Empirical scaling of Fourier amplitude spectra in former Yugoslavia

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SUMMARY – In this paper, empirical scaling of the Fourier spectral amplitudes of strong earthquake ground accelerations in former Yugoslavia is presented. This work incorporates all current improvements relative to our earlier experience with regression models for scaling Fourier and response amplitudes, which we presented before 1985, for the western United States. Since then, a frequency dependent attenuation function was developed for the Southern California region (Trifunac and Lee, 1985a). Using this attenuation function, improved regression models for Fourier and response spectra were developed for Southern California (Trifunac and Lee, 1985b, c). A frequency dependent attenuation function was recently developed for Yugoslavia (Lee and Trifunac, 1992) for periods between .04 and 2. sec, so that the empirical scaling of the Fourier spectral amplitudes in Yugoslavia using this new frequency dependent attenuation can now be formulated.

KEYWORDS – Fourier spectra, strong motion

Introduction

Empirical scaling equations for peaks and for spectral amplitudes of strong ground motion have been evolving over the past 20 years. In Southern California, with one of the largest and most complete earthquake data bases so far, these scaling equations have reached a level where it is now possible to relate the results with independent estimates of long (T > 10 sec), intermediate, and short (T < .1 sec) period seismological studies. Clearly, the physical processes of strong ground motion are continuous functions of frequency and distance. The strong motion data and its analyses typically correspond to frequencies between .1 and 25 Hz, and to distances less than 100 km. In contrast, most seismological observations are at epicentral distances much greater than 50 km and tend to cover longer period ground motion (Trifunac, 1993). Analyses and interpretations of the functional link between near source (strong motion) and more distant (seismological) observation also depend on the regional characteristics of the attenuation. Since the attenuation depends on the characteristics of the earth crust, the geometry and depth of the sources, the statistical characteristics of the seismogenic zones and the scattering and inelastic attenuation in the area (Q), the whole process is also region dependent. Thus, since much of our experience with strong earthquake motion comes from southern California, it becomes very useful to understand how and what will change when observing this motion elsewhere. In this respect, the possibility to compare the empirical scaling equations for spectral amplitudes in Yugoslavia with those for California becomes particularly useful.

The main purpose of this paper is to find whether it is possible to formulate (independently) regression equations for scaling the spectral amplitudes in Yugoslavia, using strong motion data recorded there. This data is less complete than the data base which we used in California and, so, this analysis will also show how for this region future data gathering should be organized. We will show that such scaling is possible, in a preliminary way, but with sufficient detail to point out the nature and the extent of the differences relative to the strong shaking amplitudes in California.

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Scaling of PSV(T) in Yugoslavia in Terms of the MAG-SITE-SOIL MODEL

The current models in the western U.S. Trifunac (1987) and Lee (1987) recently completed a study on scaling of Fourier amplitude spectra, $FS(T)$, and of pseudo relative velocity spectra, $PSV(T)$, in terms of magnitude, M, «representative» source-to-station distance, Δ, focal depth, H, «size» of the fault, S, component orientation, v, local geology, characterized by the local geologic site conditions, s, ($s = 0$ for sediments, $s = 1$, for intermediate sites and $s = 2$ for sites on basement rock, Trifunac and Brady, 1975), and local soil conditions, s_L ($s_L = 0$, for «rock» sites, $s_L = 1$, for stiff soil sites and $s_L = 2$, for deep soil sites, Seed et al., 1974). Their scaling relation for $FS(T)$ (and similarly for $PSV(T)$) takes the form

$$\begin{aligned} \log_{10}[FS(T)] &= M + \mathcal{A}tt(\Delta, M, T) \\ &+b_1(T)M + b_2^{(1)}(T)S^{(1)} + b_2^{(2)}(T)S^{(2)} + b_3(T)v \\ &+b_3^{(1)}(T)S^{(1)}v + b_3^{(2)}(T)S^{(2)}v + b_4(T) + b_5^{(1)}(T)S_L^{(1)} \\ &+b_5^{(2)}(T)S_L^{(2)} + b_6(T)M^2 \end{aligned} \tag{1}$$

where $S^{(1)}$ and $S^{(2)}$ are indicator variables for the site condition s, defined as

$$S^{(1)} = \begin{cases} 1 & \text{if } s = 1 \text{ (intermediate sites)} \\ 0 & \text{otherwise,} \end{cases}$$

$$S^{(2)} = \begin{cases} 1 & \text{if } s = 2 \text{ (basement rock)} \\ 0 & \text{otherwise,} \end{cases}$$

and $S_L^{(1)}$ and $S_L^{(2)}$ are the indicator variables

$$S_L^{(1)} = \begin{cases} 1 & \text{if } s_L = 1 \text{ (stiff soil)} \\ 0 & \text{otherwise,} \end{cases}$$

$$S_L^{(2)} = \begin{cases} 1 & \text{if } s_L = 2 \text{ (deep soil)} \\ 0 & \text{otherwise,} \end{cases}$$

used to characterize the soil at the site. $\mathcal{A}tt(\Delta, M, T)$ is the frequency dependent attenuation function for Yugoslavia (Lee and Trifunac, 1992). It takes the form:

$$\mathcal{A}tt(\Delta, M, T) = \begin{cases} \mathcal{A}_0(T)\log_{10}\Delta & R \le R_0 \\ \mathcal{A}_0(T)\log_{10}\Delta_0 - \dfrac{(R-R_0)}{200}, & R > R_0 \end{cases} \tag{4}$$

where Δ, the representative source-to-station distance, is given by

$$\Delta = S\left(\ln\frac{R^2 + H^2 + S^2}{R^2 + H^2 + S_0^2}\right)^{-1/2} \tag{5}$$

and

$$\Delta_0 = S\left(\ln\frac{R_0^2 + H^2 + S^2}{R_0^2 + H^2 + S_0^2}\right)^{-1/2} \tag{6}$$

where S_0 is the coherence radius of the source (Gusev, 1983). The term $\mathcal{A}_0(T)\log_{10}\Delta$ is used to calculate the attenuation at distance R less than some transition distance R_0, (when $\Delta = \Delta_0$). For distance $R > R_0$, the attenuation becomes a linear function of R with slope equal 1/200, as in the case of Richter (1958) attenuation for Southern California. The transition distance, R_0, is given by:

$$R_0 = 1/2\left\{\frac{-200\mathcal{A}_0(T)(1 - S_0^2/S^2)}{\ln 10} + \left[\left[\frac{200\mathcal{A}_0(T)(1 - S_0^2/S^2)}{\ln 10}\right]^2 - 4H^2\right]\right\},$$

which depends on M, H, S, S_0 and $\mathcal{A}_0(T)$. Detailed description of the attenuation function in Yugoslavia is presented in Lee and Trifunac (1992).

The Strong-Motion Data in Yugoslavia

The strong-motion accelerograph network was first installed throughout Yugoslavia in the early 1970's, as a result of the cooperative US-Yugoslav project, organized jointly by the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje, Yugoslavia, and the U.S. National Science Foundation (NSF). Since then, this strong-motion network recorded hundreds of excellent strong-motion data. In 1983, a cooperative project has been initiated between IZIIS, Skopje, Yugoslavia, and the Civil Engineering Department of the University of Southern California in Los Angeles, California, U.S.A., to digitize and to process all strong-motion data recorded in free field. By 1987, the programme on digitization of 449 records was completed (Jordanovski et al, 1987). The resulting data consists of digitized accelerograms from more than 200 earthquakes between 1975 and 1983. Among these data, records from 183 contributing earthquakes have been identified and cross-referenced with various regional catalogues for a total of 325 recorded accelerograms.

Table I illustrates the data available from the 183 identified earthquakes. It shows the distribution of records from earthquakes between 1975 and 1983, of magnitudes between 2.5 and 7.25, of mostly shallow depths (< 25 km), and for small epicentral distances, typically less than 50 km. The majority of these earthquakes are for magnitudes 3 to 6. Table II is a list of the earthquakes used in the database (adapted from Lee et al., 1990).

Table I – (from Lee et al., 1990) The available strong-motion records versus magnitude, M, and distance $D = (R^2 + H^2)^{1/2}$ (km)

	$\log_{10} D$(km)								
M_p	.7*	.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3
6.76-7.25			2	2	1	2	1	9	6
6.26-6.75									
5.76-6.25				3	11	5	3	1	
5.26-5.75		1	3		3	2	3	5	1
4.76-5.25		1	3	9	11	5		1	2
4.26-4.75	4	4	13	28	19	4			
3.76-4.25	1	3	15	25	12	6	1		
3.26-3.75	1	1	34	10	4	3			
2.76-3.25	2	3	21	6	6	2			

* Intervals 0.2 units wide, centered at .7, .9, 1.1,..

