_{Lg} 6.0 to 6.5 (moment magnitude M 5.6 to 6.3 at 70-130 km.

The conversion from m_{Lg} to moment magnitude was performed using the relationship by Boore and Atkinson (1987)

$$M = 2.715 - 0.277 m_{Lg} + 0.127 m_{Lg}^2$$

(Figure 4) which is nearly identical to that obtained by Toro et al. (1988).

These magnitude-distance intervals, particularly the second, had to be widened in order to obtain approximately 30 horizontal records (i.e., 15 event-site pairs) in each magnitude-distance category. The final magnitude-distance intervals were M 4.8 to 5.4 at 9 to 60 km and M 5.5 to 6.5 at 15 to 180 km. There were more than 30 records in the first magnitude-distance interval,

many of them came from the same event or aftershock sequence. Some of those records were removed from consideration, prior to examining their spectral shapes, in order to obtain a more representative data set. The selected records are listed in Tables 1 and 2. All data were selected from an extensive California strong-motion dataset under development for EPRI (W. Silva, personal communication, 1993). This dataset is particularly rich, relative to other datasets, in the magnitude intervals of interest to this study.

TABLE 1. RECORDS REPRESENTATIVE OF EVENTS THAT DOMINATE PGA

Earthquake	Year	Date (mmyy)	Time	Moment Magnitude (M)	Station	Dist. (km)
San Francisco	1957	0322	1944	5.3	Golden Gate Park	9.5
Lytle Creek	1974	1128	2301	5.2	Cedar Springs	20.6
Lytle Creek	1974	1128	2301	5.2	Devis's Canyon	21.9
Lytle Creek	1970	0912	1430	5.3	Santa Anita Dam	45.9
Hollister	1974	1128	2301	5.2	Gilroy Array #1	12.3
Northern Calif	1975	0607	0846	5.2	Cape Mendocino, Petrolia	28.9
Northern Calif	1975	0607	0846	5.2	Shelter Cove, Sta A	59.2
Coalinga	1983	0509	0249	5.1	Anticline Ridge Free-field	12.6
Coalinga	1983	0509	0249	5.1	Burnett Construction	12.7
Coalinga	1983	0509	0249	5.1	Sulphur Baths (temp)	12.6
Coalinga	1983	0509	0249	5.1	Burnett Construction	12.7
Coalinga	1983	0509	0249	5.1	Skunk Hollow	12.4
Coalinga	1983	0611	0309	5.3	Sulphur Baths (temp)	9.7
Coalinga	1983	0709	0740	5.2	Sulphur Baths (temp)	17
Coalinga	1983	0709	0740	5.2	Oil Fields Fire Station	10
Coalinga	1983	0709	0740	5.2	Skunk Hollow	12.6
Coalinga	1983	0709	0740	5.2	Transmitter Hill	10.4
Coalinga	1983	0722	0343	4.9	Sulphur Baths (temp)	13.7
Coalinga	1983	0725	2231	5.2	Sulphur Baths (temp)	14.7
Coalinga	1983	0909	0916	5.3	Sulphur Baths (temp)	18.4

Table 2. RECORDS REPRESENTATIVE OF EVENTS THAT DOMINATE 1-Hz PSV

Earthquake	Year	Date (mmyy)	Time	Moment Magnitude (M)	Station	Dist. (km)
Anza	1980	0225	1047	5.5	Borrego Air Ranch	40.6
Mammoth Lakes	1980	0525	1944	6.0	Long Valley Dam (U.L.A)	19.7
Mammoth Lakes	1980	0525	1944	6.0	Long Valley Dam (Down)	19.7
Mammoth Lakes	1980	0525	1944	6.0	Long Valley Dam (L.A.)	19.7
Westmorland	1981	0426	1209	5.6	Superstition Mtn Camera	26.5
Coalinga	1983	0722	0239	5.9	Sulphur Baths (temp)	15.3
N. Palm Springs	1986	0708	0920	6.0	Anza - Red Mountain	45.6
N. Palm Springs	1986	0708	0920	6.0	Santa Rosa Mountain	43.8
N. Palm Springs	1986	0708	0920	6.0	Anza - Tule Canyon	55.4
N. Palm Springs	1986	0708	0920	6.0	Lake Mathews Dike Toe	73.7
N. Palm Springs	1986	0708	0920	6.0	Murrieta Hot Springs	63.3
N. Palm Springs	1986	0708	0920	6.0	Winchester Bergman Ran	57.6
N. Palm Springs	1986	0708	0920	6.0	Silent Valley - Poppet F	25.8
Whittier Narrows	1987	1001	1442	6.0	Carbon Canywn Dam (L.Ab.)	26.8
Whittier Narrows	1987	1001	1442	6.0	Mt Wilson - CIT Seis Sta	21.2

