ESTIMATION OF RELATIVE VELOCITY SPECTRA

by

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ABSTRACT

This paper summarizes a new method of empirical scaling of relative velocity spectrum amplitudes of a single-degree-of-freedom viscously damped oscillator subjected to strong earthquake ground motion. Regression models are presented for scaling of spectral amplitudes in terms of (a) earthquake magnitude and epicentral distance, and of (b) Modified Mercalli Intensity at a site. The effects of geologic setting of the station and the distribution of spectral amplitudes have been included.

INTRODUCTION

This paper presents two empirical scaling models for estimation of the Relative Velocity Response Spectrum Amplitudes (SV), in terms of (a) earthquake magnitude, M, and epicentral distance, R, and (b) Modified Mercalli Intensity, MMI, at the recording station. Both models consider geologic conditions at the station, direction of ground motion and the desired confidence level of not exceeding the chosen SV amplitudes.

These regression analyses represent a portion of the on-going systematic effort to develop simple, and as direct as possible, scaling methods for different characteristics of strong earthquake ground motion that may be useful for engineering applications (Trifunac, 1976; 1978; Trifunac and Anderson, 1977; 1978; Trifunac and Westermo, 1976a,b). Strong ground motion may not be described in sufficient detail with only one functional, e.g., Pseudo Relative Velocity Spectrum; thus, different types and more than one scaling function may be required for certain applications. Therefore, we present here the empirical models for scaling SV spectral amplitudes. These results may be used in conjunction with a number of other empirical models for scaling response spectra (Trifunac and Anderson, 1977; 1978) and with the models for characterizing the duration of strong shaking (Trifunac and Westermo, 1976a,b). The discussion on the choice of scaling functionals in relation to a particular problem is, however, beyond the scope of this paper. We merely note that for a nonlinear response analysis or design, the amplitudes and the duration of strong shaking may be essential.

The advantage of the method presented here is that it enables one to estimate SV spectra directly from the earthquake scaling parameters which are routinely available to the engineering and seismological communities. It is not necessary to first estimate some peak quantity, e.g., peak velocity or peak acceleration, and then apply some standard spectrum shape (e.g., Housner, 1970; Seed, et. al., 1974; Newmark and Rosenblueth, 1971). Furthermore, the method presented here computes spectral amplitudes as a frequency-dependent function of all scaling parameters so that the spectrum amplitudes and shapes change continuously with respect to all earthquake and site characteristics.

EMPIRICAL MODELS FOR SCALING RELATIVE VELOCITY RESPONSE SPECTRA

We employ the approach which was used for scaling Fourier (Trifunac, 1976), Absolute Acceleration (Trifunac and Anderson, 1977), and Pseudo Relative Velocity (Trifunac and Anderson, 1978) Response Spectra and write

$$\log_{10}[SV(T),_{p_\ell}] = M + \log_{10}A_o(R) - a(T)p_\ell - b(T)M - c(T) - d(T)s - e(T)v - f(T)M^2 - g(T)R + 0.405 \tag{1}$$

and

$$\log_{10}[SV(T),_{p_\ell}] = a(T)p_\ell + b(T)I_{MM} + c(T) + d(T)s + e(T)v + 0.405 \tag{2}$$

In these equations, $SV(T),_{p_\ell}$ represents the Relative Velocity Response Spectrum amplitudes which will not be exceeded with p_ℓ level of confidence, M is earthquake magnitude, R is epicentral distance, and I_{MM} is a level on MMI scale assigned numerical values from 1 to 12. p_ℓ is not probability but it represents a linear approximation to the probability of $SV(T),_{p_\ell}$ not being exceeded when $0.1 \le p_\ell \le 0.9$. When a continuous description of the distribution of $SV(T),_{p_a}$ is required, we propose that

$$p_a = [1 - \exp(-e^{\alpha(T)p_\ell + \beta(T)})]^{N(T)} \tag{3}$$

be used (Trifunac and Anderson, 1977; 1978). The functions $\alpha(T)$, $\beta(T)$ and $N(T)$ can be determined from actual distribution of computed SV amplitudes with respect to the models (1) and (2) and assuming that the maxima of the response of a viscously damped single-degree-of-freedom system follow approximately the Rayleigh distribution (Trifunac and Anderson, 1977; 1978).