Table II

EQ#	EQ.REF#		DATE MO/DA/YR	TIME GMT	SEC.	LAT. (N)	LONG. (E)	H KM	MAGNITUDES 1	2	3	4	5	S.M. 1	2	# OF REC	INT.	EQ NAME
1	1		9/ 7/75	1623		45.84	15.74	0	4.50					4.40	4.14		5.5MCS	BREZICE-ZAGREB
2	2		5/11/76	0532		46.20	13.11	10	4.10					4.41	4.55	2	5MCS	FRIULI
3	3	2	7/14/76	0539	33.2	46.35	13.31	6	4.40				4.30	3.96	3.47			FRIULI
4	4		9/ 7/76	1108		46.21	13.02	5	4.10				4.20	3.95	3.68		5.5MCS	FRIULI
5	5	3	9/11/76	1631	11.0	46.30	13.22	7	5.10	4.93		4.93	5.50	4.71	4.13	2	7.5MM	FRIULI
6	6	4	9/11/76	1635	2.8	46.24	13.17	11	5.60				5.70	5.51	5.18	2	9.0MM	FRIULI
7	7	5	9/11/76	1648	54.6	46.29	13.17	1	4.30	3.95		3.95		4.24	4.02			FRIULI
8	8	6	9/12/76	1953	27.8	46.29	13.24	6	4.50	4.16		4.16	4.50	4.14	3.67		7.0MM	FRIULI
9	9	7	9/13/76	1854	45.9	46.33	13.21	4	4.40	4.33		4.33	4.40	4.45	4.33	2	6.0MM	FRIULI
10	10	8	9/15/76	0315	19.4	46.28	13.18	9	5.80				6.00	5.94	5.82	2	9.0MM	FRIULI
11	11	9	9/15/76	0438	52.7	46.31	13.17	7	4.80	4.57		4.57	4.70	4.55	4.13	2	7.0MM	FRIULI
12	12	10	9/15/76	0458	41.8	46.33	13.21	5	4.60	4.46		4.46	4.40	4.25	3.77		6.0MM	FRIULI
13	13	11	9/15/76	0921	17.8	46.33	13.15	2	6.10				6.10	6.04	5.69	2	9.5MM	FRIULI
14	14		9/15/76	0945		46.30	13.14	5	4.20				4.30	4.24	4.11			FRIULI
15	15	12	9/15/76	1111	10.8	46.33	13.24	8	5.00	4.67		4.67	4.90	4.65	4.11	2	7.5	FRIULI
16	17	14	9/16/77	2348	7.5	46.28	12.97	11	5.30	4.77		4.77	5.30	4.80	4.09		8.0MM	FRIULI
17	18	15	9/28/77	0143	14.7	46.29	13.05	17	4.20	3.79		3.79		4.32	4.27			FRIULI
18	19		9/23/77	0258		41.49	20.08	37	4.70					4.75	4.63		7.0MM	BURREL,ALB.
19	20		11/ 3/77	0223		42.12	24.03	11	5.50					5.53	5.33		7.MCS	VELINGRAD,BUL.
20	21		12/ 7/77	1921		46.26	13.13	10	3.40					3.38	3.34			FRIULI
21	22	16	1/ 1/78	0423	46.3	43.30	17.60	20	3.80	4.00		4.00		3.52	3.27		5.5MCS	LISTICA
22	23	17	2/20/78	1213	33.5	46.48	13.25	0	4.00	3.62		3.62		4.62	5.08		6.0MCS	FURLANIA
23	24	18	3/16/78	0608	39.0	43.10	18.03	20	4.00	3.76	3.98	3.87		3.94	3.76		6.0MCS	STOLAC
24	25	160	6/20/78	2003	25.1	40.75	23.26	20	6.00				6.00	5.95	5.39			THESSALONIKI,GR
25	26		11/16/78	2023		41.97	21.50	0	3.50					3.59	3.59		5.5MCS	SKOPJE
26	28	21	12/17/78	0216	49.3	43.44	17.38	16	4.50					4.22	3.80	2		IMOTSKI
27	27		12/31/78	1556		41.99	23.22	21	4.60					5.07	5.37	2		BLAGOEVGRAD,BUL
28	29	22	2/17/79	2206	3.0	44.69	17.25	5	3.40	3.60	3.19	3.40		3.35	3.30		5.5MCS	BANJA LUKA
29	112	23	3/31/79	1555	24.0	41.88	19.07	6	4.00	4.03	4.08	4.06		4.09	4.03	2		MONTE NEGRO
30	113	24	4/ 9/79	0210	19.8	41.90	19.05	0	5.20	5.04		5.04	5.10	5.33	5.26	3	7.5	MONTE NEGRO
31	114		4/10/79	1054		41.90	19.19	10	3.60					3.54	3.43			MONTE NEGRO
32	31	26	4/15/79	0619	45.8	42.02	19.07	13	7.00				6.80	7.09	6.74	23	9.0MCS	MONTE NEGRO
33	116	27	4/15/79	0631	9.4	42.16	18.74	10	4.90	4.47		4.47		4.87	4.66	3		MNT.NEGRO AFTSH.
34	117		4/15/79	0701		42.00	19.30	10	3.60					3.46	3.32			MNT.NEGRO AFTSH.
35	118	28	4/15/79	0711	27.9	41.98	19.18	11	4.20	3.90	3.74	3.82		4.18	4.00			MNT.NEGRO AFTSH.
36	119	29	4/15/79	0725	31.6	41.94	19.47	10	4.10	4.01	3.66	3.83		4.20	4.14			MNT.NEGRO AFTSH.
37	120		4/15/79	0748		41.80	19.14	10	3.80					3.88	3.82			MNT.NEGRO AFTSH.
38	121	31	4/15/79	0808	41.9	42.24	18.65	10	4.40	4.48	4.32	4.40		4.07	3.64			MNT.NEGRO AFTSH.
39	122	32	4/15/79	0813	17.1	41.92	19.24	26	4.30	4.45	4.35	4.40		4.35	4.23			MNT.NEGRO AFTSH.
40	123		4/15/79	0910		41.92	19.33	10	4.40					4.06	3.62	2		MNT.NEGRO AFTSH.
41	124	37	4/15/79	1025	25.3	1.91	19.40	15	4.90	4.86		4.86		4.85	4.62	3		MNT.NEGRO AFTSH.
42	125	38	4/15/79	1107	30.2	42.08	19.06	6	4.20	3.96	4.10	4.03		4.37	4.37	2		MNT.NEGRO AFTSH.
43	126	39	4/15/79	1142	16.5	41.93	19.41	10	3.70	3.87	3.70	3.79		3.58	3.42			MNT.NEGRO AFTSH.
44	127	40	4/15/79	1243	46.2	42.08	19.19	12	4.40	3.99	4.13	4.06		4.09	3.67	2		MNT.NEGRO AFTSH.

segue tab. II

EQ#	EQ.REF#		DATE MO/DA/YR	TIME GMT	SEC.	LAT. (N)	LONG. (E)	H KM	MAGNITUDES 1	2	3	4	5	S.M. 1	2	# OF REC	INT.	EQ NAME
45	128	41	4/15/79	1324	33.6	42.41	18.74	10	4.30		3.97	3.97		3.66	3.13			MNT.NEGRO AFTSH.
46	32	42	4/15/79	1443	5.9	42.26	18.71	9	5.80					5.58	5.11	6		MNT.NEGRO AFTSH.
47	130		4/15/79	1524		42.39	18.87	10	4.50					4.15	3.69			MNT.NEGRO AFTSH.
48	131	43	4/15/79	1752	56.2	42.55	18.55	9	4.10	4.18	3.82	4.00		3.64	3.23			MNT.NEGRO AFTSH.
49	132	46	4/15/79	2049	46.8	42.00	19.21	14	4.30	4.43	4.47	4.45		4.01	3.62			MNT.NEGRO AFTSH.
50	133	49	4/16/79	0756	1.7	41.79	19.56	17	4.20	4.10	4.26	4.19		4.26	4.16			MNT.NEGRO AFTSH.
51	134	51	4/16/79	1004	39.1	41.92	19.24	10	4.90	5.03		5.03		5.17	5.25	2		MNT.NEGRO AFTSH.
52	135	53	4/16/79	1430	51.9	42.00	19.03	15	4.10	4.32	4.09	4.20		4.21	4.17	2		MNT.NEGRO AFTSH.
53	228		4/16/79	1535		41.82	19.21	14	3.30					4.17	4.85	1		MNT.NEGRO AFTSH.
54	136	55	4/16/79	1551	7.3	41.81	19.37	10	3.80	3.57	3.59	3.58		3.68	3.50	2		MNT.NEGRO AFTSH.
55	137	56	4/16/79	2300	27.0	41.86	19.38	11	4.20	4.30	4.10	4.20		4.48	4.59	3		MNT.NEGRO AFTSH.
56	138	58	4/17/79	0353	32.4	41.80	19.48	10	4.20	3.86	3.95	3.91		4.14	3.93			MNT.NEGRO AFTSH.
57	33	59	4/17/79	0539	57.9	42.45	18.62	0	4.90	5.10		5.10		4.61	4.15	2		MNT.NEGRO AFTSH.
58	140	61	4/17/79	1806	16.0	42.04	19.05	1	4.00	3.92	4.17	4.05		4.22	4.28			MNT.NEGRO AFTSH.
59	141	64	4/18/79	0245	12.1	41.89	19.10	8	3.70	3.96	4.03	3.99		3.63	3.48			MNT.NEGRO AFTSH.
60	142	65	4/18/79	0350	4.9	41.91	19.14	7	4.10	4.17	4.07	4.12		3.95	3.69	3		MNT.NEGRO AFTSH.
61	30	67	4/18/79	1519	20.4	46.34	13.29	21	4.80	4.92		4.92		4.78	4.59	2	7.0MM	FRIULI
62	143	68	4/18/79	1951	13.4	42.01	19.06	5	4.60	4.43		4.43		4.56	4.36	4		MNT.NEGRO AFTSH.
63	144	69	4/19/79	0017	35.3	41.90	19.18	10	4.50	4.42		4.42		4.71	4.75	3		MNT.NEGRO AFTSH.
64	145	70	4/19/79	0542	49.8	42.04	19.03	2	4.60	4.36		4.36		4.63	4.50	4		MNT.NEGRO AFTSH.
65	146	71	4/19/79	0707	5.4	42.01	19.02	3	4.00	4.29	4.15	4.22		3.78	3.51			MNT.NEGRO AFTSH.
66	147		4/20/79	2341		41.88	19.16	10	3.60					3.08	2.81			MNT.NEGRO AFTSH.
67	148		4/21/79	0136		41.80	19.10	5	3.50					3.44	3.36			MNT.NEGRO AFTSH.
68	149		4/21/79	0149		41.85	19.10	5	3.20					3.51	3.67			MNT.NEGRO AFTSH.
69	150	72	4/21/79	0238	5.7	41.98	19.20	20	4.30	4.66		4.66		4.90	5.34	2		MNT.NEGRO AFTSH.
70	151		4/21/79	0404		41.83	19.37	10	3.80					3.73	3.58			MNT.NEGRO AFTSH.
71	152	73	4/21/79	0433	1.2	41.80	19.18	5	4.30	4.19	4.30	4.24		4.17	3.90	2		MNT.NEGRO AFTSH.
72	153	74	4/21/79	0454	26.9	41.83	19.16	5	3.90	3.87	4.27	4.07		3.78	3.57			MNT.NEGRO AFTSH.
73	154		4/22/79	0444		41.95	19.27	10	3.50					2.96	2.72			MNT.NEGRO AFTSH.
74	155	78	4/22/79	0632	12.0	41.92	19.24	5	4.50	4.43	4.45	4.44		4.52	4.39	3		MNT.NEGRO AFTSH.
75	156	79	4/22/79	0732	7.4	41.78	19.32	16	4.00	3.91	3.71	3.81		3.52	3.13			MNT.NEGRO AFTSH.
76	157	80	4/23/79	1252	46.3	41.92	19.26	8	3.20	3.19		3.19		2.81	2.71			MNT.NEGRO AFTSH.
77	158		4/24/79	0023		41.81	19.29	10	3.60					3.53	3.42			MNT.NEGRO AFTSH.
78	159		4/24/79	1645		41.81	19.10	10	3.60					4.10	4.44			MNT.NEGRO AFTSH.
79	160	81	4/24/79	2226	24.9	41.94	19.28	10	3.60	3.54	3.67	3.60		3.37	3.20	2		MNT.NEGRO AFTSH.
80	161	82	4/25/79	0636	46.3	41.92	19.25	6	3.80	3.92	4.08	4.00		3.96	3.96			MNT.NEGRO AFTSH.
81	162	83	4/25/79	1514	32.0	41.83	19.19	11	3.80	3.93	4.07	4.00		3.85	3.77			MNT.NEGRO AFTSH.
82	164		4/25/79	1812		41.94	19.13	5	3.30					3.81	4.13			MNT.NEGRO AFTSH.
83	163	84	4/25/79	1912	17.6	41.85	19.26	11	3.60	3.78	3.92	3.85		3.59	3.51			MNT.NEGRO AFTSH.
84	165	85	4/28/79	0338	2.6	42.19	18.81	2	4.50	4.56		4.56	4.50	4.21	3.79	2	7.0	MNT.NEGRO AFTSH.
85	166	86	4/29/79	1024	17.7	42.00	19.23	10	3.90	4.00	4.08	4.04		3.52	3.19			MNT.NEGRO AFTSH.
86	167	87	4/30/79	1700	5.7	42.27	18.82	4	4.50	4.33		4.33		3.72	3.07			MNT.NEGRO AFTSH.
87	168	88	5/ 1/79	0639	6.4	41.93	19.26	4	3.20	3.40	3.41	3.41		3.32	3.38			MNT.NEGRO AFTSH.
88	169	90	5/ 3/79	1639	45.7	41.85	19.13	5	3.50	3.66	3.71	3.68		3.61	3.62			MNT.NEGRO AFTSH.
89	170		5/ 6/79	2252		41.89	19.36	10	3.50					3.23	3.07			MNT.NEGRO AFTSH.
90	34	92	5/12/79	0330	34.2	42.26	18.91	9	5.20	5.08		5.08	5.00	5.25	5.11	6		MNT.NEGRO AFTSH.
91	172	93	5/14/79	0953	7.6	41.93	19.19	10	4.60	4.60		4.60		4.85	4.93	2		MNT.NEGRO AFTSH.
92	173	94	5/20/79	0845	28.5	42.19	18.82	5	4.30	4.59		4.59		4.42	4.38	2		MNT.NEGRO AFTSH.
93	35	95	5/24/79	1723	18.2	42.15	18.76	5	6.20				6.10	6.25	5.99	12	7.5MM	MNT.NEGRO AFTSH.
94	175		5/24/79	1942		42.16	18.71*	56	3.80					4.15	4.32			MNT.NEGRO AFTSH.
95	176		5/24/79	2228		42.21	18.65	10	4.10					4.00	3.77			MNT.NEGRO AFTSH.
96	177		5/25/79	0332		42.29	18.76	10	3.70					3.93	4.00			MNT.NEGRO AFTSH.
97	178		5/25/79	0722		42.20	18.73	10	4.10					3.65	3.24			MNT.NEGRO AFTSH.
98	179		5/25/79	1145		42.14	18.76	10	4.30					4.23	4.00	2		MNT.NEGRO AFTSH.
99	180		5/27/79	1447		42.15	18.78	10	4.40					4.59	4.59			MNT.NEGRO AFTSH.
100	181		5/28/79	1327		42.12	18.68	10	4.20					4.38	4.39			MNT.NEGRO AFTSH.
101	182		5/30/79	0538		41.85	19.06	10	4.10					4.01	3.79			MNT.NEGRO AFTSH.
102	183		5/30/79	2347		42.30	18.76	10	4.40					3.86	3.33	2		MNT.NEGRO AFTSH.
103	184		6/ 1/79	0929		42.37	18.60	10	3.80					3.68	3.49			MNT.NEGRO AFTSH.
104	185		6/ 4/79	0251		42.13	18.78	8	4.40					4.40	4.24			MNT.NEGRO AFTSH.
105	186		6/18/79	0956		42.19	18.65	10	4.30					4.25	4.05			MNT.NEGRO AFTSH.
106	187		6/20/79	2118		42.17	18.69*	49	4.80					4.68	4.38	2		MNT.NEGRO AFTSH.
107	188		7/14/79	1407		42.26	18.76	10	3.90					4.27	4.47	2		MNT.NEGRO AFTSH.
108	189	96	7/20/79	0256	2.9	41.86	19.21	5	3.60	3.60	3.53	3.57		4.10	4.43			MNT.NEGRO AFTSH.
109	190		8/ 2/79	1414		42.06	19.04	10	4.20					4.73	5.09			MNT.NEGRO AFTSH.
110	191		8/ 6/79	0748		42.31	18.58	10	4.10					4.12	3.93			MNT.NEGRO AFTSH.
111	192		8/17/79	0530		41.89	19.31	3	4.40					4.30	4.03			MNT.NEGRO AFTSH.
112	193		8/24/79	1016		42.16	18.79*	38	3.90					4.04	4.03			MNT.NEGRO AFTSH.
113	36	149	9/ 7/79	1257	56.9	44.84	17.38	0	3.20	3.54	3.15	3.35		2.92	2.85		5.0MCS	BANJA LUKA
114	194	100	9/21/79	1202	41.7	41.95	19.36	4	4.20	3.90	4.17	4.04		4.11	3.86			MNT.NEGRO AFTSH.

