Frequency dependent attenuation of strong earthquake ground motion in Yugoslavia

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ABSTRACT – Frequency dependent attenuation of Fourier spectrum amplitudes of strong earthquake ground motion in Yugoslavia is presented for periods between .04 and 2 seconds. For distances less than 100 km it is shown that there is a frequency dependent variation of the amplitude attenuation rates with distance, the attenuation of higher frequencies being faster. The trends of the strong motion attenuation in Yugoslavia are similar to those in the western United States, with high frequency strong motion amplitudes (f > 3 Hz) in California attenuating faster.

Introduction

Analyses of the frequency dependent attenuation of strong motion amplitudes became feasible only recently, because recorded accelerograms with all the required supporting information were not available uniformly for sufficiently large intervals of the relevant scaling parameters (earthquake magnitude, source to station distance, local site conditions etc). While the data available today is still far from adequate, several systematic analyses enabled us to decipher the first impressions on how the frequency dependent attenuation functions may look (Trifunac and Lee 1987).

The strong motion data recorded in Yugoslavia (Jordanovski et al. 1987), by itself, is not sufficient to enable independent development of the functional forms which describe the frequency dependent attenuation. However, it can be used to test the hypothesis that the forms developed for the Western United States can be applied to interpret the recorded strong motion data in South Eastern Europe. In this paper we show that this can be done well and that the differences for the two regions appear to exist only for frequencies higher than about 5 to 10 Hz. Eventual analyses of this type for other neighboring countries (Italy, Bulgaria and Greece) which will allow mapping of the regional variations in the parameters which describe the frequency dependent attenuation of strong motion, will be of particular interest. When such studies are completed, it will become possible to relate the results to the geologic and tectonic features of the respective areas and to understand how to extrapolate such parametric representations to other European countries lacking sufficient strong motion data.

In the early 70's in the regression analyses of the peaks of strong ground motion the following expression was used (Trifunac and Brady, 1975)

$$\log_{10}\begin{Bmatrix} a_{\max} \\ v_{\max} \\ d_{\max} \end{Bmatrix} = M + \log_{10} A_0(R) - \log_{10}\begin{Bmatrix} a_0(M,R,v,s) \\ v_0(M,R,v,s) \\ d_0(M,R,v,s) \end{Bmatrix} \tag{1.1}$$

where $a_{\max}$, $v_{\max}$, and $d_{\max}$ represent respectively the peak acceleration, peak velocity and peak displacement amplitudes, M is the local earthquake magnitude (M_L), and $\log_{10} A_0(R)$ is the amplitude attenuation function (Richter, 1958) versus epicentral distance, R. The amplitude attenuation function was determined empirically for Southern California and is representative for wave frequencies centered near the middle of the earthquake engineering frequency band (0.1 Hz to 25 Hz). $a_0(M, R, v, s)$, $v_0(M, R, v, s)$ and $d_0(M, R, v, s)$ were the

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empirical scaling functions for acceleration, velocity and displacement, dependent upon magnitude, epicentral distance, component orientation ($v = 0$ for horizontal, $v = 1$ for vertical) and geological site condition ($s = 2$ for basement rocks, $s = 0$ for sediments, and $s = 1$ for intermediate site conditions). This representation of strong-motion amplitudes was later generalized to Fourier spectral amplitudes, $FS(T)$, at a selected set of discrete periods, T, (Trifunac, 1976b).

Trifunac and Lee (1978) further refined this analysis by using the depth of sedimentary deposits, h, in place of the geologic site condition, s. Their scaling equation had the form

$$\log_{10}[FS(T)] = M + \log_{10} A_0(R) - b(T)\,M - c(T) - d(T)h - e(T)v - f(T)M^2 - g(T)R, \quad (2)$$

where the functions $b(T)$, $c(T)$, ... and $g(T)$ were estimated by regression analysis at 91 periods T between .04 sec and 15 sec. Although these functions were period (frequency) dependent, the Richter attenuation term, $\log_{10} A_0(R)$, was still independent of the period (frequency). The term $\log_{10} A_0(R)$ contained only information on the average properties of wave propagation through the crust, characteristic for Southern California. Its shape, however, did not depend on magnitude, source dimension or focal depth of the earthquake.

