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A technique for uniform hazard spectra estimation in the US

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ABSTRACT: Methods have recently been developed for the estimation of uniform hazard spectra for earthquake ground motion on a regional basis in the United States. These methods provide a new, alternative approach for the development of design spectra. This approach does not depend upon the use of peak ground acceleration (or effective acceleration) and/or peak ground velocity. Using this new approach, we have developed a new series of hazard maps which present the five percent damped, spectral response acceleration at a discrete periods (0.3 and 1.0 sec) for two time periods of interest (50 and 250 years) with a 10 percent chance that the map values will be exceeded. Detailed studies of spectral shapes at a number of sites throughout the United States were undertaken by computing the probabilistic acceleration response at 12 periods ranging from 0.1 to 4.0 sec. These spectral shapes provide two interesting results: (1) in general, the entire response spectra can be adequately modelled using spectral ordinates at only the two mapped periods (0.3 and 1.0 sec), and (2) spectra have distinctive regional shapes. Analytical expressions for the shapes of the acceleration response spectra are presented for the characteristic spectra in each geographic area.

1 INTRODUCTION

The results in this study represent a significant milestone in the evolutionary development of the probabilistic evaluation of earthquake ground motion in the United States on a national scale. The first national probabilistic ground motion map of the U.S. was developed for peak acceleration in rock, with a 10 percent chance of being exceeded in 50 years (Algermissen and Perkins, 1976). This early map, with some modification, was adopted as an earthquake design map in a national study of seismic provisions for buildings (Applied Technology Council, 1978). Subsequently, probabilistic peak acceleration and velocity maps with a 10 percent chance of exceedance in exposure times of 10, 50 and 250 years were published for Alaska (Thenhaus and others, 1982) and for the contiguous U.S. (Algermissen and others, 1982). Variability in attenuation and length of fault rupture was included in the most recent acceleration and velocity maps of the contiguous U.S. (Algermissen and others, 1990). The Algermissen and Perkins (1976) acceleration map has been used in all editions of the "National Earthquake Hazard Reduction Program (NEHRP) Recommended Provisions for the Development of Seismic Regulations for New Buildings" (hereafter referred to as the NEHRP Provisions) through the current 1991 edition (Building Seismic Safety Council, 1985, 1988, 1991).

Our new maps represent a significant departure from past practice in that they allow the construction of response and design spectra for recommended seismic provisions of building codes, directly from mapped spectral ordinates rather than from mapped values of peak acceleration and/or velocity.

2 GROUND MOTION MODEL

The calculation of ground motion is based on the assumption that earthquakes are exponentially distributed with regard to magnitude and interoccurrence time, and are uniformly distributed in space with regard to source zones and source faults. The exponential magnitude distribution is an assumption based on empirical observation. The assumption of an exponential interoccurrence time is that of a uniform distribution in time (the Poisson process) and is consistent with historical earthquake occurrence insofar as it affects the probabilistic hazard calculation and the estimation of damaging ground motion. However, we are investigating the effect of incorporating fault slip rate data from paleoseismic studies in California in a Poisson model or, alternately, making use of a time dependent probabilistic model for the magnitude range of earthquakes over which fault slip data are available (Thenhaus and others, 1992).

The seismotectonic elements of the model, the seismic source zones, and the magnitude distribution of earthquakes within each source given are those used by Algermissen and others (1990). A more complete discussion of the seismotectonic model, seismicity data and the development of the probabilistic model is given by Algermissen and others (1982 and 1990). Fault rupture length is modelled using an expression given by Mark (1977).

