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# Should peak accelerations be used to scale design spectrum amplitudes?

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ABSTRACT: Shapes of the response spectra of strong earthquake ground motion depend on many scaling parameters, making it difficult to represent all possibilities with one average spectral shape. If one average shape is used in design applications, scaling its amplitudes with representative peak acceleration contributes additional uncertainties, since strong motion peak acceleration characterizes only the high frequency portion of spectral amplitudes. It is recommended that the response spectrum amplitudes should be scaled directly, using parameters which describe the source, the propagation path and the local soil and geologic conditions. Whenever possible, spectral amplitudes should be determined from microzonation maps, in terms of prescribed exposure time, probability of exceedance, and period of motion.

## INTRODUCTION

Realizing that the strong earthquake shaking results in additional horizontal loads, during the period spanning nearly the first half of this century, most countries have now adopted design codes requiring that such forces be included in the design. During the middle and the last decades of this century, these codes have evolved to a rather detailed, and often lengthy and complex, set of regulations. A typical code requires that the structure resists a minimum total lateral seismic force $V$ which is (e.g. IAEE, 1984)

$$V = ZIKCSW. \qquad (1)$$

$Z$ is a numerical coefficient dependent upon the zone defined by the map of a region or of a country, and $I$ is the occupancy importance factor. The coefficient $K$ depends on the structural type and the arrangement of its resisting elements, $C = C(T)$ (e.g. $C = 1/(15\sqrt{T})$ and $C \leq 0.2$), $S$ characterizes the site structure response, and $W$ is the total dead weight of the structure. The function $C(T)$, where $T$ represents the period of a mode of vibration of a multi story structure, specifies the variation of $Z$ with respect to the period of vibration, and thus a simplified, reduced in amplitude, "response spectrum" of strong ground motion. Since its amplitudes depend on $Z$, one could think of $C(T)$ as being the "spectral shape function" ($SSF$). The coefficient $Z$ is analogous to the expected peak acceleration in the region which is outlined by a zonation map, but its amplitude is normalized for consistency with other terms in equation (1). The final horizontal force $V$, which must be distributed along the building height, incorporates, using mostly intuitive experience of the design profession, the consequences of our desire to design structures which will experience large nonlinear deformations, via an approximate and simplified, equivalent static, and linear design criteria. Using this rough and simple approach, earthquake engineers have achieved major improvements in designing safer earthquake resistant structures. Coupled with good engineering and attention to design details, most developed societies have now succeeded to reduce the expected loss of life from major earthquakes to the remarkably low levels of occurrence.

In spite of these achievements, much challenging new work must be done to further develop the earthquake design codes. With increasing density of population and advanced industry in technologically developed societies, the thrust of future losses from earthquakes will be of economical nature and will be associated with (1) the need to reduce and to minimize disruption of business and (2) indirect costs associated with this interruption. On the other hand, in many undeveloped and developing countries, it will be necessary to consider the design code levels which society can afford, so that the code developments there will also require economical optimization. This will in turn require more precise scaling of $SSF$ and the shapes which lead to balanced and uniform design criteria for a broad family of structural systems. Since such scaling cannot be achieved by one fixed shape $SSF$ and by one amplitude factor (peak acceleration, $Z$,...), in this paper, the factors which influence the shape of $SSF$ will be reviewed. Also, the physical properties of $SSF$ will be discussed, leading to a negative answer to the question posed in the title of this paper.

## FACTORS INFLUENCING THE VARIATIONS IN SPECTRAL SHAPE

In the following, we outline the main factors which modify the shape of response spectra, starting with the earthquake source and propagation path, and ending with the spatial and temporal contributions of the earthquake sources, and with the regional and geological characteristics of the area.

*Earthquake source.* Larger earthquakes occur on larger faults, and are thus capable of contributing longer period components to the strong shaking. Thus, the spectra of strong ground motion become broader and with relatively larger long period amplitudes, as the earthquake size (magnitude, epicentral intensity) increases (Fig. 1, Trifunac, 1978). If the response spectra were normalized to have unit peak acceleration, the changes of spectral shape with magnitude would be as illustrated in Fig. 1.