segue tab. II

EQ#	EQ.REF#		DATE MO/DA/YR	TIME GMT	SEC.	LAT. (N)	LONG. (E)	H KM	MAGNITUDES 1	2	3	4	S.M. 1	2	# OF REC	INT.	EQ NAME
115	195		11/ 5/79	1824		42.00	19.31	11	3.20				3.46	3.59			MNT.NEGRO AFTSH.
116	196	101	11/ 6/79	0805	25.6	41.90	19.26	6	3.10		3.65	3.65	3.58	3.87			MNT.NEGRO AFTSH.
117	198	102	11/ 9/79	0148	49.7	41.88	19.30	17	4.10	3.84	4.17	4.00	4.32	4.38			MNT.NEGRO AFTSH.
118	199		11/ 9/79	0238		41.82	19.19	7	3.10				3.49	3.71			MNT.NEGRO AFTSH.
119	200	103	11/ 9/79	0420	2.2	41.87	19.24	4	3.70	3.61	3.57	3.59	3.35	3.10			MNT.NEGRO AFTSH.
120	201	104	11/10/79	0419	34.7	41.90	19.37	6	4.20		4.38	4.38	5.11	5.85			MNT.NEGRO AFTSH.
121	202	105	11/20/79	1831	59.3	42.01	18.96	8	4.50	3.90	3.78	3.84	4.77	4.87	2		MNT.NEGRO AFTSH.
122	37	157	5/18/80	2002	57.9	43.21	20.97	6	5.70				5.87	5.81	8	8.0MCS	KOPAONIK
123	38	159	5/18/80	2026	42.7	43.24	20.96	11	5.00				5.07	4.96	2		KOPAONIK
124	39		5/18/80	2019		43.26	20.90	10	4.30				4.56	4.66			KOPAONIK
125	40		5/18/80	2041		43.29	20.89	1	4.90				4.81	4.53			KOPAONIK
126	42	106	5/21/80	0922	41.0	43.33	21.00	7	3.80	3.90	3.79	3.85	3.52	3.26		6.0MM	KOPAONIK
127	43	107	5/23/80	1226	23.9	43.28	21.04	0	4.50	4.58		4.58	4.81	4.96			KOPAONIK
128	44	108	5/23/80	1237	35.5	43.19	21.02	5	3.20	3.28		3.28	3.48	3.62			KOPAONIK
129	45		5/23/80	1340		43.12	21.30	10	3.00				3.44	3.71			KOPAONIK
130	46	109	5/25/80	0603	36.2	43.26	21.06	13	3.60	3.72	3.79	3.76	4.14	4.51			KOPAONIK
131	47	110	5/25/80	0708	49.4	43.27	20.95	9	3.60	3.58	3.22	3.40	3.53	3.41			KOPAONIK
132	48	111	5/26/80	0025	37.1	42.87	20.98	10	3.40	3.07		3.07	3.32	3.26			KOPAONIK
133	50		5/31/80	1642		43.30	20.80	10	2.80				2.98	3.17			KOPAONIK
134	51	113	6/ 1/80	2124	44.6	43.28	21.01	8	3.40	3.53	3.50	3.51	3.93	4.27			KOPAONIK
135	52	114	6/ 3/80	1908	5.7	43.25	21.00	10	3.50	3.50	3.34	3.42	3.58	3.57			KOPAONIK
136	53	115	6/ 4/80	0321	43.3	43.27	20.99	4	3.10	2.94		2.94	3.30	3.43			KOPAONIK
137	54		6/ 4/80	2129		43.31	20.80	10	3.20				3.21	3.23			KOPAONIK
138	55		6/ 5/80	0603		43.27	21.00	10	3.00				3.13	3.26			KOPAONIK
139	56	116	6/ 9/80	0811	22.7	43.07	20.73	10	2.90				3.21	3.43			KOPAONIK
140	57	117	6/10/80	2125	1.8	43.34	21.05	10	4.10	4.02	3.95	3.99	4.07	3.89	2		KOPAONIK
141	58	118	6/12/80	2346	26.7	43.05	20.98	12	3.50	3.49	3.05	3.27	4.11	4.54			KOPAONIK
142	59		6/14/80	0642		43.01	20.61	10	3.30				3.97	4.43			KOPAONIK
143	60	119	6/14/80	0220	21.6	43.05	20.97	18	3.30	3.07		3.07	3.53	3.62			KOPAONIK
144	61	120	6/17/80	0952	6.0	43.25	20.95	10	3.70	3.80	3.57	3.68	3.96	4.04	2		KOPAONIK
145	62	121	6/17/80	2214	39.5	43.23	20.95	10	3.70	3.84	3.50	3.67	3.81	3.80	2		KOPAONIK
146	63	122	6/19/80	0147	2.3	43.19	20.92	10	3.60	3.57	3.55	3.56	3.95	4.13			KOPAONIK
147	64	123	6/19/80	0442	16.1	43.27	21.07	10	3.50	3.31	3.47	3.39	3.28	3.14			KOPAONIK
148	65	124	6/28/80	0610	12.0	43.22	20.94	6	3.40	3.27	3.16	3.21	3.59	3.66			KOPAONIK
149	66	125	6/29/80	0552	11.7	43.21	20.88	9	3.70	3.84	3.49	3.66	3.49	3.30			KOPAONIK
150	68	126	7/ 1/80	0643	11.4	43.26	20.96	9	3.10		2.99	2.99	3.03	3.05			KOPAONIK
151	69	127	7/ 2/80	1423	52.1	43.27	20.97	8	3.10				2.91	3.02			KOPAONIK
152	70		7/13/80	2054		43.29	20.63	10	3.10				3.82	4.33			KOPAONIK
153	71	128	7/13/80	2207	53.3	44.73	17.31	7	3.40		2.96	2.96	2.95	2.77	4		FOJNICA-KON.
154	41	129	7/19/80	0037	57.9	41.45	20.38	12	4.50	4.80		4.80	4.72	4.86		?6.5MCS	ZERCAN,ALB.
155	72	130	7/31/80	2152	39.3	43.31	20.95	10	3.20	3.44	3.42	3.43	3.61	3.84			KOPAONIK
156	74	132	9/ 3/80	1159	40.9	43.26	20.93	10	3.20	3.51	3.26	3.39	3.29	3.34			KOPAONIK
157	75	134	10/10/80	0103	46.7	43.23	20.91	10	2.80				2.85	3.00			KOPAONIK
158	76	135	10/11/80	1055	12.0	43.28	20.95	10	3.00				2.80	2.81			KOPAONIK
159	77		10/11/80	2339		43.20	20.30	0	2.90				3.28	3.52			KOPAONIK
160	78	136	10/21/80	1943	11.1	43.23	20.88	10	3.90				3.93	3.82	2		KOPAONIK
161	79	151	11/ 3/80	1911	45.7	43.22	20.85	10	3.80		3.68	3.68	3.68	3.49	2		KOPAONIK
162	81	152	12/ 8/80	0632	0.9	43.31	21.03	10	3.30	3.51		3.51	3.41	3.45			KOPAONIK
163	82	153	12/14/80	0254	48.6	43.27	21.07	10	3.90	4.10	4.28	4.19	4.22	4.38	2		KOPAONIK
164	83	154	12/22/80	1909	39.9	43.22	20.99	10	3.70	3.88	3.49	3.68	3.93	4.00	2		KOPAONIK
165	87		2/28/81	2253		42.95	20.56	0	3.90				4.00	3.96	2		KOPAONIK
166	91	156	3/ 7/81	0653	16.0	42.95	20.78	0	3.80	3.74	3.82	3.78	3.70	3.52			KOPAONIK
167	92		3/ 8/81	1310		42.84	20.68	10	3.40				3.54	3.56			KOPAONIK
168	98		5/11/81	1325		43.27	18.53	10	3.40				3.53	3.55		5.5MCS	FOCA-TJENT.
169	99	137	7/24/81	0253	43.1	44.71	17.27	5	3.00	3.15	3.14	3.14	2.70	2.67	3		BANJA LUKA
170	100	138	7/24/81	0255	51.6	44.67	17.24	10	2.90	2.90	2.79	2.84	2.67	2.71	2		BANJA LUKA
171	101	139	8/13/81	0258	13.5	44.70	17.22	7	5.40				5.89	6.16	4	8.0MCS	BANJA LUKA
172	102	140	8/13/81	0437	12.4	44.69	17.19	7	3.50	3.56		3.56	2.97	2.73	2		BANJA LUKA
173	103	142	8/14/81	0444	54.4	44.73	17.22	10	3.20	3.32	3.19	3.29	2.95	2.89	2		BANJA LUKA
174	204		8/19/81	2043		42.17	18.95	10	4.50				4.39	4.13			MNT.NEGRO AFTSH.
175	104		8/21/81	0330		44.89	17.37	11	3.20				3.30	3.36	3		BANJA LUKA
176	105		8/30/81	0311		44.98	17.40	10	2.80				2.82	2.97	2		BANJA LUKA
177	110		6/ 2/82	0542		43.35	20.94	2	4.6				5.04	5.30		7.5MCS	KOPAONIK
178	106	144	7/ 3/82	0341	32.5	44.68	17.19	6	2.80		3.18	3.18	2.66	2.75	3	5.0MCS	BANJA LUKA
179	109	158	7/14/82	1614	53.8	42.13	21.43	7	4.40		4.42	4.42	3.97	3.48	3	6.0MCS	KACANIK
180	107	146	10/12/82	0133	59.3	44.69	17.14	6	3.30				3.20	3.16	4	5.0?MM	BANJA LUKA
181	108		11/22/82	1857		44.58	16.80	10	2.9				3.49	3.88	3		KLJUC
182	203	147	1/ 5/83	0403	30.5	41.96	19.19	10	3.80		3.98	3.98	4.38	4.78			MNT.NEGRO AFTSH.
183	111	148	2/25/83	1822	13.6	41.95	21.66	6	4.50		4.17	4.17	4.29	3.93	9	6.5MCS	SKOPJE