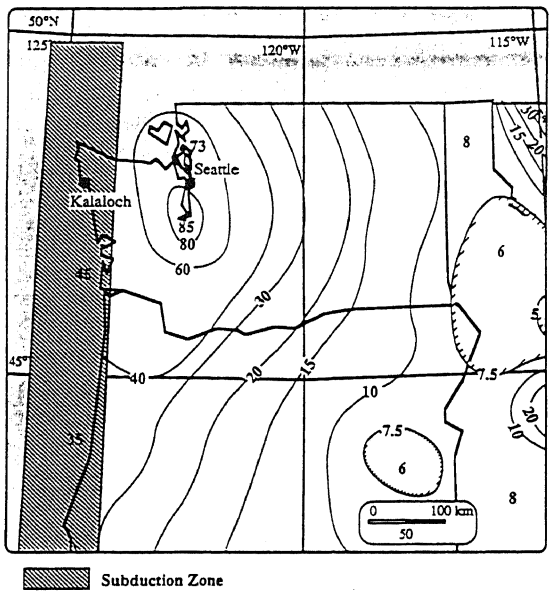

Figure 1. Ground motion map of the Pacific Northwest (Washington and portions of Oregon and Idaho) showing spectral response acceleration (in percent of g) for 0.3 sec. period, 5% damping and 10% probability of exceedance in 50 years.

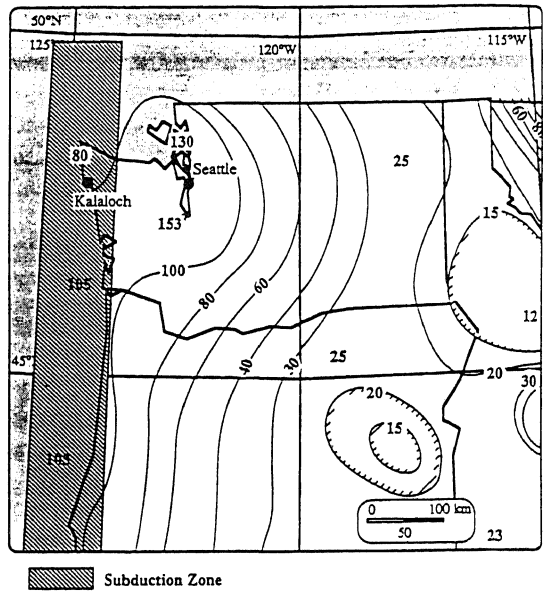

Figure 3. Ground motion map of the Pacific Northwest (Washington and portions of Oregon and Idaho) showing spectral response acceleration (in percent of g) for 0.3 sec. period, 5% damping and 10% probability of exceedance in 250 years.

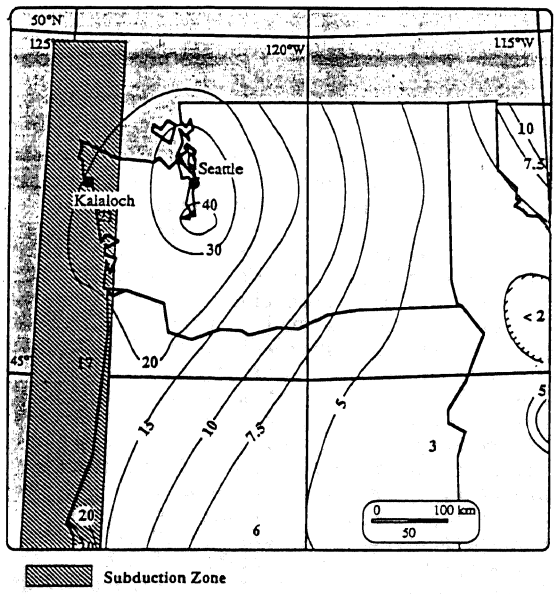

Figure 2. Ground motion map of the Pacific Northwest (Washington and portions of Oregon and Idaho) showing spectral response acceleration (in percent of g) for 1.0 sec. period, 5% damping and 10% probability of exceedance in 50 years.