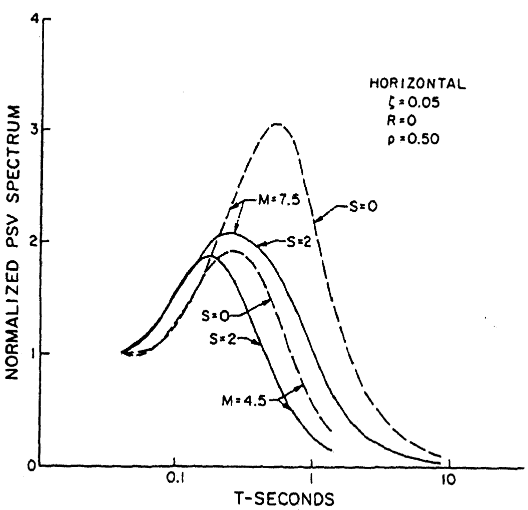


Fig. 1 Normalized PSV spectra for magnitudes $M = 4.5$ and 7.5, for probability of exceedance $p = 0.5$, fraction of critical damping $\varsigma = 0.05$, at zero epicentral distances, $R = 0$, on basement rock ($s = 2$) and on sediments ($s = 0$) (after Trifunac, 1978).

*Horizontal versus vertical motion.* For many years, it has been assumed that a constant could be adopted for the ratio of horizontal to vertical peak accelerations, response spectra, Fourier spectra etc. The currently available data shows that this ratio is not constant, and that it depends on the frequency, the distance from the source, and on the local geologic and soil conditions at the site. Near the source, and for high frequencies ($f > 10$Hz), the vertical motions can exceed the horizontal motions. With increasing epicentral distance, and for longer period ground motions, the vertical amplitudes of strong motion are smaller than the horizontal motions (Trifunac, 1976).

*Geologic site conditions* ($s = 0$ sediments, $s = 1$ for intermediate sites, and $s = 2$ for basement rock sites, Trifunac and Brady, 1975). In California, the high frequency spectral amplitudes are smaller on sediments. With increasing period, this trend is reversed, and the average spectral amplitudes are 2 to 3 times larger on sediments ($s = 0$) than on basement rock ($s = 2$, basalts, granites) (Fig. 1). For periods $T > 4H/\beta$ ($H$ is the layer thickness and $\beta$ shear wave velocity) this amplification begins to diminish, and it disappears as $T \to \infty$ (Trifunac, 1990).

*Local soil conditions.* ($s_L = 0$ for "rock", $s_L = 1$ for stiff soil sites, and $s_L = 2$ for deep soil sites, Seed et al., 1976). The effects of the local soil on the recorded spectral amplitudes are very similar to the effects of the local geologic conditions, with $s_L = 0$ corresponding to $s = 2$ and $s_L = 1$ and 2 to $s = 0$. Since the geological erosion and transport processes tend to create local soil conditions which are "softer" over "soft" geologic deposits ($s = 0$), these two effects tend to further amplify the trends already shown in Fig. 1. It is interesting to note, that most earthquake design codes recognize the local soil conditions, and in some instances provide correction factors to incorporate their effects. Essentially, no codes address the geologic site conditions explicitly (IAEE, 1984).

*Frequency dependent attenuation.* The waves with high frequency usually attenuate faster, but it was not possible to show this experimentally for strong ground motion until the 1980's. Furthermore, in strong motion seismology, the source to station distances, $\Delta$, are often comparable to the source dimension $S$, and, so, the point source representation of the source cannot be used. As different wave lengths (frequencies) interfere during radiation from an extended source, the integration of the geometric spreading effects from a finite source gives rise to "frequency dependent attenuation" even in the perfectly elastic nonattenuating material. Thus the total overall picture near the source consists of a frequency dependent attenuation function of strong motion amplitudes, which involves mainly these two processes. The consequence is that the shape of the response spectrum will also depend on how far the site is from the source, even when one considers the same source and events of equal magnitude (Trifunac, 1989, 1991).

*Regional variations in attenuation.* The geological age, the geological activity, and the overall nature of the site environment may result in profound differences in the observed attenuation rates of strong ground motion. It is known, for example, that the attenuation of high frequency waves is faster in California than in the eastern United States. This can be explained by larger values of the quality coefficient, $Q$, in the eastern U.S. This will not only result in larger areas shaken by the same energy release at the source in eastern U.S., but will also introduce systematic differences in the observed shapes of strong motion spectra in these two regions.