* REPORTED FOCAL DEPTHS ARE NOT RELIABLE

Table III – Number of records in Yogoslav data base in different magnitude intervals and grouped by the site parameters s and s_L

	$s = 2$ (basement rock)			$s = 1$ (intermediate)			$s = 0$ (sediment sites)		
M	$s_L = 0$	1	2	$s_L = 0$	1	2	$s_L = 0$	1	2
2.0-2.9	0	4	0	0	0	0	9	0	0
3.0-3.9	0	35	0	5	13	0	18	32	1
4.0-4.9	4	4	0	28	26	0	0	59	3
5.0-5.9	3	0	0	12	4	0	4	12	2
6.0-6.9	1	0	0	6	4	0	1	2	0
7.0	3	2	0	3	5	0	3	5	0
Total	11	43	0	54	52	0	35	110	6

Table IV – Distribution of the available records with respect to $M = 4.25$, and s and s_L

(a)	$s = 2$ (basement rock)	$s = 1$ (intermediate)	$s = 0$ (sediment sites)	Total
	$s_L =$ 0, 1, 2	$s_L =$ 0, 1, 2	$s_L =$ 0, 1, 2	
All magnitudes:	11, 45, 0	54, 52, 0	35, 110, 6	313
$M \geq 4.25$:	11, 4, 0	40, 31, 0	8, 57, 5	156

(b)	$s_L = 0$	$s_L = 1$	$s_L = 2$	Total
All magnitudes:	100	207	6	313
$M \geq 4.25$	59	92	5	156

Column 1 in Table II shows the earthquake number (1-183). Columns 2 and 3 give the cross-references with the earthquake numbers listed respectively in Tables I and A2 of Yugoslav EQINFOS data (Jordanovski et al., 1987). Column 4 gives the date of the earthquake in the format of month/day/year. Columns 5 and 6 give the time of the earthquake in GMT with minutes and seconds. Columns 7 and 8 show the latitude and longitude of the epicenter. Column 9 gives the focal depth in km. Column 10 lists the published magnitude M_p. Columns 11 to 14 present different magnitude estimates as discussed in Lee et al. (1990). Columns 15 and 16 are the strong motion magnitudes M_L^{SM}, also discussed in Lee et al. (1990). Column 17 shows the number of strong motion stations which recorded each event. Column 18 gives the epicentral intensity. The last column, column 19, gives the name of the earthquake.

The next step in the database preparation was to gather at each recording site information on both the local geological and local soil site characteristics. As a first step, the geological classification is given by the site condition parameters, s (Trifunac and Brady, 1975; Trifunac, 1976a, b; $s = 0$ for sediments, $s = 2$ for basement rock and $s = 1$ for intermediate sites). The soil classification is given by the soil parameter, s_L (Seed, et al., 1974; «rock», stiff soils, and deep soils).

This new data base has been used recently to determine strong-motion magnitudes from strong-motion records in Yugoslavia (Lee et al., 1990), to calibrate the levels of shaking associated with the Mericalli-Cancani-Sieberg (MCS) intensity scale (Trifunac et al., 1991) and to compare the modified Mercalli Intensity (MMI) used in the western United States with the MCS in Yugoslavia (Trifunac and Živčić, 1991), and to calibrate the regional magnitude estimates in south-eastern Europe (Trifunac and Herak, 1992). This same database has been used to estimate the frequency dependent strong-motion attenuation function for Yugoslavia (Lee and Trifunac, 1992).

The Direct 1-step Model for Fourier Spectrum Amplitudes in Yugoslavia

Following the studies in the western U.S.A. and the model mentioned in the previous section (Eqn. (1)), the regression equation for the Fourier spectral amplitudes now takes the form

$$\begin{aligned}\log_{10}[FS(T)] &= \mathrm{M} + \mathcal{A}tt(\Delta, M, T)\\ &+b_1(T)M + b_2^{(1)}(T)S^{(1)} + b_2^{(2)}(T)S^{(2)} + b_3(T)v. \quad (8)\\ &+b_4(T) + b_5^{(1)}(T)S_L^{(1)} + b_5^{(2)}(T)S_L^{(2)} + b_6(T)M^2\end{aligned}$$

Note that the terms $b_3^{(1)}(T)S^{(1)}v$ and $b_3^{(2)}(T)S^{(2)}v$, appearing in Eqn. (1), are deleted, since the regression

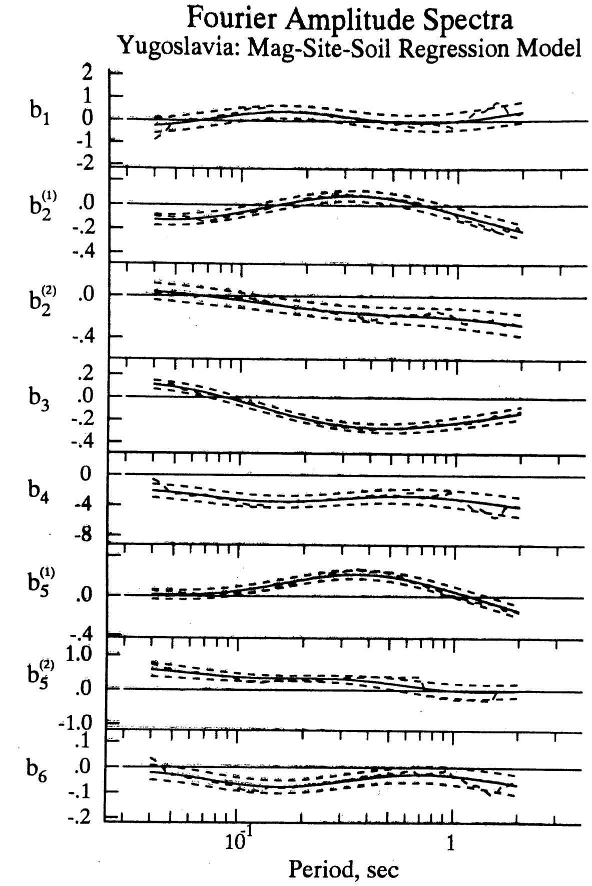

Fig. 1 – Scaling function $\hat{b}_1(T)$ through $\hat{b}_6(T)$.

analysis of the currently available strong motion data in Yugoslavia shows that those are insignificant. To include only the records with large signal-to-noise ratio, regression on periods from T = .04 sec up to only T = 2 sec is performed. The data beyond period T = 2 sec. are not adequate for any meaningful regression at this time. Another limitation results from the uneven distribution of records in different magnitude ranges. Table III shows the distribution of records in different magnitude ranges, for different site classifications (s = 0,1 and 2) and for different soil classifications (s_L = 0, 1, 2).