The frequency dependent attenuation function

Trifunac and Lee (1985, 1987, 1990) proposed a new attenuation function to replace the Richter's $\log_{10} A_0(R)$ function. Four different forms of this function have been studied. In all four models, a parameter, Δ, the representative distance from the source to the recording site, is introduced to replace the epicentral distance R. Δ depends on the distance, R, focal depth, H, and «size» of the fault, S. The attenuation equation proposed in their Model III has been adopted and used in subsequent regression analyses of strong-motion data (Trifunac and Lee 1985b, c). Here we present a brief summary of this attenuation function (Model III in Trifunac and Lee, 1985a, 1990).

The definition of «representative» distance from the earthquake source to the recording site, Δ, was adopted from Gusev (1983). Gusev investigated a descriptive statistical model of earthquake source radiation applied to the estimation of short-period strong earthquake ground motion. He considered a concept of a subsource, as an element of the main rupture process. The source radiation was described by overlapping the source functions and radiation pulses of different sizes. The «representative distance» from the earthquake source of size S, at focal depth H and at distance R to the site is given by

$$\Delta = S\left(\ln \frac{R^2+H^2+S^2}{R^2+H^2+S_0^2}\right)^{-1/2}, \quad (3)$$

where S_0 is the correlation radius of the source function. S_0 is approximated by one half of the wavelength λ in a frequency band centered around f, i.e.

$$S_0 \approx \lambda/2 = C_s/2f = C_sT/2, \quad (4)$$

where C_s is the shear wave velocity. Equation (3) has the property that when $S^2 << R^2 + H^2$,

$$\Delta \sim \left[\frac{(R^2+H^2)}{1-(S_0/S)^2}\right]^{1/2}. \quad (5)$$

This means that at higher frequencies (at which $S_0 \sim 0$), $\Delta \sim [R^2 + H^2]^{1/2} = \mathcal{D}$, the hypocentral distance. The frequency dependent attenuation function $\mathcal{A}tt(\Delta, M, T)$ then became

$$\mathcal{A}tt(\Delta, M, T) = \mathcal{A}_0(T)\log_{10}\Delta, \quad (6)$$

with $\mathcal{A}_0(T)$ an empirically determined function of the period (Trifunac and Lee, 1985a). The fault size S in the definition of Δ (Eq. (3)) was taken to be a linear function of the magnitude,

$$S = S(M) = 0.2 + \frac{(M-3)}{3.5}(S_{6.5} - .2), \quad (7)$$

such that $S = 0.2$ at $M = 3$, and $S = S_{6.5}$ at $M = 6.5$. The parameter $S_{6.5}$ is the «size» of the fault of an event of magnitude 6.5; it is empirically determined and has value close to 30 km for the earthquakes in California.

The above description of the attenuation of strong-motion amplitudes could be used with California data for distances within 100 to 150 km from the source of the earthquake. The distance of 150 km practically represents an upper bound of the epicentral distances of sites with strong-motion records. At distances exceeding this range, the recorded data, if any, will consist primarily of surface waves and the attenuation of recorded strong-motion amplitudes would be slower than for the sites closer to the source. For smaller magnitude earthquakes, most strong-motion instruments may not even trigger at these and larger distances. Reliable estimates of the attenuation function at these and larger distances with currently available data is difficult, if not impossible. To include these larger distances, $\mathcal{A}tt(\Delta, M, T)$ in Eq. (6) is assigned the empirically determined slope of $-1/200$ (same as for the Richter's attenuation function, $\mathcal{A}_0(R)$, for California).