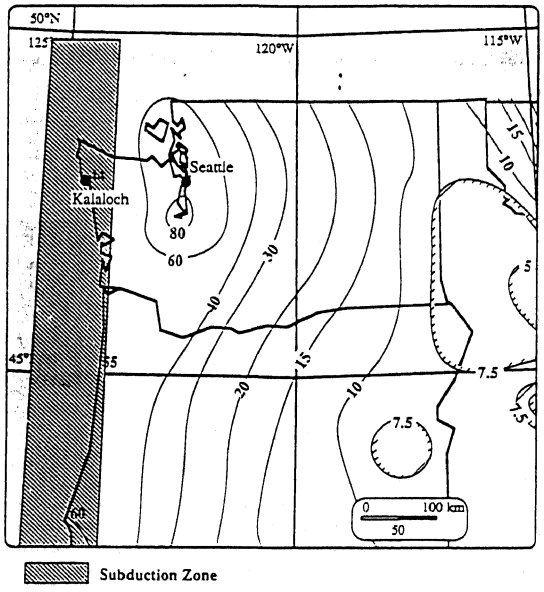

Figure 4. Ground motion map of the Pacific Northwest (Washington and portions of Oregon and Idaho) showing spectral response acceleration (in percent of g) for 1.0 sec. period, 5% damping and 10% probability of exceedance in 250 years.

The development of the spectral response acceleration maps presented here has been made possible by recently published relations between spectral acceleration and attenuation for both the eastern and western areas (west of the eastern front of the Rocky Mountains) of the United States. The attenuation of spectral acceleration used for shallow earthquakes in the Western United States is that of Joyner and Boore (1982). The standard deviation varies slightly according to the period; however, a representative value of log (spectral response acceleration) is 0.33 at a period of 1.0 sec. The attenuation of spectral acceleration used for the central and eastern United States (the areas east of the eastern front of the Rocky Mountains) is that of Boore and Joyner (1991). These authors have suggested using the same variability as in the paper of Joyner and Boore (1982). Modelling of attenuation in the Pacific Northwest (Washington and Oregon) is more complicated because there are three distinct sources of earthquakes: (1) large, subduction zone earthquakes that have been assumed capable of rupturing a 100 km-wide zone down dip of the offshore ocean trench axis from the Strait of Juan de Fuca to the Oregon-California border. These subduction zone earthquakes are modelled as having magnitudes of Mw=8.5 and average recurrence times of 500 years (based on our assessment of data of Atwater (1987), (2) large (up to Mw=7.3) intraplate shocks that historically have occurred in the Puget Sound depression at focal depths of 50-70 km beneath the Olympia-Seattle, Washington area, and (3) shallow earthquakes that may occur throughout the entire Pacific Northwest. The spectral response acceleration attenuation used for the subduction zone and the intraplate earthquakes is that given by Youngs and Coppersmith (1989). The attenuation of shallow earthquakes was modelled using the relation developed by Joyner and Boore (1982), the same attenuation we used for shallow earthquakes throughout the rest of the western United States.

3 GROUND MOTION MAPS

Spectral response acceleration maps (contours as a percent of gravity) have been developed for the entire contiguous United States, at periods of 0.3 sec and 1.0 sec for an S2 soil profile for exposure times of 50 and 250 years (return periods of 474 and 2372 years). A type S2 soil profile is defined in the NEHRP Provisions (1991) as a profile with deep cohesionless or stiff clay condition where the soil depth exceeds 200 feet and the soil types overlying rock are stable deposits of sands, gravels or stiff clays. We presented two of the maps in the national series described above in an earlier publication (Algemissen and others, 1991). Here, we present and discuss additional maps in the series together with analyses of spectral shapes constructed from these maps.