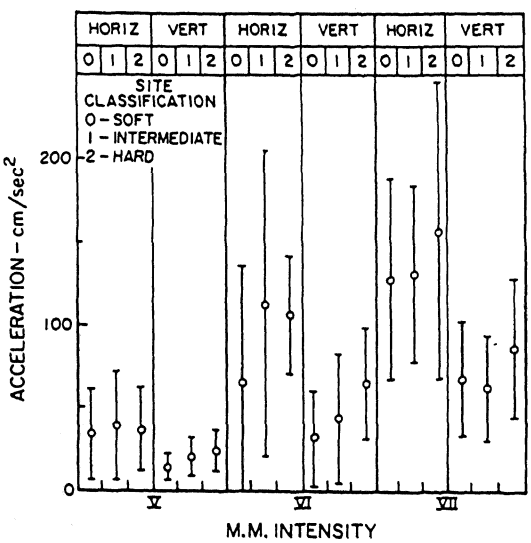


Fig. 2 Mean amplitudes (circles) and standard deviations (error bars) of peak ground accelerations in California classified by site and component direction, versus Modified Mercalli Intensity (MMI) (after Trifunac and Brady, 1975).

For example, using the standard shape of response spectra (determined mainly from the strong motion data recorded in California), and scaling the spectral amplitudes via peak acceleration (presumably with an attenuation equation which has been calibrated for eastern U.S.) may result in too large intermediate and long period spectral estimates. On the other hand, scaling via some attenuation equation of the intensity of shaking, may result in underestimating of the high frequency amplitudes (if "standard" response spectrum shapes and peak velocity are used to anchor the spectral amplitudes).

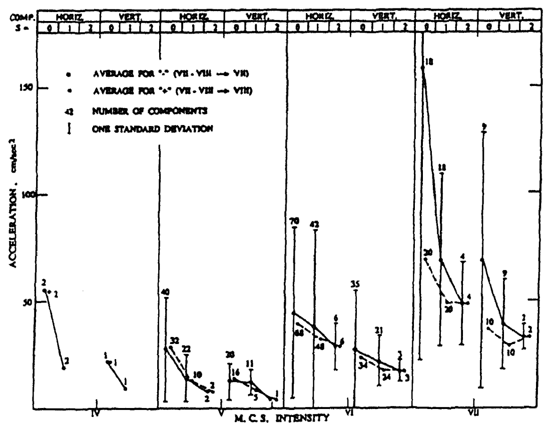


Fig. 3 Mean amplitudes (circles) and standard deviations (error bars) of peak accelerations in Yugoslavia, classified by site and component direction versus Mercalli-Cancani-Sieberg Intensity (MCS). Numbers over error bars indicate the number of peaks in the data base (after Trifunac et al., 1991).

The regional attenuation characteristics, the distribution of $Q$ with depth, and the overall average values of $Q$ may result in opposite trends of recorded peak motions in different geologic regions. For example, we believe that the peak acceleration is slightly larger on basement rock sites in California, relative to sites on sediments, because the low $Q$ and the resulting inelastic attenuation result in stronger effects than the amplification of waves propagating from "hard" to "soft" medium. Fig. 2 illustrates this for peak accelerations in California. Analogous studies of strong motion data in Yugoslavia lead to opposite trends, implying slightly larger peak accelerations on geologically "soft" materials (Fig. 3). This observation is confirmed by the comparison with the studies of the frequency dependant attenuation in the same region, which shows that the frequencies higher than $\sim 5$ Hz are attenuated faster in California than in Yugoslavia (Lee and Trifunac, 1992). Clearly, using in Yugoslavia some empirical attenuation equation of peak acceleration (for example, developed on the basis of data recorded in California), and then scaling the standard shape design spectra by such peak acceleration would result in ground motion estimates which would probably have little if any relationship with the local and regional characteristics of strong ground motion. Since it is a very common practice world wide, to "borrow" foreign attenuation equations and "foreign" spectral shapes, this example should serve as a warning to the designer about potential uncertainties, biases and mistakes that can result from such approach. Many regions of the world do not have adequate data base of strong motion recordings to develop their own scaling equations or to modify and to calibrate the foreign equations. In such circumstances, carefully and well organized studies of attenuation using other than strong motion recordings may be used to resolve this difficulty and to develop reliable and locally meaningful empirical attenuation laws.