The new attenuation function then takes the form

$$\mathcal{A}tt(\Delta, M, T) = \begin{cases} \mathcal{A}_0(T)\log_{10}\Delta & R \le R_0 \\ \mathcal{A}_0(T)\log_{10}\Delta_0 - (R-R_0)/200, & R > R_0 \end{cases} \quad (8)$$

where Δ is the representative distance as defined above (in equation (3)) and Δ_0 is the corresponding representative distance at the transition distance R_0. Eq. (8) indicates that for distances $R > R_0$ the attenuation function is a linear function with slope $-1/200$. The value of the transition distance R_0 is the distance R at which the attenuation function $\mathcal{A}_0(T)\log\Delta$ reaches a slope of $-1/200$. The slope of the attenuation function is

$$\frac{d}{dR}(\mathcal{A}_0(T)\log\Delta) \sim \frac{\mathcal{A}_0(T)\,(1-S_0^2/S^2)R}{(R^2+H^2)\ln 10}, \tag{9}$$

which, when equated to $-1/200$, gives

$$R^2 + \frac{200\mathcal{A}_0(T)\,(1-S_0^2/S^2)}{\ln 10}R + H^2 = 0,$$

a quadratic equation in R. The solution, R_0, is given by

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

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

Strong motion attenuation equations must be extended carefully to distances $R > R_0$, so that the seismic risk studies (Trifunac, 1988, 1990, Trifunac et al., 1987b) can be carried out with realistic and unbiased attenuation of strong motion amplitudes. In California, significant contributions to the seismic risk come from a radius of about 250 km surrounding the site. For the eastern United States, this radius must be extended to at least ~ 350 km (Trifunac et al., 1980). In Yugoslavia and in Albania, the experience with estimation of local magnitudes, (based on M_L and $\log_{10} A_0(R)$, Trifunac and Herak, 1992) suggests that the slope of ~ $-1/200$ may be a good first approximation. As magnitude scales and attenuation equations in South-eastern Europe become better calibrated, it will become possible to improve this first estimate. In any case, the functional form of the frequency dependent attenuation, valid for $0 < R < R_0$, should not be extended beyond $R \sim R_0$, or the distances beyond which the strong motion data is rarely or never recorded. Beyond 75 to 100 km, the strong motion amplitudes are mainly associated with higher frequency surface waves, whose regionally dependent attenuation must be carefully studied and calibrated, before it is included in Eq. (8) for $R > R_0$. Thus, our use of the slope equal to $-1/200$ here represents only the first and rough approximation, adopted to illustrate this method, which must be improved as data and the regionally specific results become available.

3. 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 at 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).

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 then 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 (adopted from Lee et al., 1990).

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

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

	$\log_{10} \mathcal{D}$ (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.
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	4.18		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.

Table II (cont.)

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
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	3.98			MNT.NEGRO AFTSH.

Table II (cont.)

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
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.
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

Table II (cont.)

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
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

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 parameter, s (Trifunac, 1976a, b; $s = 0$ for alluvium, $s = 2$ 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, deep cohesionless soils and soft to medium clay).

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 Mercalli-Cancani-Sieberg (MCS) intensity scale (Trifunac et al., 1991a), and to compare the modified Mercalli Intensity (MMI) used in the western United States with the MCS in Yugoslavia (Trifunac et al., 1991b). This same database can now be used to estimate the frequency dependent strong-motion attenuation function for Yugoslavia.

The frequency dependent attenuation function of strong-motion in Yugoslavia

We wish to consider the regression equation of Fourier spectral amplitudes in terms of magnitudes and site conditions at discrete periods T,

$$\begin{aligned} \log_{10} FS(T) &= M + \mathcal{A}tt(\Delta, M, T) + \\ &+ b_1(T)M + b_2^{(1)}(T)S^{(1)} + b_2^{(2)}(T)S^{(2)} + \\ &+ b_3(T)v + b_4(T) + b_5(T)M^2 \end{aligned} \tag{11}$$

for 91 discrete periods ranging from .04 sec. to 14 sec. For each component of each record in the database, the Fourier amplitude data, $FS(T)$, are usually oscillatory in the period range of interest. Before the regression, the Fourier spectrum amplitudes of each component are first smoothed. Figure 1 shows a plot of the Response and Fourier Spectra for a typical accelerogram. The oscillatory curves are the actual data and the smooth curves correspond to the smoothed data. Note that, depending on the amplitudes of the corresponding accelerations, the spectral data for each component are considered only for those periods whose signal-to-noise ratio is greater than one (Amini et al., 1982, 1987). The majority of records in the database do have spectral data up to the period of 2 seconds, beyond which the number of available data significantly decreases. Therefore, it was decided that the regression should be carried out only up to $T = 2$ sec.