In equations (1) and (2), s represents the local geologic conditions. s=0 should be used for alluvium sites, s=2 for basement rock sites, and s=1 for intermediate and borderline cases or when the geology is too complicated to choose s=0 or s=2 (Trifunac and Brady, 1975). v=0 is used with horizontal motion and v=1 with vertical motions. The constant at the end of (1) and (2) equal to 0.405 converts the units of SV(T) into cm/sec from in/sec as originally developed by Trifunac and Anderson (1978).

Equation (1) applies only in the range $M_{min} \leq M \leq M_{max}$ (see Trifunac and Anderson, 1977 for a detailed discussion of this effect) where $M_{min} = -b(T)/2f(T)$ and $M_{max} = [1-b(T)]/2f(T)$. M_{min} flucuates between 4 and 5.5 while M_{max} is between 7.5 and 8.5 for periods ranging from 0.04 to 12 seconds.

The coefficient functions a(T), b(T), ..., through g(T) have been determined by a regression analysis at 91 periods and by carefully selecting the data sets to avoid undue bias from large concentration of data near magnitude 6.5, uneven distribution among s=0 and s=2 sites, and a limited range of MMI levels for which data is now available (Trifunac, 1976). The smoothed versions of these functions are shown in Figures 1 and 2 corresponding to equations (1) and (2), respectively.

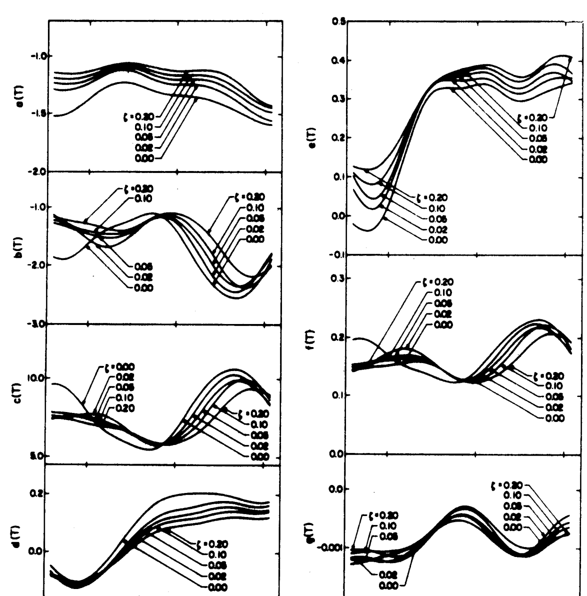

Figure 1

Tables I and II also present the amplitudes of these functions at selected periods and for fractions of critical damping $\zeta = 0.00$, 0.02, 0.05, 0.10 and 0.20.

The term $\log_{10}A_0(R)$ in (1) represents an empirical description of amplitude attenuation with distance appropriate for use in southern

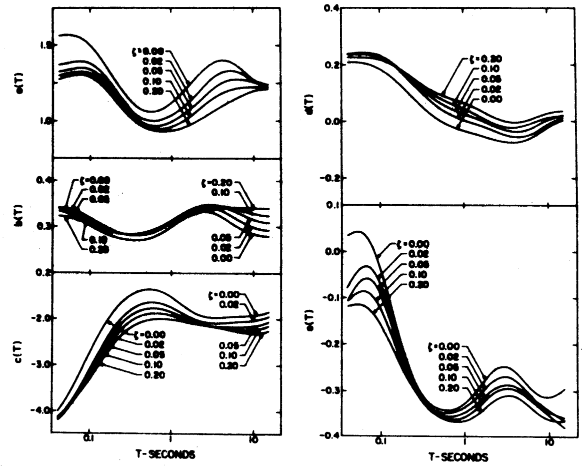

Figure 2

California (Table III, Richter, 1958). It should be replaced with an equivalent function if equation (1) is to be used outside the southern California region.