It is seen from Table III, that more than half of the records are in the small magnitude range $M < 5$ and, thus, less than half of the records are from earthquakes of magnitudes $M \geq 5$. Many records of small magnitudes are at least 10 km and some are over 20 km distant from the epicenters, and, thus, have small signal-to-noise ratio for most of the periods in the range of interest.

Note, that the proposed dependence of Fourier amplitudes on magnitudes, is of the form, (from Eqn. (8)):

$$\log_{10} FS(T) = M + \dots + b_1(T)M + \dots + b_6(T)M^2 \quad (9)$$

which is a parabola with respect to the magnitude, M. It is expected that the dependence of $FS(T)$ on M will be linear for small to intermediate magnitudes, and that it will level off to a certain maximum level at some intermediate to large magnitude. In other words, the parabola for M should have a maximum, or the sign of $b_6(T)$ should be negative. If all of the data from earthquakes of large and small magnitudes were used in the subsequent regression, it would be found that the term $b_6(T)$ is positive (> 0), or that the parabola is convex upward. This would be caused by the presence (clustering) of many data points near, at, or even below the level of recording and processing noise with Fourier spectral amplitudes near 1 cm/sec. To ensure that $b_6(T) < 0$ in the period range [0.04, 2.0] sec, only the data from earthquakes with $M \geq 4.25$ have been considered. The resulting scaling functions, $b_1(T)$ through $b_6(T)$, are plotted in Figure 1.

For given values of s, v, Δ, M and s_L, $\log_{10} FS(T)$ represents a parabola when plotted versus M at each period, T. With $b_6(T) < 0$, the parabola has a maximum at $M = M_{max}(T)$ where

$$M_{max}(T) = -(1 + b_1(T))/(2b_6(T)). \quad (10)$$

As in our previous analyses (Trifunac and Lee, 1987), it is again assumed that the regression equation applies only in the range $M_{min} \leq M \leq M_{max}$, where

$$M_{min}(T) = -b_1(T)/(2b_0(T)) \quad (11)$$

is the value of the magnitude at which the parabola has unit slope. The regression equation (1) will then be modified to

$$\begin{aligned}\log_{10} \hat{FS}(T) = {} & M_< + \mathcal{A}tt(\Delta, M, T) + \\ & b_1(T)M_{<>} + b_2^{(1)}(T)S^{(1)} + b_2^{(2)}(T)S^{(2)} + b_3(T)v + b_4(T) + \\ & b_5^{(1)}(T)S_L^{(1)} + b_5^{(2)}(T)S_L^{(2)} + b_6(T)M_{<>}^2 \end{aligned} \quad (12)$$

where $\log_{10} \hat{FS}(T)$ is the estimated spectral amplitude at period T,

$$M_< = M_<(T) = \min(M, M_{max}(T)),$$

and

$$M_{<>} = M_{<>}(T) = \max(M_<(T), M_{min}(T)). \quad (13)$$

With $FS(T)$ and $\hat{FS}(T)$ representing the actual and the predicted Fourier amplitudes at period T, the residues, $\epsilon(T)$, are calculated as (Trifunac and Lee, 1987)

$$\epsilon(T) = \log_{10}(FS(T)) - \log_{10}[\hat{FS}(T)]. \quad (14)$$

It is assumed that $\epsilon(T)$ can be described by a normal distribution function with mean $\mu(T)$ and standard deviation, $\sigma(T)$, as follows:

$$p(\varepsilon, T) = \frac{1}{\sigma(T)\sqrt{2\pi}} \int_{-\infty}^{\epsilon(T)} \exp\left[-1/2\left(\frac{x - \mu(T)}{\sigma(T)}\right)^2\right] dx,$$

$$= \text{Prob}\,[\log_{10}[FS(T)] - \log_{10}[\hat{FS}(T)] \le \epsilon(T)] \qquad (15)$$

Figure 2 shows a plot of the residuals corresponding to $p(\varepsilon, T) = 0.1$ through 0.9 for $\log_{10} FS(T)$. Figure 3 shows the plot of the statistical parameters in the description of the residues: $\hat{\mu}(T)$, $\hat{\sigma}(T)$, $\chi^2(T)$ and $KS(T)$. A more detailed discussion of the statistical parameters used can be found in Trifunac and Lee (1985b, c).

The Residue 2-Step Model

The approach in the previous section that uses the regression Eqn. (8), involving the attenuation function, the magnitude, and the site and soil conditions at the site, is simple and straightforward. We recall from Eqn. (9) that for the dependence of $FS(T)$ on M to be parabolic, with the «correct» shape ($b_6(T) < 0$), it is necessary to include in the regression only those records from earthquakes with magnitudes $M \ge 4.25$. Unfortunately, this eliminates almost half of the database, as Table IV shows. For all magnitudes, and only for those with $M \ge 4.25$, Table IV(a) lists the number of records available in the database for the geologic site conditions $s = 2$, 1 and 0. For each site condition the data is further classified according to various soil conditions. Similarly Table IV(b) presents a summary of the records available for the three soil classifications, $s_L = 0$, 1 and 2. It is seen that if only data from earthquakes with $M \ge 4.25$ are included, only about half of the available records (from 313 down to 156) are left. As a result, the scaling functions $b_5^{(1)}(T)$ and $b_5^{(2)}(T)$ respectively for the indicator variables $S_L^{(1)}$, $S_L^{(2)}$ of the soil parameter s_L are not representative of the complete set of database in Yugoslavia. A look at Table IV(b) further shows that of the total 313 soil records with known soil classifications ($s_L = 0$, 1 and 2) in the database, only 6 are for the classification $s_L = 2$ (deep soil). There is thus insufficient information on data from deep soil sites. It is therefore necessary to delete the deep soil classification ($s_L = 2$) from the database and so the regression in this paper will be performed only for data with «rock» ($s_L = 0$), and stiff soil ($s_L = 1$) classifications. Furthermore, a 2-step procedure will be adopted. Instead of performing the regression analysis directly in one step as in the previous section, the regression will be performed now in two steps. This so-called residue-2-step method is not new. It has also been used for regression of $FS(T)$ and $PSV(T)$ in the western U.S.A. (Trifunac, 1987; Lee, 1987). A brief description of this procedure is summarized below.

In the previous section we dealt with the direct, 1-step model where the scaling of Fourier spectra in terms of M, R, H, s, s_L and v is performed in one step with the soil indicator variables included in the regression equation directly. Because of the lack of data as discussed above, a 2-step regression model will be considered here also. The first step of the regression will not include the site soil classification. The estimated amplitude, $\log_{10} \hat{FS}(T)$, is given by

$$\begin{aligned} \log_{10} \hat{FS}(T) &= M_{<} + \mathcal{A}tt(\Delta, M, T) + \\ &+ c_1(T)M_{<>} + c_2^{(1)}(T)S^{(1)} + c_2^{(2)}(T)S^{(2)} + c_3(T)v. \qquad (16) \\ &+ c_4(T) + c_5(T)M_{<>}^2 \end{aligned}$$

where $c_i(T)$ are the scaling functions in the first step of the regression analysis. Again, only the data from earthquakes with magnitudes > 4.25 are included in the regression, so that the scaling function $c_5(T)$ for M^2 will have the proper sign (< 0).

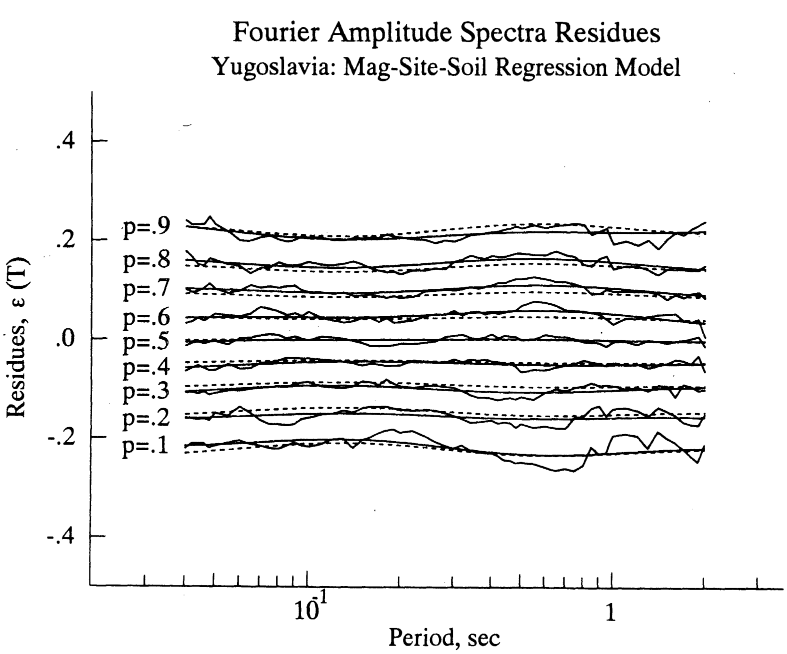

Fig. 2 – Residues, $\varepsilon(T) = \log_{10} FS(T) - \log_{10} \hat{FS}(t)$ corresponding to $p(\varepsilon, T) = .1, .2, ..., .9$

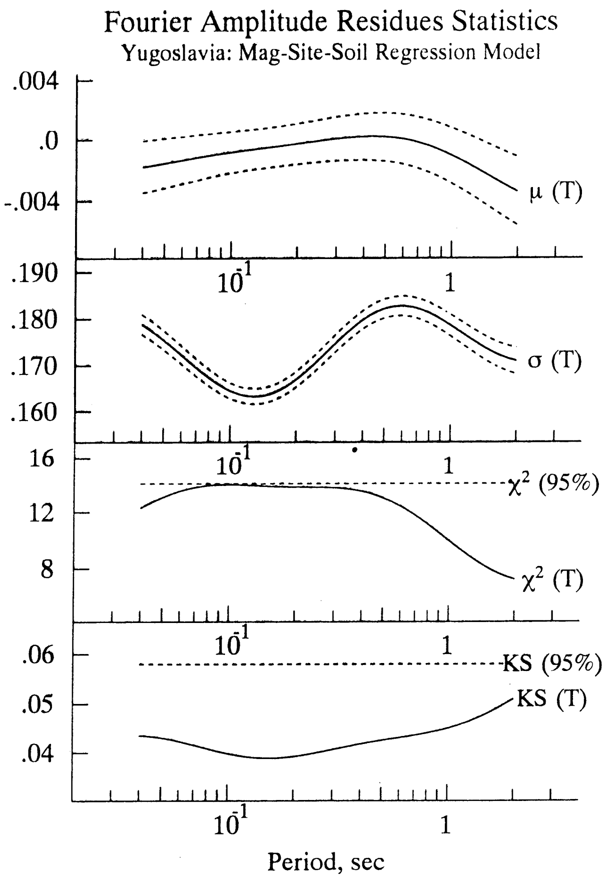

Fig. 3 – Statistical parameters $\overline{\mu}(T)$, $\hat{\sigma}(T)$, and $KS(T)$.