Eq. (11) is similar to the equation used for the determination of the frequency dependent attenuation function in Western U.S.A., except that the site condition s is used here instead of the depth of alluvium, h, which is available only for Western United States sites. The site condition s used here ($s = 0$, sediments; $s = 1$, intermediate sites; and $s = 2$ basement rock) is characterized by the indicator variables (Trifunac, 1987; Lee, 1987), $S^{(1)}$ and $S^{(2)}$ where

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

and

$$S^{2} = \begin{cases} 1 & \text{if } s = 2 \\ 0 & \text{otherwise.} \end{cases}$$

The case $s = 0$ corresponds to both $S^{(1)} = S^{(2)} = 0$. Recall that the «representative» source-to station distance, Δ, is given by Eq. (3) with the correlation radius, S_0 (given by Eq. (4)), and size $S = S(M)$ (given by Eq. (7)), with $S_{6.5}$ the «size» of the fault for earthquakes of magnitude $M = 6.5$.

For a predetermined value of $S_{6.5}$, at each period, Δ is known and Eq. (11) shows that the scaling functions $\mathcal{A}_0(T)$ and $b_1(T)$) through $b_5(T)$ can be determined through the regression analysis of the database of records from 183 earthquakes at 61 discrete periods between 0.04 sec and 2 sec. It is found that the results of the regression analysis are not very sensitive to the choice of the value for $S_{6.5}$ at each period. Thus, as for the attenuation function in the western U.S., the empirical value of $S_{6.5}$ = 30 km is adopted for all periods.

Figure (2) shows a plot of the regression coefficient $\mathcal{A}_0(T)$ at 61 discrete periods from T = 0.04 sec to T = 2 sec, with its 95% confidence interval represented by the dashed lines. The coefficient $\mathcal{A}_0(T)$ changes between –1.5 and –.7 for T ranging from .04 to 2 sec. Figure (3) shows a plot of the estimated Fourier amplitudes versus distances for 4 period bands [.04, .08], [.085, .18], [.42, .85] and [.9, 2] (in seconds) and for magnitudes from M = 3.5 to M = 7.5, in steps of 0.5 (bottom to top).

An iterative procedure (as for the western United States) was used to determine the frequency dependent attenuation function. Eq. (11) was first written in the form

$$\log_{10} FS(T) - M - \mathcal{A}tt(\Delta, M, T) = b_1(T)M + b_2^{(1)}(T)S^{(1)} + b_2^{(2)}(T)S^{(2)} + + b_3(T)v + b_4(T) + b_5(T)M^2 \tag{12}$$

where the right-hand-side excludes the assumed attenuation function. Regression was then performed on Eq. (12) to get the scaling functions b_1 (T) through b_5 (T). Let $\hat{b}_1(T)$ through $\hat{b}_5(T)$ be the estimated scaling functions. For each point of the database, with given values of $\log_{10}FS(T)$, and the corresponding parameters, M, s and v, we define the logarithm of modified spectral amplitudes, $\log_{10}\widehat{FS}(T)$, at each period T, as

$$\log_{10} \widehat{FS}(T) = \log_{10} FS(T) - \hat{b}_1^{(1)}S^{(1)} - \hat{b}_2^{(2)}S^{(2)} - - \hat{b}_3(T)v - \hat{b}_4(T). \tag{13}$$