CALCULATIONS AND COMPARISONS IN THE 0.5 TO 10-Hz RANGE

We calculate response spectra (for 5% damping) for each record and then compute statistics on log-amplitudes and log [amplitude ratios] for each group of records. Figures 5 and 6 show the ratio $PSV(f)/PGA$ (in units of cm/sec/g). Figures 7 through 10 show the dimensionless ratios $PSV(f)/PSV(10\text{ Hz})$ and $PSV(f)/PSV(2.5\text{ Hz})$.

Focusing on Figures 5 and 6, we note that the median spectra peak at approximately 5 and 2 Hz, respectively. The corresponding mean+sigma spectra (which are approximately equal to 84 percentile spectra) peak at slightly lower frequencies. This is consistent with the peaks observed in records from earthquakes in CEUS (Figures 5-13 and 5-14 of Risk Engineering, 1992). Figures 7 through 10 show similar results for their median shapes. These two sets of observations indicate that the spectra from the earthquakes that dominate the hazard at Oak Ridge are expected to peak in the range of 2 to 5 Hz.

Comparing Figures 5 and 6, we observe the effect of magnitude on spectral shape: the smaller-magnitude earthquakes contain a lower proportion of low-frequency energy and have narrower spectra. The same effects are observed in Figures 7 through 10.

Continuing on the issue of spectral shapes, Figures 11 and 12 compare the observed spectral shapes to three spectra derived as part of the Oak Ridge seismic hazard study (Risk Engineering, 1992) and follow-up work by Martin Marietta Energy Systems. These spectra are as follows:

1. The median uniform-hazard spectrum for 10^{-3} annual exceedance probability obtained directly as part of conventional seismic-hazard calculations (combining EPRI and LLNL results, including LLNL ground-motion expert 5). This spectrum is lower than the other two because it is associated with median, as opposed to mean hazard.
2. The pseudo-mean spectrum developed for 10^{-3} annual exceedance probability from the EPRI and LLNL seismic hazard results by following the Department of Energy Interim Position on the use of EPRI and LLNL results (Kimball, 1992).
3. The design spectrum for 10^{-3} annual exceedance probability developed by Martin Marietta Energy Systems.

For these comparisons, the spectral shapes calculated earlier have been scaled so as to coincide with the Interim-Position spectra at 10 Hz (for the magnitudes that dominate PGA) and at 2.5 Hz (for the magnitudes that dominate 2.5 Hz PSV).

Figure 11 shows that the spectra from earthquakes that dominate PGA (they also dominate 10-Hz PSV) are substantially narrower than the spectra obtained from the seismic hazard results. The slope between 5 and 10 Hz is higher for the California records than for the three spectra derived above. This is probably due to the East-West differences in high-frequency energy, which are already apparent at 10 Hz. As a result of this higher slope, the spectra from the California records is somewhat higher than the Interim Guidelines spectrum at frequencies near 5 Hz, when both spectra are made to coincide at 10 Hz.

Figure 12 shows consistency between observed and calculated spectral shapes over the range of 1 to 10 Hz. Outside this range, the observed spectra are narrower than the calculated spectra.