3.1 *Pacific Northwest*

Earthquakes in the Pacific Northwest have been modelled as occurring in three general types of seismic source zones described earlier. The subduction zone (shown hatchured in Figure 1) has been modelled as a plane dipping 12 deg. east from the surface intersection of the Juan de Fuca and North American plates beneath the coastal areas of Washington and Oregon. The plate is modelled as being 1200 km long, extending from the Strait of Juan de Fuca to 200 km south of the Oregon-California border. The subduction zone earthquakes considered by us as most likely to occur are modelled as shocks with magnitudes of Mw=8.5, with a rupture surface of 200 km along the strike and 100 km down dip from the surface intersection of the two crustal plates. Other seismic source zones, which model intraplate earthquakes at depths of 50-60 km beneath the Puget Sound Basin and shallow shocks throughout the region are the same as used in the study of Algermissen and others (1982). Figure 1 shows the map for the 0.3 sec period, 5% damped, 10% probability of exceedance in 50 years spectral response for the states of Washington and Oregon. Figures 2, 3, and 4 show spectral response acceleration maps for other spectral periods and exposure times. Figure 5 illustrates the contribution of the subduction zone earthquakes to the total probabilistic ground motion (spectral response acceleration at 0.3 sec) for a site at Kalaloch, on the west coast of Washington over the subduction zone, and at Seattle, Washington, for three exposure times (10, 50 and 250 years). Note that subduction zone earthquakes contribute little to the total probabilistic ground motion at Seattle for any exposure time up to at least 250 years, and this is true for all inland Washington and Oregon. Subduction zone earthquakes do affect the spectral response acceleration values in the coastal areas of Washington and Oregon. For exposure times of 50 years, the inclusion of subduction zone earthquakes in the model increases spectral values about 10% in coastal areas. For an exposure time of 250 years, the increase is 30 to 40% in coastal areas depending on period (0.3 sec. or 1.0 sec). Examination of the maps shows that the most prevalent source of damaging ground motion in Seattle and other large cities of the Puget Sound Basin is intraplate earthquakes that occur frequently (such as in 1939, 1946, 1949 and 1965) which in this area are at depths of 50-60 km.

3.2 *California and Nevada*

An example of probabilistic ground motion modelling of a major strike slip plate boundary (western California) and a large area of extensional faulting (Nevada) is shown in Figure 6 which is a 50-year, 1.0 sec. spectral response acceleration for California and Nevada and is a companion map to the 0.3 sec., 50-year map published earlier (Algermissen and others, 1991). The rates of seismic activity used in the preparation of the California maps discussed and presented here are based primarily on historical seismicity. Work is currently underway to evaluate the effect of incorporation of the data on slip rates that has been developed for a number of faults in California (Thenhaus and others, 1992).

3.3 *Central and Eastern United States*

Ground motion modelling in the central and eastern

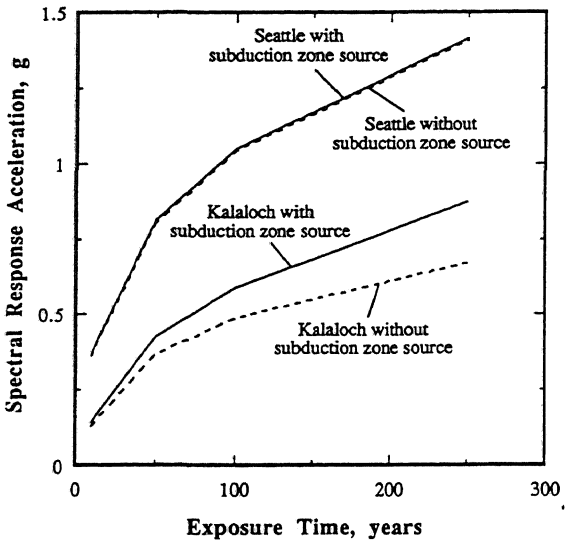

Figure 5. Comparison of 0.3 sec. spectral response acceleration, as a fraction of gravity, versus exposure time with and without a subduction zone as a seismic source zone. The results are shown for Seattle and Kalaloch, Washington (see figure 1 for locations). The subduction zone has little effect on the probabilistic ground motion in Seattle which is removed from the subduction zone. The effect at Kalaloch, located over the subduction zone, is significant.