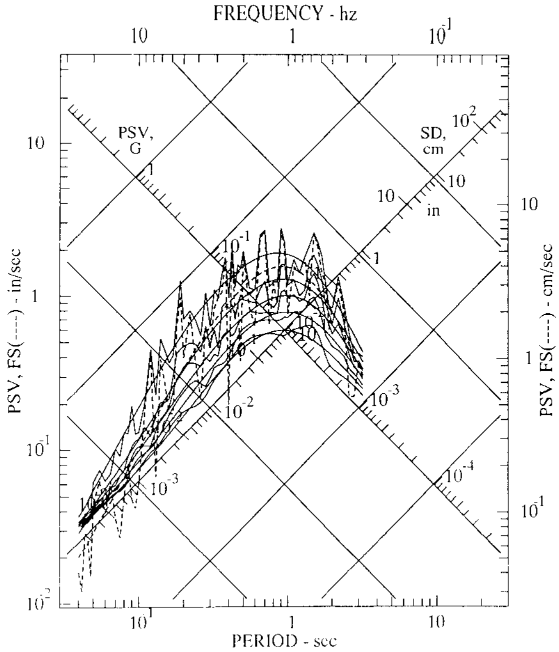

Fig. 1 – Fourier (dashed lines) and Response (for five damping values of 0.0, 0.02, 0.05, 0.10 and 0.20) spectral amplitudes for a typical recording in Yugoslavia, computed and smoothed spectral amplitudes are shown.

In Eq. (13), $\log_{10}\widehat{FS}(T)$ represents the logarithm of spectral amplitudes at the corresponding recording site «modified» to have the site condition $s = 0$ and to represent a horizontal component $v = 0$. Consider then the equation

$$\log_{10}\widehat{FS}(T) = M + \mathcal{A}_0(T)\log_{10}\Delta + c_1(T)M + + c_2(T) + c_3(T)M^2 \tag{14}$$

fitting the logarithm of the modified spectral amplitudes with respect to magnitude M and the attenuation function $\mathcal{A}_0(T)$ log Δ. The scaling functions $\mathcal{A}_0(T)$, $c_1(T)$ $c_2(T)$ and $c_3(T)$ can be determined through the regression analysis of the database on $\log_{10}\widehat{FS}(T)$. The new form of the attenuation function $\mathcal{A}tt(\Delta, M, T) = \mathcal{A}_0(T)\log_{10}\Delta$ can then be substituted back into Eq. (12) and the iteration process repeated. The «convergence» of the attenuation function $\mathcal{A}_0(T)$ $\log_{10}\Delta$ was found to be very satisfactory after just a few iterations of the above procedure. The coefficient $\mathcal{A}_0(T)$ is close to that of the Western U.S. (Fig. 2). Figure 3 shows a plot of the corresponding Fourier amplitudes versus distances for the four typical period bands.

The above iterative procedure, starting with Eq. (12), can be initiated by taking the first representation for $\mathcal{A}tt(\Delta, M, T)$ in the form of 1) the Eq. (8) and treating $\mathcal{A}_0(T)$ as a coefficient in the direct regression fit at all 61 discrete periods, 2) $\log_{10}\mathcal{A}_0(R)$, the empirical attenuation law given by Richter (1958), and 3) $\mathcal{A}tt(\Delta, M, T)$ determined from strong motion data in the western United States (Trifunac and Lee 1985, 1990). We tried all these models and found that they converge after only several iteration steps. We selected the model

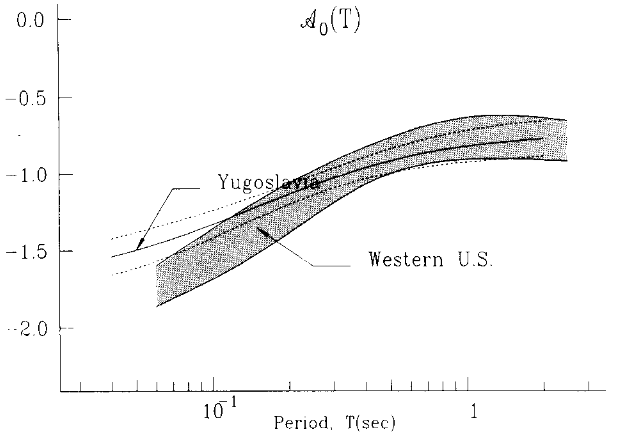

Fig. 2 – Comparison of $\mathcal{A}_0(T)$ versus T for Yugoslavia and western U.S. strong motion data.