So far, we have presented relative comparisons, focusing on spectral shapes rather than absolute amplitudes, and we have shown that the spectral shapes used in the Oak Ridge design spectrum and other calculated spectra are consistent (if not conservative) in relation to observations from relevant magnitudes and distances. Figures 13 and 14 will show comparisons that consider amplitudes, as well as shapes. In Figure 13, the observed amplitudes from each record in the first category (earthquakes that dominate the PGA hazard) have been scaled to M 5.1 and 38 km distance using the Boore et al. (1993) attenuation equation for PGA in California. The logarithmic mean and mean σ are then computed from the scaled observations. The resulting spectra are compared to the spectral shape predicted by the Toro et al. (1988) CEUS attenuation functions for the corresponding m_{Lg} and the same distance. There is very close agreement for all frequencies below 10 Hz. The differences above 10 Hz are the result of well understood differences in high-frequency energy between California and CEUS.

A similar procedure is followed in Figure 14 for records in the second category (earthquakes that dominate the 1-Hz hazard), this time scaling to M 6.1 and 100 km using the Boore et al. (1993) attenuation equation for 1-Hz PSV in California. There is very close agreement in the 2 to 10-Hz range and, as expected, the CEUS attenuation functions are higher above 10 Hz. At frequencies below 2 Hz, the CEUS attenuation functions over-predict the amplitudes, suggesting that the attenuation functions are conservative for intermediate to high magnitudes and low frequencies. Atkinson and Boore (1993) have reached this conclusion using a larger data set. There is a mounting body of evidence that suggests that attenuation functions based on point-source stochastic ground-motion models (such as Toro et al., 1988, or EPRI, 1993) over-predict low frequency ground motions for intermediate to high magnitudes.

The results presented in Figures 5 through 12 indicate that the spectral shapes derived for Oak Ridge using results from the seismic hazard results are consistent, if not conservative, with the observed shapes from relevant California records, for frequencies below 10 Hz. Figures 13 and 14 show that CEUS attenuation equations of the type used in the seismic hazard calculations properly predict the absolute amplitudes in the same frequency range and appear to over-predict low frequencies for intermediate magnitudes. These two results justify the use of any of these derived spectral shapes, anchored at frequencies near 2.5 Hz, for deriving design spectra.

COMPARISONS OF LOW FREQUENCY TO HIGH FREQUENCY: CALIFORNIA vs. CEUS

It is generally accepted that ground motions from rock recordings of CEUS earthquakes have more high-frequency energy than their counterparts in California. This has been attributed to the presence of more competent rock in CEUS than in California.

The additional high-frequency energy of CEUS earthquakes generates higher PGA and higher PSV above 10 Hz than California earthquakes of comparable magnitudes and distances. This is

generally accepted and is easily observed by comparing attenuation functions for CEUS and California (after allowing for differences in magnitude scales).

This additional high-frequency energy has no effect on PSV values near 1 Hz or on peak ground velocity (PGV). This is easily shown using random-vibration theory or time-domain integration.

As a result, CEUS ground motions have spectral shapes different from California ground motions with the same magnitudes and distances, when looking at a wide frequency range. This is in contrast to the comparisons presented earlier, which focused on the narrower 1 to 10-Hz range.

One common measure of the ratio of low frequency to high frequency is the PGV/PGA (typically referred to as the V/A ratio). The logarithmic average of the V/A ratios for the two sets of California records in Tables 1 and 2 is 38 (equal for both categories; for a total of 58 records); the corresponding logarithmic standard deviation is 0.4. Similar calculations for the CEUS records in Table 5.4 of the Oak Ridge Seismic Hazard study (Risk Engineering, 1982) yield logarithmic averages of 29 for events near magnitude 5.2 (12 records) and 25 for events near magnitude 6 (10 records); the corresponding standard deviation is also 0.4.

These V/A ratios are compared in Table 3 to the ratios predicted by CEUS and California attenuation functions and to the ratio implicit in some design spectra.