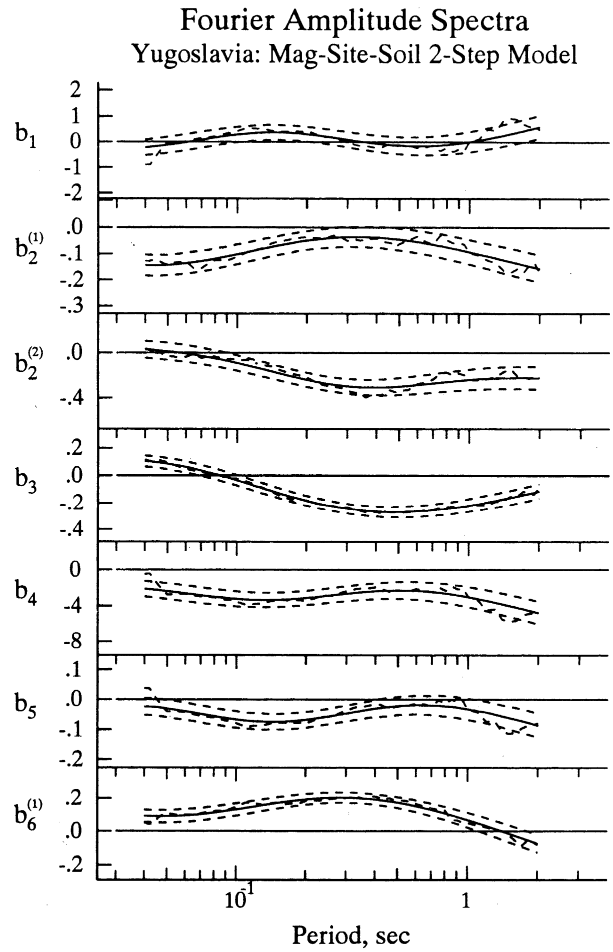

Fig. 4 – Scaling functions $\hat{b}_1(T)$ through $\hat{b}_6^{(1)}(T)$ (two-step model).

The contributions of soil classification to the Fourier amplitudes may next be included. The residues with respect to the above regression are calculated by

$$\epsilon(T) = \log_{10} FS(T) - \log_{10} \hat{FS}(T), \qquad (17)$$

with $\log_{10} FS(T)$ representing the actual Fourier amplitudes. The residues at each site where soil classification is available are next fitted by the equation

$$\epsilon(T) = c_6^{(1)}(T)S_L^{(1)} + c_7(T). \qquad (18)$$

Note that the data from earthquakes of all magnitudes are now included in the second step. Here, as before, $S_L^{(1)}$ is the indicator variable for s_L. Eqn. (18) can now be combined with Eqn. (16) to give

$$\begin{aligned} \log_{10} \hat{FS}(T) &= M_< + \mathcal{A}tt(\Delta, M, T) + \\ &+ b_1(T)M_{<>} + b_2^{(1)}(T)S^{(1)} + b_2^{(2)}(T)S^{(2)} + b_3(T)v + \\ &b_4(T) + b_5(T)M_{<>}^2 + b_6^{(1)}(T)S_L^{(1)} \end{aligned} \qquad (19)$$

where $b_i(T) = c_i(T)$, except for $b_5^{(1)}(T) = c_6^{(1)}(T)$ and $b_4(T) = c_4(T) + c_7(T)$. This procedure will be referred to as the residue «2-step» model in contrast to the direct 1-step model in the previous section. Figure 4 shows a plot of the resulting scaling functions, $b_1(T)$ through $b_6(T)$. Note that the scaling function $b_6^{(1)}(T)$ for the soil classification $s_L = 1$ stiff soil in the second step of the regression is calculated from the complete database of records from earthquakes of all magnitudes, and is «better behaved» or more «significant» now. Figs. 5 and 6 show the corresponding plots of $\mu(T)$, $\sigma(T)$ and the residue statistics. Comparison with the corresponding direct 1-step model (Fig. 2) shows that the residues at the 9 probability levels have a similar width.

Examples of Estimated Fourier Spectra

Figure 7 presents four plots of estimated $FS(T)$ spectra using Eqn. (19). The top two plots are examples of $FS(T)$ computed for magnitudes M = 4.5, 5.5, 6.5 and 7.5 at epicentral distance R = 0, focal depth N = 5 km, for soil parameter s_L = 1 (stiff soil), for $p(\varepsilon, T)$ = 0.5, and for horizontal and vertical motions. The solid lines in both figures correspond to the geologic site condition s = 2 (basement rock), while the dashed lines correspond to s = 0 (sediments). The diagonal dashed lines represent the average Fourier amplitudes of digitization

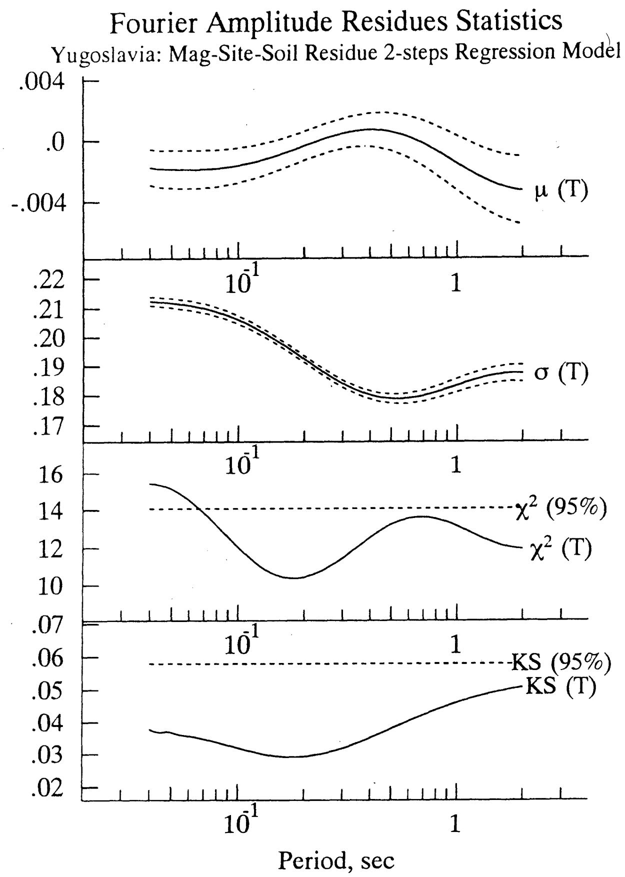

Fig. 5 – Statistical parameters $\hat{\sigma}(T)$, $\hat{\sigma}$, $\chi^2(T)$ and $KS(T)$ (two-step model).

noise. The lower left plot illustrates the effect of epicentral distance R on the changes of spectral amplitudes for magnitude $M = 6.5$, focal depth $H = 5$ km, site condition $s = 0$, soil classification $s_L = 1$ and $p(\varepsilon, T) = 0.5$. Four sets of curves with decreasing amplitudes correspond to $R = 0$, 25, 50 and 100 km. The lower right plot illustrates the effect of focal depth H (at 5,10, 25 and 50 km) on the changes of spectral amplitudes. The solid lines in both of the lower plots are for horizontal motions while the dashed lines are for vertical motions.

The trends of the computed $FS(T)$ amplitudes in Figure 7 are in many ways similar to those presented for the western U.S. models using magnitude, site and soil statistics, except for the fact that the data here is only available up to the period $T = 2$ sec instead of $T = 14$ sec, as for the western U.S. data.

Figure 8 presents another four plots of estimated $FS(T)$ to illustrate the effects of the local soil conditions on $FS(T)$. The top two plots show examples of $FS(T)$ computed for magnitudes $M = 3.5$ to 7.5 at epicentral distance $R = 0$, focal depth $H = 5$ km, site condition $s = 0$ (sediments) for both the horizontal and vertical motions. The solid lines in both plots correspond to the local soil condition $s_L = 0$ («rock») while the dashed lines correspond to $s_L = 1$ (stiff soil). The bottom two plots show examples of $FS(T)$ for $M = 6.5$, $R = 0$, 25, 50 and 100 km, $H = 5$ km, and $s = 0$, for both horizontal and vertical motions, and for both $s_L = 0$ and $s_L = 1$.

Recall that, in the 2-step model, every available record with soil classification ($s_L = 0$ or 1) is used in the second step of the regression. This results in significant improvement and in stability in computing the amplitudes of the scaling function $b_6^{(1)}(T)$ for the soil indicator variable $S_L^{(1)}$.

Fig. 9 and 10 summarize the differences in the effects of the local geologic site conditions and of the local soil conditions on $FS(T)$. It can be concluded from these two figures that the estimated FS amplitudes

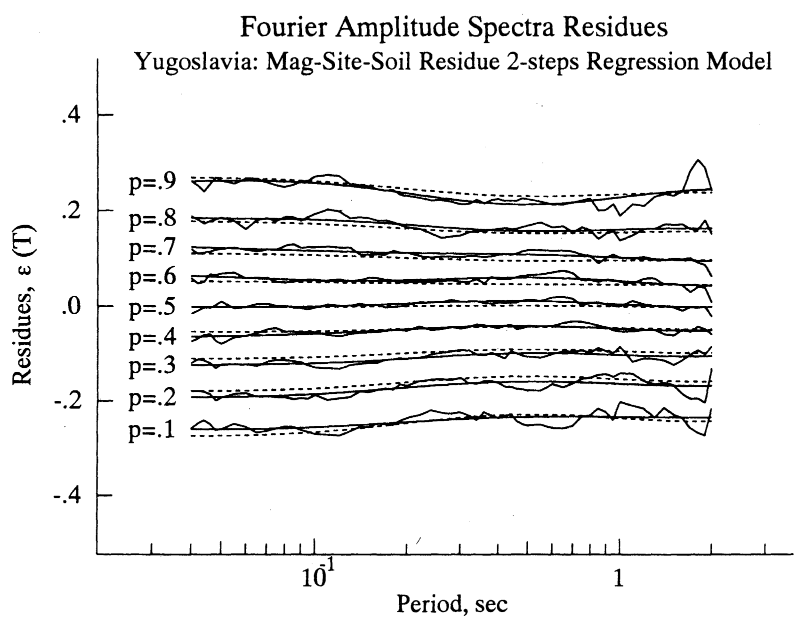

Fig. 6 – Residues corresponding to $p(\varepsilon, T) = .1, .2, ..., .9$ (two-step model).