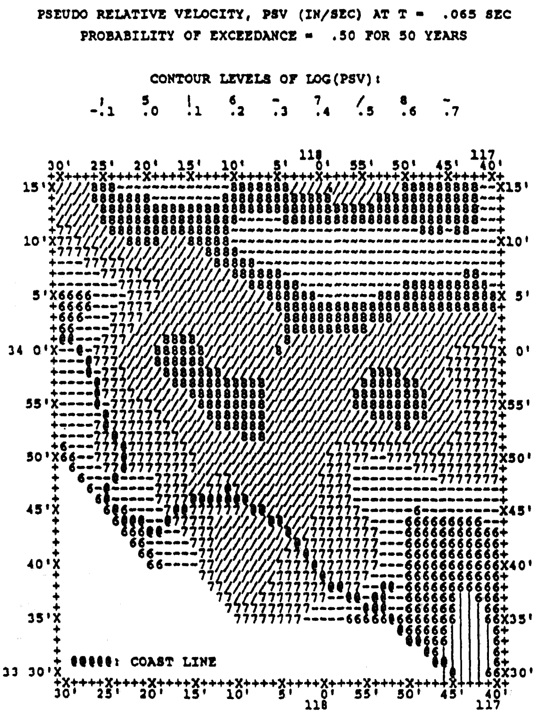


Fig. 4 Microzonation map for PSV amplitudes at $T = .065$ sec, with probaiblity of exceedance $p = 0.5$, during exposure time of 50 years.

*Factors influencing the shape of Uniform Risk Spectra (URS).* Since the mid 1970's, we have used and continued to develop the concept of uniform risk spectra (Trifunac et al., 1987). This spectrum has the property that at all frequencies its amplitudes have the same probability of being exceeded by any earthquake contributing to the shaking at the site. It has been developed to provide a balanced representation of all regional contributions to the risk at a site, and, thus, to provide a vehicle for integrating contributions from frequent small, rare large, close and distant events, as described by detailed, fault by fault, and source by source description of the seismicity surrounding the site. Since the 1980's, we have used this approach to construct microzonation maps for selected periods of vibration, $T$, and probabilities of exceedance (Fig. 4, Trifunac, 1988), so that from a family of such maps, for different periods $T$, and for different probabilities of exceedance, one can construct the URS at a site.

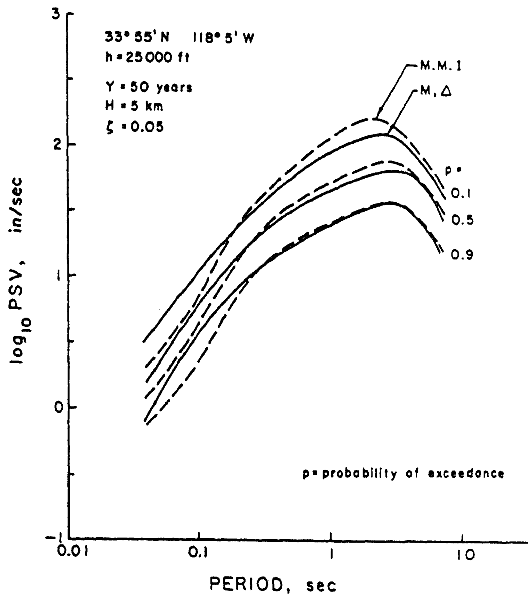


Fig. 5 Uniform risk spectrum at site 33° 55′ N, 118° 5′ W, with thickness of sediments $h = 25000$ ft, for surrounding sources at depth $H = 5$ km, fraction of critical damping $\varsigma = 0.05$ and for exposure time of 50 years. Dashed lines show URS amplitudes computed via MMI, and solid lines for amplitude attenuation in terms of magnitude $M$, and hypocentral distance $\Delta$.