TABLE 3. COMPARISON OF V/A RATIOS

Source	m_L 5.6 (M 5.1) at 38 km	m_L 6.35 (M 6.0) at 100 km
CEUS Records used in Risk Engineering (1992)	29	25
California Records, this study	38	38
Atkinson and Boore (1990) attenuation equations for CEUS	22	44
Atkinson and Boore (1993) attenuation equations for CEUS	14	23
Toro et al. (1988) attenuation equations for CEUS	18	37
Boore and Joyner (1988) attenuation equations for WUS	27	47
Newmark-Hall (1982) design spectrum (Fig 5)	N/A	132
Newmark, Blume and Kapur (1973)	N/A	120

The V/A ratios from records and from attenuation functions show that there is a significant difference in V/A ratios between CEUS and California. Even if one allows for the small number of CEUS events available for analyses of this type, it is unlikely that the observed differences in V/A ratios are due to chance. These differences are a consistent manifestation of differences in spectral shape.

These ratios also indicate the tendency of V/A to increase with magnitude. The CEUS data in Risk Engineering (1992) do not exhibit this tendency because of the Saguenay earthquake and its unusual frequency content, but it is reasonable to conclude that this tendency applies also to CEUS.

The most striking result from Table 3 is that the V/A ratios implied in standard spectral shapes are much higher than the observed and predicted V/A, ratios for the magnitudes and distances that dominate seismic hazard at Oak Ridge. This is true even for the California data and attenuation functions.

As a result of these differences, use of standard spectral shapes based on California ground motions (which imply high V/A ratios) anchored to PGA values that are appropriate for CEUS, results in spectra that overestimate the hazard for low-frequency structures. The fact that a number of the records represented in standard spectral shapes were obtained at deep-soil sites and from larger earthquakes, makes this situation worse. This conclusion is valid for sites like Oak Ridge that are on rock and are not exposed to seismic sources capable of large-magnitude earthquakes.

CONCLUSIONS

The comparisons presented here serve to reinforce several well known facts about ground motions at typical rock sites in CEUS, as follows:

1. For a given magnitude and distance, the ground motions in the 1 to 10-Hz frequency range at rock sites in CEUS and California are approximately equal and are properly represented by uniform-hazard spectra and by the CEUS attenuation functions in current use.
2. Because CEUS ground motions are higher than California ground motions at high frequencies and comparable to California ground motions at low frequencies, CEUS ground motions have different spectral shapes and lower V/A ratios than California ground motions. As a result, use of a California-based spectral shape anchored to a CEUS design, PGA would lead to conservatism at low frequencies.
3. The V/A ratios implied in typical design spectral shapes are much higher than the observed or predicted V/A ratios for the magnitude-distance interval that dominates seismic hazard at Oak Ridge. Thus, use of a standard spectral shape anchored to the Oak Ridge design PGA would grossly overestimate spectral amplitudes at frequencies near 1 Hz.

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Figure 4: Relationship between seismic moment M and m_{Lg} . The curves labeled BA87 and EPRI are from Boore and Atkinson (1987) and Toro et al. (1988). The rectangles and dots represent data from Boore and Atkinson (1987). Source: Boore et al. (1993).

PSV(f) / PGA Ratios
M 4.8-5.4 Records

Figure 5

PSV(f) / PGA Ratios
M 5.5-6.5 Records

Figure 6

PSV(f) / PSV(10Hz) Ratios
M 4.8-5.4 Records

Figure 7

PSV(f) / PSV(10Hz) Ratios
M 5.5-6.5 Records

Figure 8

PSV(f) / PSV(2.5Hz) Ratios
M 4.8-5.4 Records

Figure 9

PSV(f) / PSV(2.5Hz) Ratios
M 5.5-6.5 Records

Figure 10

Scaled Spectra from M 4.8-5.4 Records vs. Oak-Ridge Spectra

Figure 11

Scaled Spectra from M 5.5-6.5 Records vs. Oak-Ridge Spectra

Figure 12

Response Spectra Normalized to M 5.1,
R 38km vs. CEUS Attenuation Function

Figure 13

Response Spectra Normalized to M 6,
R 100km vs. CEUS Attenuation Function

Figure 14

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