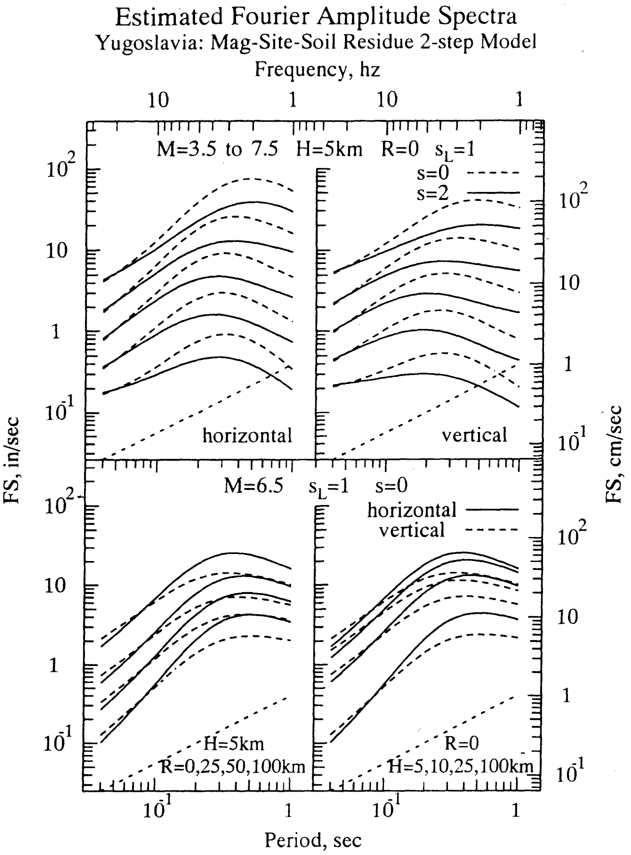

Fig. 7 – Estimated *FS(T)* for different magnitudes, source depths, component directions and site geology (two step model).

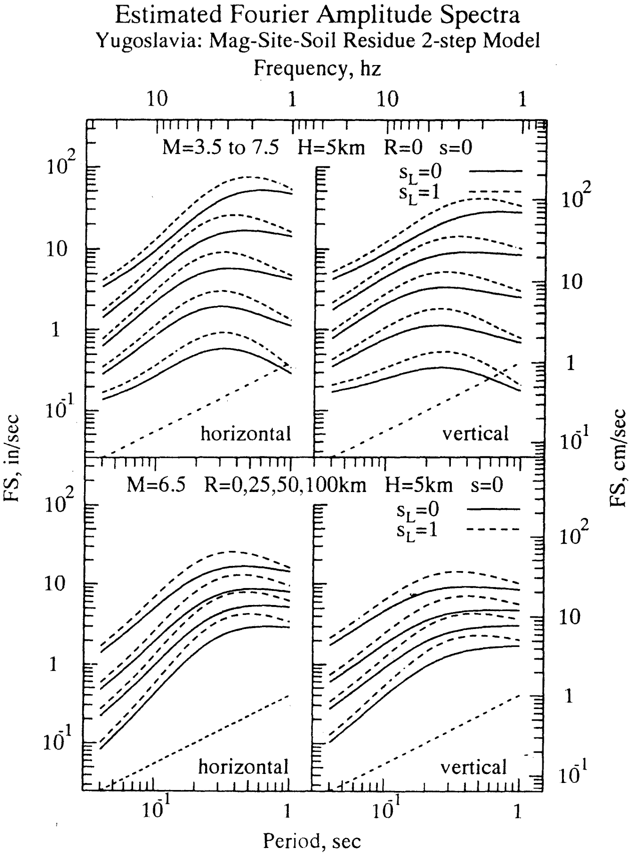

Fig. 8 – Effects of local soil conditions on *FS(T)* (two-step model).

are higher on «stiff» soil (s_L = 1) than on «rock» (s_L = 0). Note that, in figure 10, the plot of the estimated spectra at the site with s_L = 2 (soft soil) is left blank, since no regression is performed with respect to that classification, with only «rock» soil (s_L = 0) and stiff soil (s_L = 1) being represented in the data base.

Fig. 11 compares the amplitudes of the Fourier spectra at a selected site using Eqn. (19). The parameters used are as shown in the figure. For each component, the top and bottom curves represent the estimated Fourier spectrum amplitudes at 2.5% and 97.5% confidence levels. As it is seen from these figures, the agreement between the recorded and empirically predicted spectra is satisfactory.

Discussion and conclusions

In the forgoing, we presented the most detailed models from a class of models described by Eqn. (1), that can be supported by the strong motion data in former Yugoslavia. We found that the models in Eqn. (8) (direct one-step model) and in Eqn. (19) (residue, 2-step model) both lead to scaling coefficient functions which are significantly different from zero. However, more detailed perusal of the regression details shows that without using our experience with the strong motion data in California, it would have been difficult to describe (from first principles and independently) these models for strong motion data in Yugoslavia. Thus the models presented here must be viewed only as a first step towards developing more detailed, reliable and complete models for this area. Clearly this will be possible only after future strong motion recordings contribute two to three times larger data base.

Our analysis shows that the amplitudes and the shapes of the average Fourier amplitude spectra are different in former Yugoslavia from those recorded in the western U.S.. In the high frequency range, the spectral amplitudes in the western U.S. (grey, 20% confidence intervals in Fig. 12) decay faster with frequency than in Yugoslavia (solid lines in Fig. 12). This may be explained by larger overall value of the quality factor Q in Yugoslavia. This plausible, but not unique interpretation, is in excellent agreement with several other studies which all point in the same direction (Lee et al, 1990; Trifunac and Živčić, 1991; Trifunac et al., 1991). At all frequencies, the rate of growth of the spectral amplitudes with magnitude is also different for these two regions. This is evident from Fig. 12, and is further illustrated in Figs. 13a and 13b, where the data points and the solid line show the trend of the spectral amplitudes versus magnitude, but for different frequency

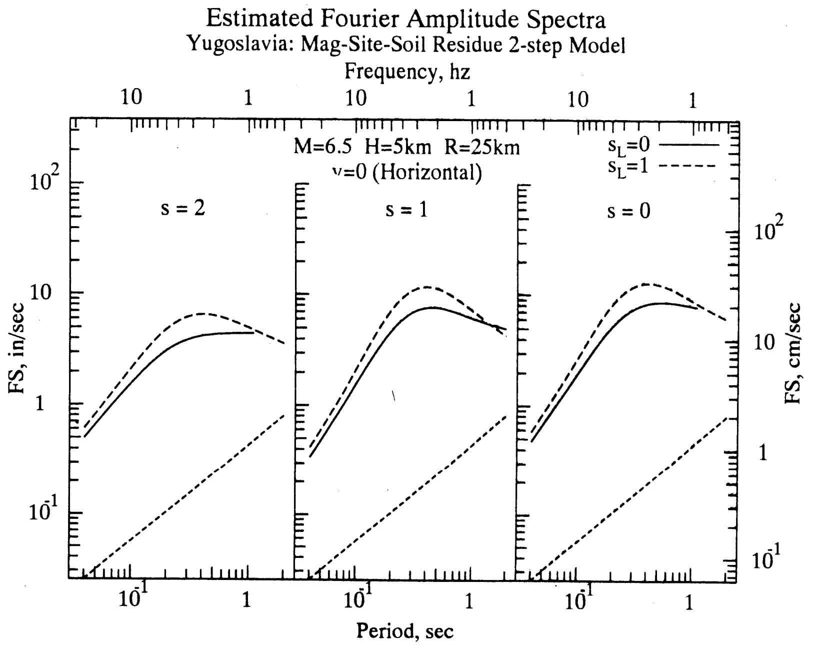

Fig. 9 – Changes in the shape of $FS(T)$ for $s_L = 0$ and 1 at different «geological» sites (s = 0, 1 and 2).

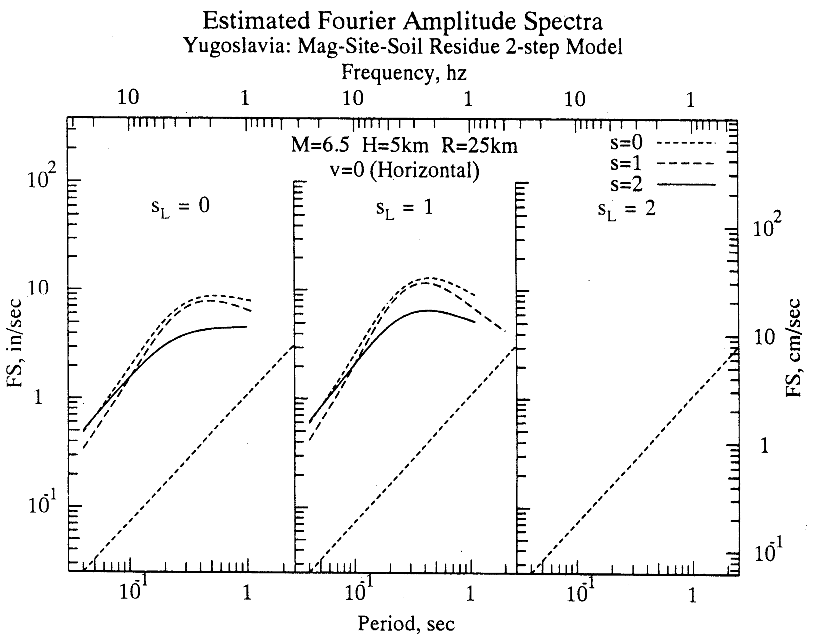

Fig. 10 – Changes in the shape of $FS(T)$ for s = 0, 1 and 2 at different «soil» sites (S_L = 0 and 1).

bands, in Yugoslavia. The corresponding trend for the strong motion data in the western U.S., shown by the dashed lines, is steeper for low magnitudes, but then levels off for larger magnitudes. Perusal of $D(\overline{M}_L^{SM}) = \overline{M}_L^{SM} - M_p$ (see Fig. 2 in Lee et al., 1990), where $\overline{M}_L^{SM}$ is the local magnitude computed from strong motion data, and M_p is the magnitude published for the same event, shows more prominent curvature for the California data than for the Yugoslav data, and is also in agreement with the differences implied by Fig. 13a and b. These trends can be interpreted also as being caused by lower Q in California (western U.S.) than in Yugoslavia, but a more detailed and more conclusive analysis of this interpretation will have to wait for more strong motion recordings in Yugoslavia. If these differences in the spectral shapes and in their amplitudes can be supported further by other independent data, the consequences will be important for site specific analyses and for prediction of design criteria for structures in South-Eastern Europe. This is important because many empirical scaling laws for design spectrum amplitudes in Europe tend to use the empirical trends developed for strong motion data in California, and as this study suggests, this may not be feasible due to the regional differences in Q, overall wave amplitude attenuation, and magnitude and intensity scaling differences.