Majority of microzonation studies focus on the characteristics of the local site, and assume that it will be the local soil and geologic conditions alone that will govern and modify the shape of the response spectra. Our microzonation studies using URS (Trifunac, 1988) show that such approach contributes only a small part to the end result and that the relative distribution of distances and levels of the activity at the contributing sources yield the overwhelming contribution to the changes of the response spectrum shape. To illustrate this, we plotted URS computed from a family of microzonation maps such as that illustrated in Fig. 4, for two sites located within the metropolitan Los Angeles area. One site is at 33° 55′ $N$, 118° 5′ $W$ (Fig. 5) and the other at 33° 45′ $N$ and 118° 20′ $W$ (Fig. 6). Comparison of these two figures shows how different the spectral shapes can be for two sites in the same urban area. These variations of spectral shape cannot be determined experimentally (microtremors, small historical earthquakes), or by considering only local soil and geologic site conditions, but have to be balanced with proper weighting of all contributing factors, as it is currently done by NEQRISK program (Trifunac et al., 1987) which computes all contributions to URS.

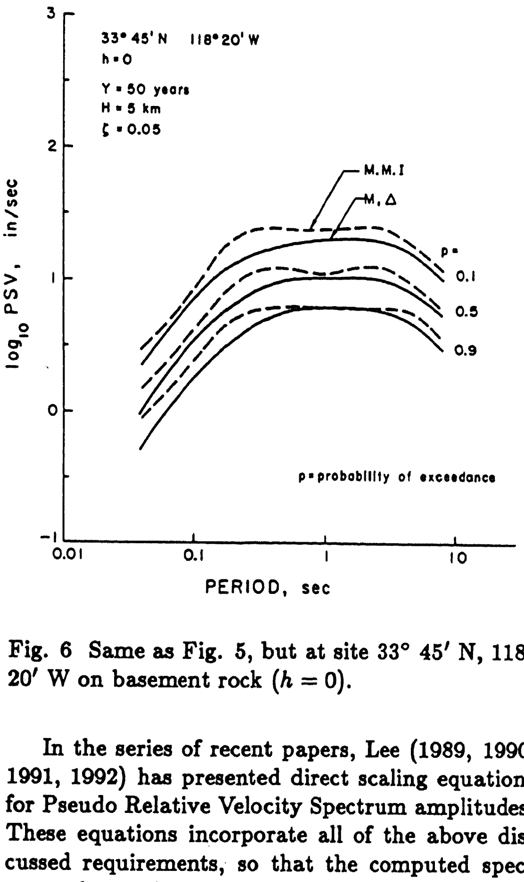


Fig. 6 Same as Fig. 5, but at site 33° 45′ N, 118° 20′ W on basement rock ($h = 0$).

In the series of recent papers, Lee (1989, 1990, 1991, 1992) has presented direct scaling equations for Pseudo Relative Velocity Spectrum amplitudes. These equations incorporate all of the above discussed requirements, so that the computed spectrum shape changes with magnitude (intensity), horizontal versus vertical motion, geologic and soil site conditions, and with frequency dependent attenuation. His equations are based on "coefficient" functions which describe spectral amplitudes at 12 discrete periods, starting from 0.04 sec and ending at 14 sec. The distribution of residuals about this empirical model is also described in terms of an analytical approximation which has been tested by Kolmogorov-Smirnov and $\chi^2$ tests to agree with the observed residuals. Thus, Lee's equation can be also used to determine spectral amplitudes with any desired probability of exceedance.

## CONCLUSIONS AND RECOMMENDATIONS

We conclude that scaling and selection of a design spectrum shape should not be performed via one scaling parameter (peak acceleration, peak velocity, peak displacement) and the standard spectrum shape as provided by code regulations (e.g. $C(T)$), or by the design guidelines for important structures (e.g. Regulatory Guide 1.60, Trifunac et al., 1987). In this age of personal computers, it is difficult to reconcile such simplified approach with the wealth of data and data analyses in the areas where strong motion data has been available.

In those regions where strong motion data is not available, or where the regional studies have not been carried out, it is even more difficult to justify selection of the design criteria via scaling by peak strong motion acceleration. In such cases, regional difference in earthquake sources, attenuation, magnitude scaling (Trifunac and Herak, 1992), and intensity definitions (Trifunac et al., 1991; Trifunac and Živčić, 1991) may all result in very uncertain design spectrum, and one should look for alternative procedures to test and to calibrate the proposed scaling relations.

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