TABLE I

Regression Parameters for Equation (1) and α(T), β(T) and N(T) at Eleven Selected Periods

$\log_{10}T$(sec)	-1.398	-1.168	-0.938	-0.708	-0.478	-0.247	-0.017	0.213	0.443	0.673	0.903
$\zeta = 0.0$											
a(T)	-1.521	-1.469	-1.340	-1.241	-1.247	-1.310	-1.343	-1.359	-1.405	-1.479	-1.566
b(T)	-1.857	-1.836	-1.539	-1.327	-1.195	-1.105	-1.365	-1.905	-2.363	-2.549	-2.339
c(T)	9.629	9.059	7.491	6.365	5.753	5.502	6.490	8.419	10.041	10.645	9.975
d(T)	-0.047	-0.099	-0.083	-0.011	0.079	0.157	0.194	0.202	0.203	0.191	0.173
e(T)	-0.020	-0.033	0.065	0.227	0.321	0.329	0.338	0.330	0.297	0.307	0.330
10f(T)	1.961	1.912	1.644	1.456	1.332	1.227	1.390	1.781	2.126	2.304	2.169
1000g(T)	-1.203	-1.214	-1.219	-1.049	-0.749	-0.542	-0.600	-0.872	-1.111	-1.045	-0.721
α(T)	1.142	1.135	1.143	1.198	1.273	1.501	1.803	2.299	2.646	3.973	4.387
β(T)	0.669	0.662	0.653	0.636	0.595	0.309	-0.081	-0.711	-1.205	-2.577	-2.799
N(T)	20	20	20	20	19	11	6	3	2	1	1
$\zeta = 0.02$											
a(T)	-1.290	-1.286	-1.213	-1.130	-1.138	-1.212	-1.250	-1.253	-1.294	-1.391	-1.511
b(T)	-1.225	-1.357	-1.612	-1.664	-1.435	-1.181	-1.241	-1.691	-2.219	-2.447	-2.199
c(T)	7.627	7.583	7.736	7.393	6.499	5.810	6.189	7.745	9.509	10.283	9.545
d(T)	-0.066	-0.118	-0.104	-0.037	0.043	0.108	0.141	0.155	0.170	0.172	0.159
e(T)	0.068	0.019	0.100	0.251	0.339	0.350	0.354	0.345	0.316	0.332	0.356
10f(T)	1.490	1.579	1.770	1.791	1.575	1.315	1.309	1.640	2.047	2.236	2.059
1000g(T)	-1.173	-1.181	-1.236	-1.102	-0.769	-0.478	-0.510	-0.837	-1.104	-1.000	-0.630
α(T)	1.160	1.132	1.120	1.181	1.280	1.536	1.849	2.342	2.688	3.990	4.358
β(T)	0.661	0.665	0.674	0.657	0.598	0.289	-0.116	-0.746	-1.235	-2.595	-2.781
N(T)	20	20	20	20	19	11	6	3	2	1	1
$\zeta = 0.05$											
a(T)	-1.235	-1.239	-1.186	-1.108	-1.106	-1.172	-1.207	-1.203	-1.237	-1.331	-1.445
b(T)	-1.275	-1.376	-1.487	-1.523	-1.392	-1.187	-1.207	-1.541	-2.039	-2.342	-2.175
c(T)	7.796	7.700	7.450	7.050	6.427	5.875	6.116	7.272	8.913	9.914	9.439