The differences in the shape of the Fourier amplitude spectra between the western U.S. and Yugoslavia also illustrate the difficulties and uncertainties which will result from selection of engineering design criteria based on peak acceleration and some «standard» spec-

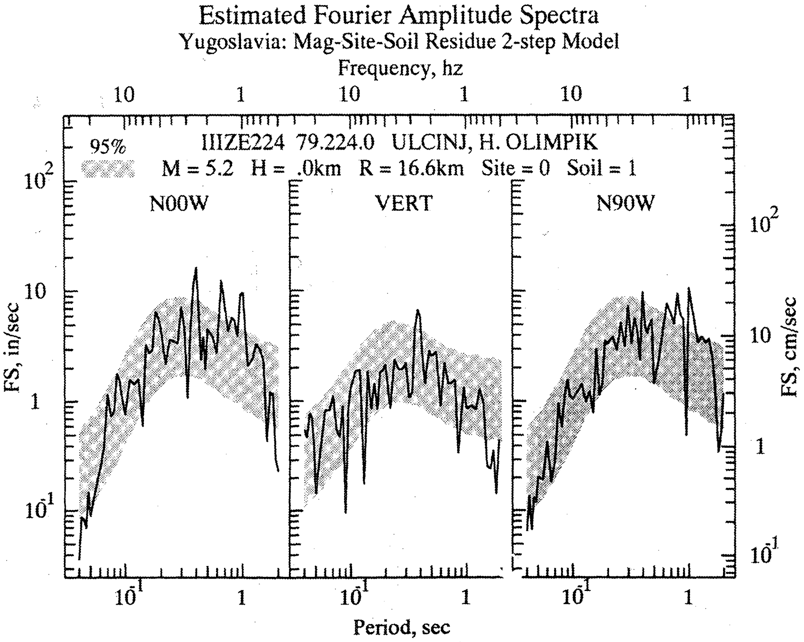

Fig. 11 – Comparison of estimated and actually computed $FS(T)$. Gray zones show the 95% confidence intervals for computed $FS(T)$ (two-step model).

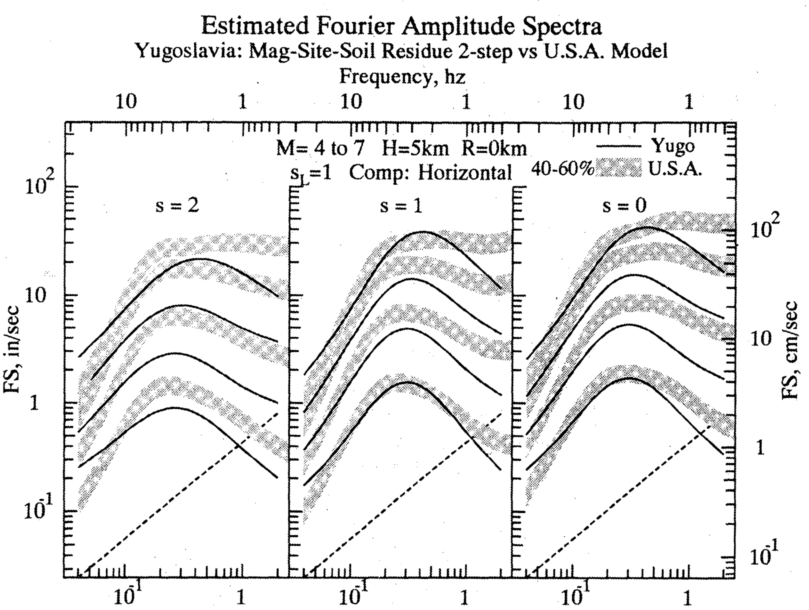

Fig. 12 – Comparison of estimated Fourier amplitude spectra in Yugoslavia (solid lines) and in the western U.S. (20% confidence, intervals are shown with shaded zones) for magnitudes 4, 5, 6 and 7.

tra shape only (Trifunac, 1992). Since the peaks of a random time function scale with the root mean square peak amplitude, $\bar{a}$, which can be related to the root mean square, a_{rms}, of the function and to its Fourier spectrum, $FS(T)$, via the Parseral's Theorem (e.g. Amini and Trifunac, 1985; Gupta and Trifunac, 1988; 1991), and because the main contribution to $\bar{a}$ and a_{rms} for the peak accelerations comes from high frequencies, the tends in Figure 12 imply higher high frequency peak accelerations in Yugoslavia than in the western U.S.. Using regionally determined attenuation equations of peak acceleration with «standard» spectral shapes based on the data from the western U.S. could clearly overestimate the design forces by factors in excess of 2 and 3. Or, using the regionally calibrated spectral shapes and the scaling equations for peak acceleration from the western U.S. could underestimate the design criteria. When one adds to this the regional variations in frequency dependent attenuation and several other factors (seismicity, distribution of active faults, their activity, maximum magnitudes, ...), which all can have profound effect on determining the shape of the design spectrum (Trifunac 1988; 1990; 1992), it becomes clear that we must abandon scaling of design ground motions via peak accelerations and that we should employ the direct scaling of spectral amplitudes in terms of regionally gathered and processed strong motion data. To achieve this goal it is essential that the recording, processing and analysis of strong motion data are con-

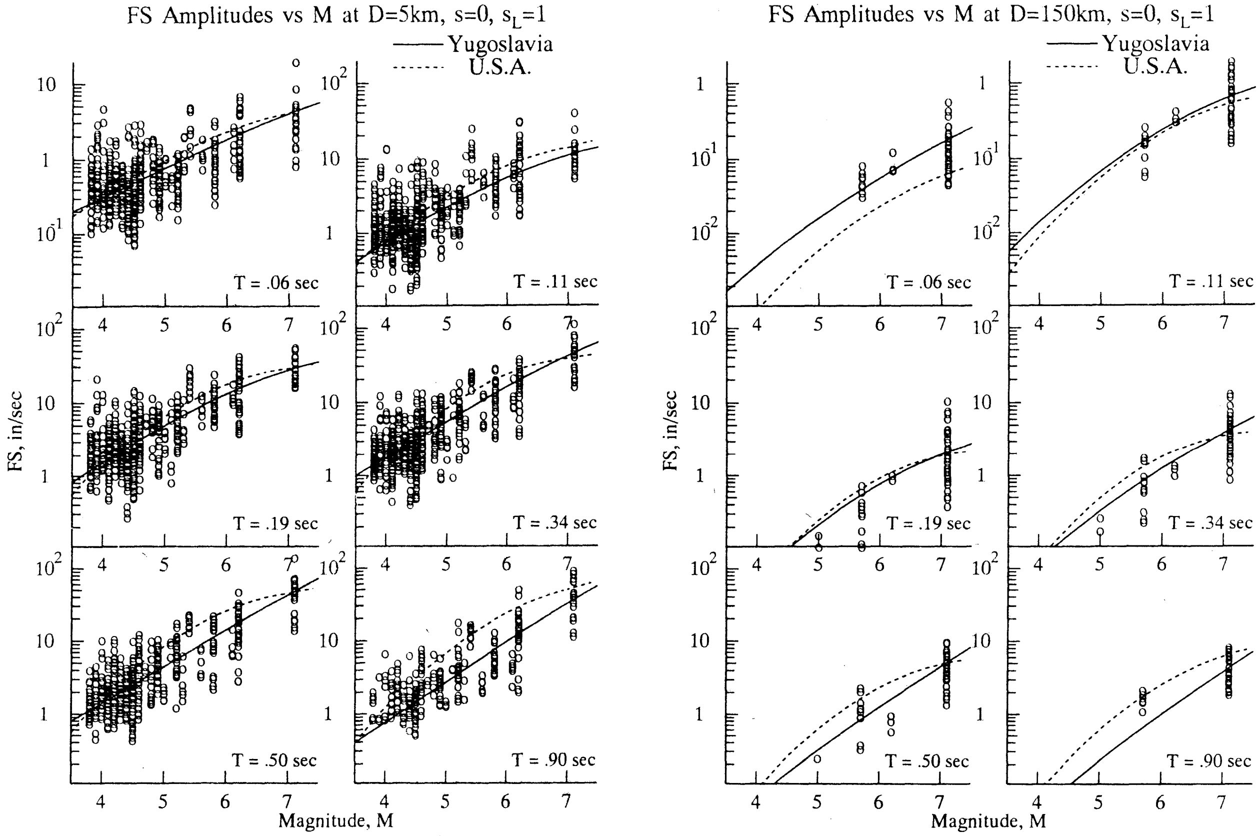

Fig. 13 – a) Variation of Fourier spectrum amplitudes at six center periods ranging from.06 to.9 seconds versus magnitude in Yugoslavia (circles and solid lines), at source to station distance Δ = 5 km. Dashed lines show the trend for the western U.S. b) same as a) but for source to station distance Δ = 150 km.

tinued and expanded and modified to provide more data for S_L = 2 («rock») and s = 2 (basement rock) sites.

The strong motion data base used in this study comes from four regions in former Yugoslavia, which were seismically active between 1976 and 1983, when this data was recorded. These regions are «Friuli», «Banja Luka», «Montenegro» and «Kopaonik» (e.g. Fig. 1 in Trifunac and Herak, 1992). Following the Monte Negro, M = 7.0, earthquake of 15 April, 1979, many aftershocks occurred along the Adriatic coast. Also several smaller events occurred in northern Macedonia and near Albania-Macedonia border. Further studies of strong motion amplitudes will have to find whether and to what degree the regional tectonic differences between these main contributing regions influence our results. Obviously, this is beyond the scope of this study, since the number of records in each of the four regions is too small to investigate these differences in detail. In their study of the attenuation of seismic intensities in the Balkan region Shebalin et al. (1974) considered «natural» boundaries between different geographical zones. These «natural» seismological zones were chosen for their different tectonic and geologic environment and on the scale which could allow identification of the differences in attenuation of the regionally determined intensities. The territory of former Yugoslavia was divided into two zones. one of these zones covers the area of the Dinarides and the Illyrides (all of Dalmatian coast and Albania), and contains all events in this study in the region referred to as «Montenegro». The other region represents the inner part of the Balkan Penisula, west of Romania and Bulgaria, north of Greece (e.g. Fig. 1 and 2 in Trifunac and Todorovska, 1989), and north and north-east of the first region. The Friuli earthquakes occurred near northwestern boundary of this zone, while the Banja Luka and Kopaonik earthquakes occurred inside this zone.

Our studies of the attenuation of site intensities with distance do not show significant differences in attenuation rates for the above two «natural» zones (Trifunac and Todorovska, 1980), but the possible directional dependence of attenuation, for example, parallel and perpendicular to the Dinarides has not been tested so far. Therefore, at present, we have no clear indication that the attenuation and scaling of strong motion spectral amplitudes is very different in any of the four regions which contributed strong motion data to this study, and so the empirical equations presented here can be viewed as representing the average overall attenuation of strong motion spectral amplitudes in Yugoslavia. As more strong motion data become available, it will be possible to test and to refine these observations.

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