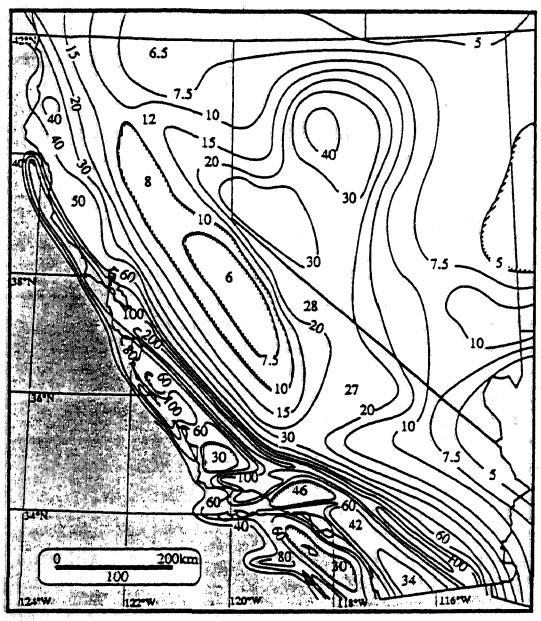

Figure 6. Ground motion map of California and Nevada showing spectral response acceleration (in percent) for 1.0 sec. period, 5% damping and 10% probability of exceedance in 50 years.

United States is dominated by the large earthquakes that occurred in southeast Missouri in 1811-12, and by the Charleston, South Carolina earthquake of 1882. Figure 7 shows the 50-year, 0.3 sec spectral response acceleration map for the central and eastern portion of the United States. As in California, this map is a companion map to the 1.0 sec, 50-year map published earlier (Algermissen and others, 1991). In the eastern United States the 0.3 sec spectral accelerations are a factor of 2 to 3 higher than the 1.0 sec spectral accelerations in the same areas. However, this same ratio in the New Madrid seismic zone in southeast Missouri and in California is only a factor of 1 to 2 higher. These differences in the ratio of short to long period energy are believed to be related to the tendency of attentuation (and consequently ground motion) to saturate in areas of high seismicity and high maximum magnitude earthquakes.

3.4 *Western mountain and central plains*

The western mountain and central plains are areas of diverse seismotectonic style and earthquake occurrence. Some examples of areas with potential for significant levels of damaging ground motion are

Figure 7. Ground motion map of Central and Eastern United States showing spectral response acceleration (in percent g) for 0.3 sec. period, 5% damping and 10% probability of exceedance in 50 years.

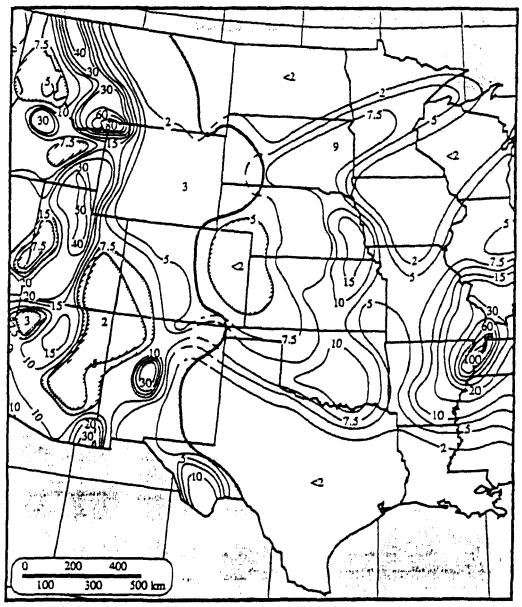

Figure 8. Ground motion map of the western mountains and central plains showing spectral response acceleration (in percent g) for 0.3 sec. period, 5% damping and 10% probability of exceedance in 50 years. The heavy shaded line marks the change in attenuation function used from the west to east (see text).