d(T)	-0.067	-0.115	-0.105	-0.044	0.031	0.091	0.120	0.132	0.150	0.155	0.144
e(T)	0.102	0.044	0.118	0.255	0.342	0.359	0.369	0.360	0.330	0.350	0.369
10f(T)	1.533	1.594	1.672	1.691	1.556	1.332	1.294	1.538	1.923	2.169	2.048
1000g(T)	-1.283	-1.202	-1.111	-0.987	-0.731	-0.467	-0.475	-0.773	-1.081	-1.103	-0.869
α(T)	1.159	1.133	1.127	1.186	1.288	1.545	1.868	2.385	2.764	4.104	4.457
β(T)	0.662	0.667	0.669	0.650	0.592	0.284	-0.129	-0.775	-1.279	-2.654	-2.835
N(T)	20	20	20	20	19	11	6	3	2	1	1
$\zeta = 0.10$											
a(T)	-1.190	-1.195	-1.156	-1.097	-1.087	-1.139	-1.170	-1.166	-1.191	-1.279	-1.400
b(T)	-1.132	-1.337	-1.426	-1.458	-1.367	-1.174	-1.150	-1.392	-1.876	-2.318	-2.299
c(T)	7.377	7.598	7.327	6.950	6.441	5.899	5.976	6.810	8.373	9.799	9.781
d(T)	-0.080	-0.105	-0.095	-0.044	0.023	0.078	0.106	0.115	0.130	0.141	0.136
e(T)	0.110	0.081	0.141	0.261	0.343	0.366	0.379	0.374	0.348	0.367	0.391
10f(T)	1.409	1.565	1.629	1.644	1.543	1.332	1.259	1.430	1.813	2.163	2.156
1000g(T)	-1.097	-1.065	-1.052	-0.969	-0.710	-0.397	-0.365	-0.698	-1.051	-1.049	-0.781
α(T)	1.151	1.131	1.130	1.190	1.288	1.550	1.877	2.418	2.830	4.206	4.537
β(T)	0.659	0.671	0.671	0.649	0.593	0.281	-0.133	-0.791	-1.306	-2.688	-2.855
N(T)	20	20	20	20	19	11	6	3	2	1	1
$\zeta = 0.20$											
a(T)	-1.144	-1.152	-1.120	-1.076	-1.068	-1.103	-1.132	-1.130	-1.138	-1.223	-1.368
b(T)	-1.165	-1.245	-1.307	-1.391	-1.350	-1.165	-1.103	-1.247	-1.593	-2.031	-2.174
c(T)	7.450	7.351	7.055	6.871	6.507	5.952	5.870	6.377	7.481	8.863	9.377
d(T)	-0.074	-0.099	-0.090	-0.046	0.013	0.061	0.086	0.096	0.110	0.121	0.117
e(T)	0.127	0.122	0.171	0.264	0.342	0.372	0.386	0.385	0.360	0.374	0.412
10f(T)	1.445	1.494	1.535	1.594	1.534	1.331	1.235	1.332	1.601	1.951	2.066
1000g(T)	-1.043	-1.057	-1.138	-1.077	-0.744	-0.371	-0.323	-0.615	-0.925	-0.986	-0.847
α(T)	1.136	1.129	1.141	1.204	1.300	1.552	1.879	2.437	2.889	4.324	4.616
β(T)	0.672	0.668	0.663	0.642	0.585	0.278	-0.136	-0.800	-1.334	-2.749	-2.889
N(T)	20	20	20	20	19	11	6	3	2	1	1

CHARACTERISTICS OF THE PROPOSED MODELS

Figure 3 presents an example of SV spectra computed for $p_{\ell} = 0.5$, $\zeta = 0.02$, and R = 0 km. It shows that the maxima of SV amplitudes are essentially reached for M = 7.5 and that the effect of softening geologic conditions is to "rotate" the spectra counterclockwise. Figure 4 presents an example of SV amplitudes computed from equation (2) and for $p_{\ell} = 0.5$ and $\zeta = 0.02$.

TABLE II

Regression Parameters for Equation (2) and $\alpha(T)$, $\beta(T)$ and $N(T)$ at Eleven Selected Periods

$\log_{10}T$(sec)	-1.398	-1.171	-0.943	-0.716	-0.489	-0.261	-0.034	0.193	0.420	0.648	0.875
ζ = 0.0											
a(T)	1.562	1.556	1.460	1.286	1.125	1.059	1.106	1.221	1.349	1.402	1.332
b(T)	0.339	0.320	0.296	0.278	0.271	0.275	0.296	0.324	0.333	0.316	0.292
c(T)	-4.010	-3.342	-2.522	-1.859	-1.473	-1.358	-1.498	-1.774	-1.956	-1.962	-1.931
d(T)	0.208	0.203	0.173	0.115	0.049	-0.002	-0.031	-0.051	-0.070	-0.074	-0.045
e(T)	0.034	0.032	-0.074	-0.221	-0.314	-0.342	-0.331	-0.287	-0.249	-0.268	-0.308
α(T)	2.487	2.486	2.515	2.591	2.627	3.867	3.859	3.807	3.644	3.518	3.574
β(T)	-1.066	-1.097	-1.134	-1.173	-1.177	-2.444	-2.454	-2.467	-2.401	-2.322	-2.329
N(T)	2	2	2	2	2	1	1	1	1	1	1
ζ = 0.02											
a(T)	1.371	1.393	1.358	1.222	1.066	0.999	1.028	1.113	1.240	1.329	1.308
b(T)	0.341	0.331	0.311	0.291	0.282	0.287	0.307	0.332	0.343	0.330	0.307
c(T)	-4.173	-3.640	-2.907	-2.228	-1.793	-1.644	-1.731	-1.935	-2.078	-2.083	-2.053
d(T)	0.237	0.243	0.221	0.164	0.097	0.040	0.007	-0.016	-0.041	-0.056	-0.034
e(T)	-0.077	-0.031	-0.098	-0.230	-0.323	-0.348	-0.338	-0.303	-0.270	-0.285	-0.329
α(T)	2.516	2.498	2.535	2.618	2.649	3.872	3.820	3.758	3.613	3.528	3.625
β(T)	-1.089	-1.110	-1.157	-1.206	-1.206	-2.464	-2.445	-2.441	-2.379	-2.324	-2.358
N(T)	2	2	2	2	2	1	1	1	1	1	1
ζ = 0.05											
a(T)	1.325	1.349	1.321	1.193	1.040	0.968	0.986	1.058	1.168	1.260	1.272
b(T)	0.340	0.328	0.307	0.288	0.282	0.290	0.310	0.333	0.347	0.341	0.323
c(T)	-4.194	-3.682	-2.984	-2.334	-1.915	-1.770	-1.837	-2.005	-2.137	-2.174	-2.169
d(T)	0.238	0.241	0.222	0.171	0.110	0.061	0.029	0.004	-0.024	-0.037	-0.015
e(T)	-0.107	-0.057	-0.118	-0.241	-0.328	-0.355	-0.349	-0.319	-0.289	-0.295	-0.327
α(T)	2.482	2.491	2.541	2.619	2.647	3.863	3.797	3.758	3.657	3.538	3.515
β(T)	-1.074	-1.105	-1.159	-1.206	-1.206	-2.461	-2.431	-2.435	-2.396	-2.328	-2.304
N(T)	2	2	2	2	2	1	1	1	1	1	1
ζ = 0.10											
a(T)	1.298	1.322	1.293	1.172	1.026	0.948	0.954	1.016	1.111	1.190	1.221
b(T)	0.333	0.322	0.304	0.287	0.282	0.291	0.309	0.329	0.342	0.343	0.334
c(T)	-4.184	-3.701	-3.052	-2.441	-2.035	-1.881	-1.917	-2.035	-2.142	-2.205	-2.240
d(T)	0.237	0.237	0.219	0.174	0.119	0.077	0.048	0.016	-0.016	-0.021	0.001
e(T)	-0.107	-0.087	-0.146	-0.251	-0.328	-0.359	-0.359	-0.329	-0.297	-0.303	-0.335
α(T)	2.475	2.501	2.553	2.620	2.652	3.878	3.797	3.758	3.684	3.569	3.515
β(T)	-1.075	-1.111	-1.161	-1.203	-1.208	-2.471	-2.430	-2.429	-2.405	-2.345	-2.313
N(T)	2	2	2	2	2	1	1	1	1	1	1
ζ = 0.20											
a(T)	1.274	1.304	1.268	1.148	1.015	0.941	0.931	0.964	1.031	1.106	1.170
b(T)	0.322	0.315	0.301	0.287	0.284	0.291	0.306	0.323	0.336	0.340	0.340
c(T)	-4.139	-3.708	-3.128	-2.567	-2.182	-2.014	-2.008	-2.074	-2.146	-2.217	-2.297
d(T)	0.226	0.225	0.211	0.173	0.127	0.093	0.068	0.039	0.006	-0.004	0.016
e(T)	-0.118	-0.120	-0.177	-0.260	-0.325	-0.360	-0.368	-0.345	-0.314	-0.317	-0.351
α(T)	2.511	2.555	2.594	2.634	2.651	3.889	3.800	3.738	3.681	3.586	3.495
β(T)	-1.094	-1.141	-1.182	-1.208	-1.207	-2.480	-2.433	-2.409	-2.387	-2.342	-2.293
N(T)	2	2	2	2	2	1	1	1	1	1	1