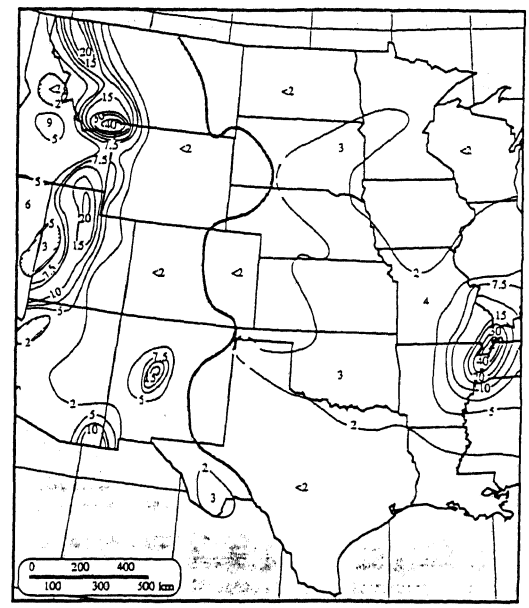

Figure 9. Ground motion map of the western mountains and central plains showing spectral response acceleration (in percent g) for 1.0 sec. period, 5% damping and 10% probability of exceedance in 50 years. The heavy shaded line marks the change in attenuation function used from the west to east (see text).

Soccorro, New Mexico, which is possibly still active as a result of the 1906-07 swarm activity (Coffman and others, 1982), southeast Arizona (the 1882 Sonora earthquake), central Utah (Wasatch fault), Yellowstone National Park (possibly related to a caldera), and western Montana and eastern Idaho (numerous recent damaging shocks). Figures 8 and 9 show the 50-year, 0.3 and 1.0 sec spectral acceleralion for this region.

4 SPECTRAL SHAPES AND APPROXIMATION OF SPECTRA

We discuss here the results of the detailed study of spectral shapes evaluated at 10 cities which are geographically dispersed throughout the country. The shapes of response acceleration spectra were evaluated at San Francisco, Oakland, Los Angeles, San Diego, Salt Lake City, Memphis, St. Louis, Chicago, New York, and Charleston by calculating response values for 12 periods (0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, and 4.0 sec). Since it would be impractical to provide maps for each of the 12 spectral ordinates, the effectiveness of approximating spectral shapes throughout the country by using only two spectral ordinates (0.3 and 1.0 sec) was then evaluated. Special attention is given to the shape of the acceleration response spectra in the period range 0.5-4.0 sec to evaluate the assumptions currently made in determining spectral shapes for building code purposes.

4.1 *Evaluation of spectral shapes*

For building code use, the portion of the response spectrum in the period (T) range of about 0.5 sec to 4.0 sec is frequently approximated using a function of $1/T$ or $1/T^{2/3}$. This approximation of the spectral shape was examined for the ten cities named above. Spectra for the ten cities studied are shown in Figure 10. The spectra have been normalized at a period of 0.3 sec by dividing each ordinate by the spectral ordinate at 0.3 sec. The spectra cluster into two groups, the four California cities exhibit a "rollover" at periods less than 0.5 sec while locations outside California exhibit much higher response at short periods.

4.2 *Period exponent*

All of the normalized spectral response acceleration data for the spectral ordinates for the four California cities are shown in Figure 11 as solid circles. Three curves are also shown. A least squares curve of best fit to the portion of the spectra between 0.5 and 4.0 sec is shown along with the equation for the curve. For comparison, the normalized spectra for San Francisco which were obtained using the mapped spectral ordinates and the aforementioned equations are also shown in the figure. The data are best approximated using T with an exponent of 0.924, although an exponent of 1.0 provides only a small overestimation

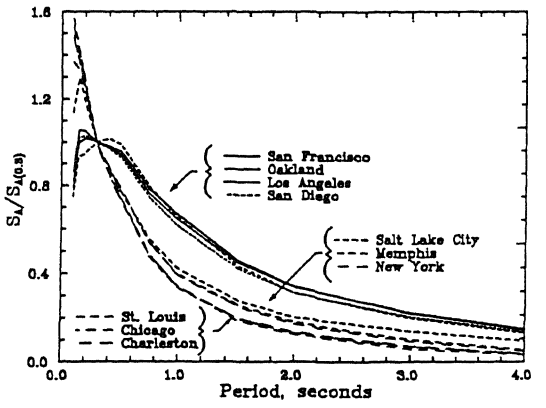

Figure 10. Normalized response spectra for ten cities for 5% damping for an exposure time of 50 years and a 90% probability of nonexceedance.