Similar effects of geologic conditions are also present. Heavy lines for MMI in the range from IV to VIII indicate the range where data are

TABLE III

$\log_{10}A_o(R)$ Versus Epicentral Distance R*

R (km)	$-\log_{10}A_o$	R (km)	$-\log_{10}A_o(R)$	R (km)	$-\log_{10}A_o(R)$
0	1.400	140	3.230	370	4.336
5	1.500	150	3.279	380	4.376
10	1.605	160	3.328	390	4.414
15	1.716	170	3.378	400	4.451
20	1.833	180	3.429	410	4.485
25	1.955	190	3.480	420	4.518
30	2.078	200	3.530	430	4.549
25	2.199	210	3.581	440	4.579
40	2.314	220	3.631	450	4.607
45	2.421	230	3.680	460	4.634
50	2.517	240	3.729	470	4.660
55	2.603	250	3.779	480	4.685
60	2.679	260	3.828	490	4.709
65	2.746	270	3.877	500	4.732
70	2.805	280	3.926	510	4.755
80	2.920	290	3.975	520	4.776
85	2.958	300	4.024	530	4.797
90	2.989	310	4.072	540	4.817
95	3.020	320	4.119	550	4.835
100	3.044	330	4.164	560	4.853
110	3.089	340	4.209	570	4.869
120	3.135	350	4.253	580	4.885
130	3.182	360	4.295	590	4.900

* Only the first two digits may be assumed to be significant.

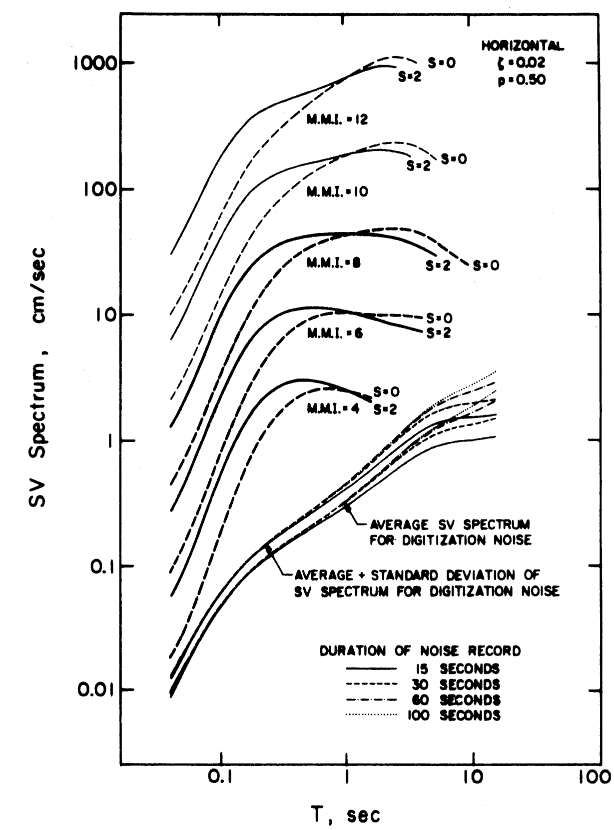

Figure 3

now available and where equation (2) may apply. The amplitudes for MMI = X and XII are presented only for completeness but are outside the range where some data are now available and where equation (2) can be used. Both Figures 3 and 4 contain the spectrum amplitudes corresponding to the average plus one standard deviation of SV spectra of digitization and processing noise (Trifunac, 1976). For periods longer than 1 to 2 seconds, spectra computed from (1) and (2) may approach the amplitudes of this noise and hence (1) and (2) should not be used here. The approximate domain where (1) and (2) may apply is illustreated by SV spectra in Figures 3 and 4 truncated at different periods for different MMI or M. Hence, for a chosen set of scaling parameters in (1) and (2), $SV(T),_{p_\ell}$ should be used only within that interval of T for which the amplitudes are well beyond the amplitudes computed from the digitization noise.

Figures 5 and 6 present an example of comparing the SV spectra computed for EW component of strong motion acceleration recorded at El Centro during the Imperial Valley, California, earthquake of 1940, with the 80% confidence intervals determined from equations (1) and (2) Each figure indicates the set of scaling parameters which have been used to compute the smooth light curves in these figures. The heavy irregular curves represent SV spectra for five dampings as computed from the recorded accelerogram. In both cases, the SV spectra computed