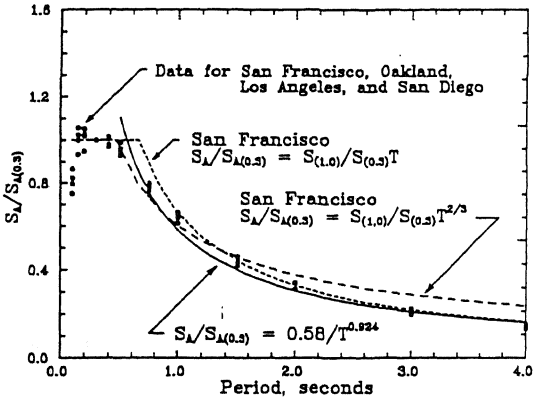

Figure 11. Normalized spectral shape for locations in California. Spectral response acceleration data used in figure 10 are shown as solid circles. The least squares curve of best fit to the data is shown as a solid line. Two dashed spectral shapes are shown for San Francisco, California, for comparison. The latter two shapes, frequently used in building codes, were obtained using mapped spectral values and the equations shown.

of the spectral values. Similiarly, spectral data for the remaining six cities are shown in Figure 12 along with a curve of best fit to the data and two normalized approximate response spectra for Memphis for comparison. The curve of best fit has a exponent of 1.30 for the period T. Once again, the assumption of an exponent of 1.0 provides only a small overestimation of the spectral values.

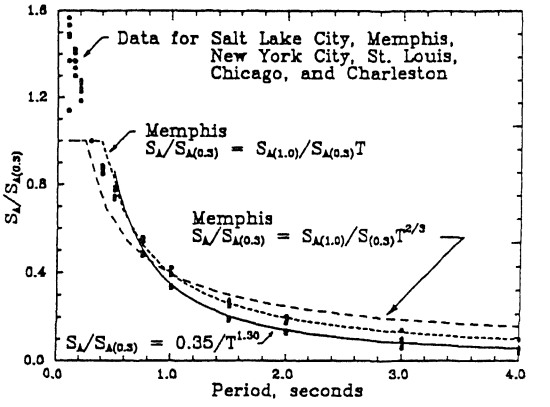

Figure 12. Normalized spectral shape for locations outside California. Spectral response acceleration data used in figure 10 are shown as solid circles. The least squares curve of best fit to the data is shown as a solid line. Two spectral shapes are shown for Memphis, Tennessee, for comparison. The latter two shapes, frequently used in building codes, were obtained using mapped spectral values and the equations shown.

5 CONCLUSIONS

National maps showing response spectral ordinates at periods of 0.3 and 1.0 sec for the United States have been presented along with a discussion of the basis for their formulation/construction. In addition to changing the basis of modeling ground motion spectra from spectral approximations based on peak acceleration and /or velocity to the use of spectral ordinates, the new maps consider interplate earthquakes that might occur in the subduction zone of coastal Washington and Oregon. Inclusion of this type of earthquake had little effect on spectral values in Seattle or other heavily populated regions with the exception of the Portland, Oregon area, that is, there was a significant effect along the Washington and Oregon coast which is much closer to the subduction zone.

Methods for using the maps as a basis for developing response spectra for use in building codes have been discussed. The data suggest that caution should be exercised when modelling an approximate shape for the spectra with the same exponent on the period for all geographic regions. An examination of response spectra for ten cities suggests that the portion of the spectra between 0.5 sec and 4.0 sec can be modelled with $1/T^n$, where n is an exponent of 0.924 for California and 1.300 for the central and eastern United States.

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