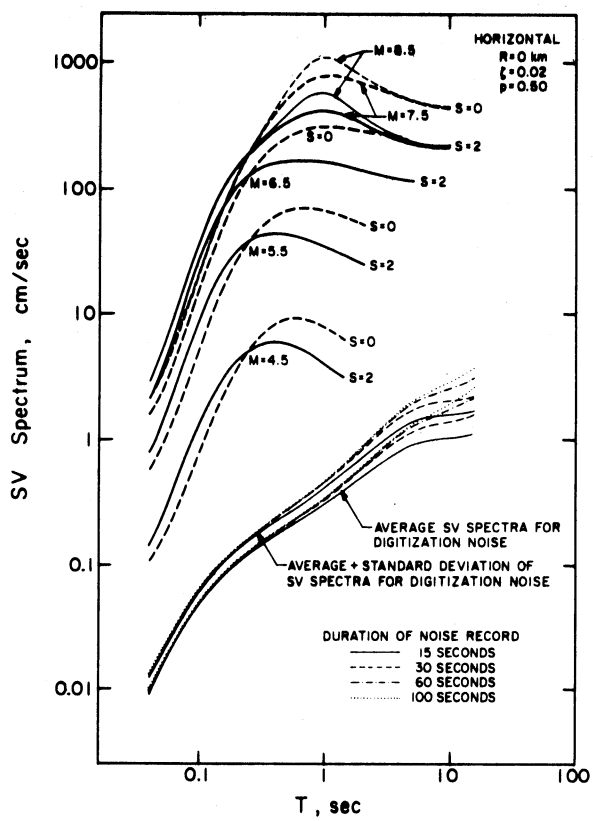

Figure 4

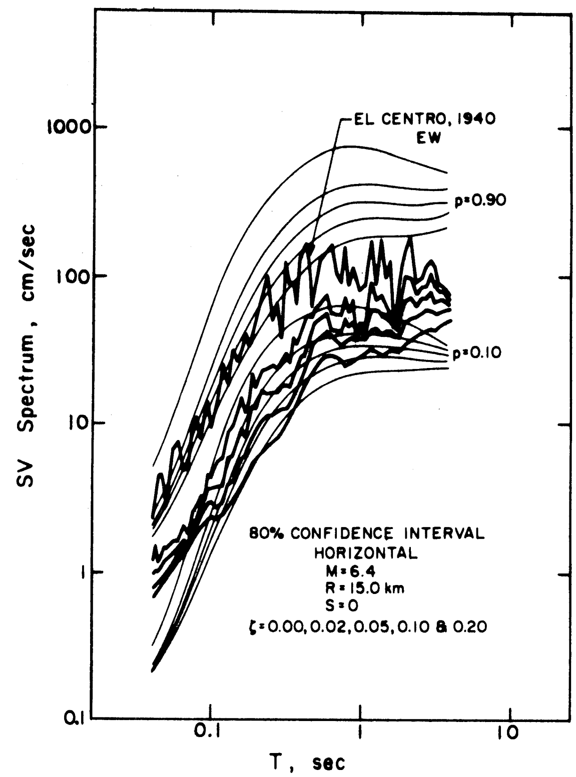

Figure 5

from the recorded motion are within 80% confidence interval, but for scaling in terms of M and R, observed SV amplitudes are at the smaller edge of the range, while for the scaling in terms of MMI observed SV amplitudes are toward the larger edge of the range. The results in these figures are indicative of the considerable uncertainties which are associated with such simplified description of strong shaking (Trifunac and Brune, 1970). It is also seen that the SV spectra for $p_\ell = 0.1$ and 0.9 differ in amplitudes by about one order of magnitude.

The functions a(T) through g(T) in equations (1) and (2) appear to be determined well for T between 0.1 and 2 sec. For longer periods, relatively small signal-to-noise ratio for many records used in this regression analysis has distorted these functions to an extent which cannot be determined from the data now available. Therefore, outside this period range, the amplitudes presented by (1) and (2) should be used with caution.

A discussion of other characteristics of these regression models is found in the references cited here. They should also facilitate a comparison of SV amplitudes presented here with other regression models of Fourier and response spectra.

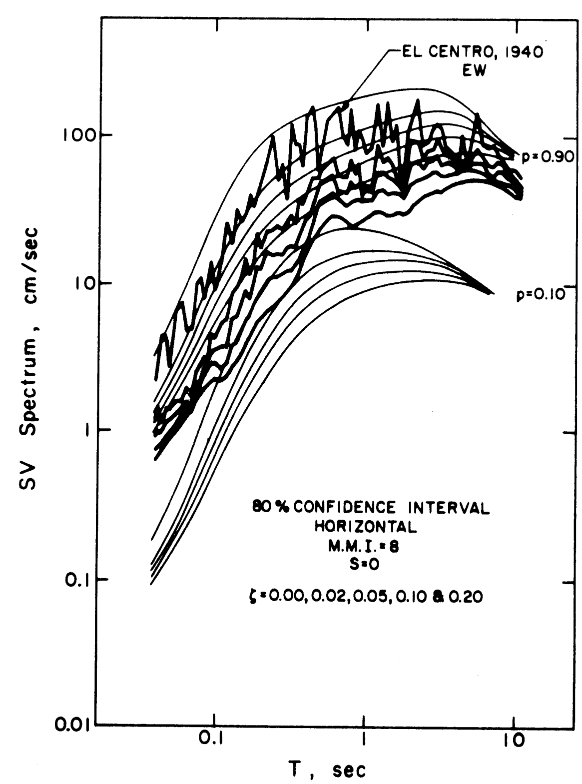

Figure 6

CONCLUSIONS

Several results of this work, consistent with our previous analysis of SA (Trifunac and Anderson, 1977) and PSV (Trifunac and Anderson, 1978) response spectra are that:

1) SV spectral shapes do not change appreciably with epicentral distance R (i.e., g(T) is small).

2) Scaling of spectral amplitudes in terms of MMI is not less reliable than scaling in terms of magnitude and epicentral distance.

3) The uncertainties associated with scaling of response spectra by means of one amplitude factor (e.g., peak acceleration, peak velocity, spectrum intensity) are now completely eliminated.

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