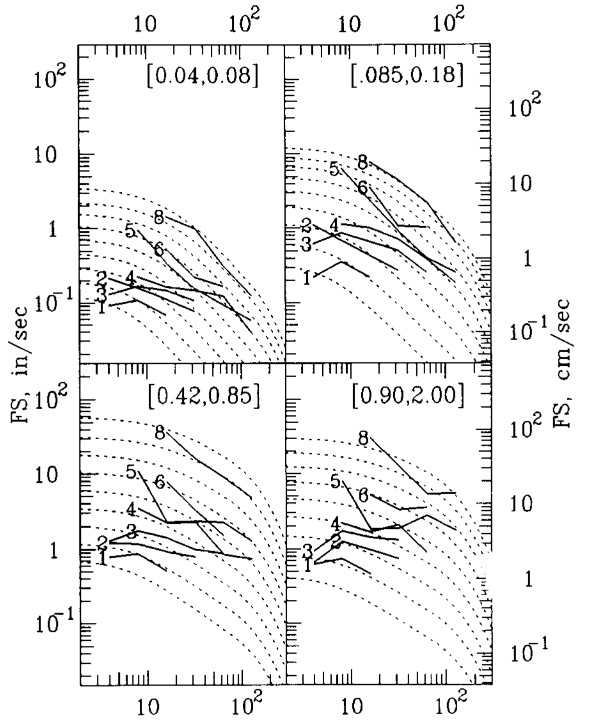

Fig. 3 – Comparison of the derived frequency dependent attenuation functions for four frequency bands ([0.04, 0.08], [0.085, 0.18], [0.42, 0.85] and [0.90, 2.00]), shown by dashed lines for magnitudes 3.5, 4., 4.5, 5, ... 7.5 bottom to top, with smoothed and averaged strong motion data in Yugoslavia.

which starts with $\mathcal{A}tt(\Delta, M, T)$ based on the western U.S. data, because the final result had the smallest overall residuals indicating good fit for the period range between .15 sec and 2 seconds.

Actual (average) versus estimated FS amplitudes

Figure 3 shows plots of the «modified average» Fourier amplitudes and of the estimated amplitudes versus hypocentral distance $\mathcal{D}$ (km), for magnitudes M = 3.5 to 7.5 in steps of 0.5, and for the 4 period bands. The solid lines represent the modified average FS amplitudes, while the dashed lines show the estimated FS amplitudes. The attenuation functions used are computed from «modified average» Fourier amplitudes, $MFS(T)$, modified from the actual database to have a site condition $s = 0$, a component parameter $v = 0$ (horizontal), to correspond to one of the closest magnitudes from the list: M = 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0 and 7.5, (the same nine magnitude levels are indicated in the plots for the estimated FS amplitudes by the dashed lines), and to have the closest hypocentral distances from among the list $\mathcal{D}$ = 1, 4, 8, 16, 32, 64 and 128 km, spaced evenly along the logarithmic scale, as can be seen from the plots.

The modified database consists of data from sites of the same site condition ($s = 0$), the same component orientation ($v = 0$), with one of the above discrete magnitudes, and it has hypocentral distances corresponding to one of the above discrete distances. For example, if the original Fourier Spectrum Amplitude, $FS(T)$, is available at an intermediate site ($s = 1$), from an earthquake of magnitude 6.3 and at hypocentral distance 42 km, the closest magnitude and hypocentral distances from among the list would respectively be 6.5 and 32 km. The modified Fourier amplitude, $MFS(T)$, is then calculated from

$$\log_{10} MFS(T) = \log_{10} FS(T) + \delta \log_{10} \widehat{FS}(T) \qquad (15)$$

where $\delta_{10}\widehat{FS}(T)$ is the estimated «correction» due to the modification from site $s = 1$ to site $s = 0$, from magnitude $M = 6.3$ to $M = 6.5$, from both horizontal ($v = 0$) and vertical ($v = 1$) component orientations to just $v = 0$, and from hypocentral distance $\mathcal{D}$ = 42 to $\mathcal{D}_1$ = 32 km. From Eq. (11), this «correction» is

$$\begin{aligned}\delta \log_{10} \widehat{FS}(T) &= 6.5 + \mathcal{A}_0(T)\log\Delta_1 + \\ &+ b_1(T)6.5 + b_5(T)6.5^2 - \\ &-(6.3 + \mathcal{A}_0(T)\log\Delta + b_1(T)6.3 + b_2^{(1)} + \\ &+ b_3(T)v + b_5(T)6.3^2)\end{aligned} \qquad (16)$$

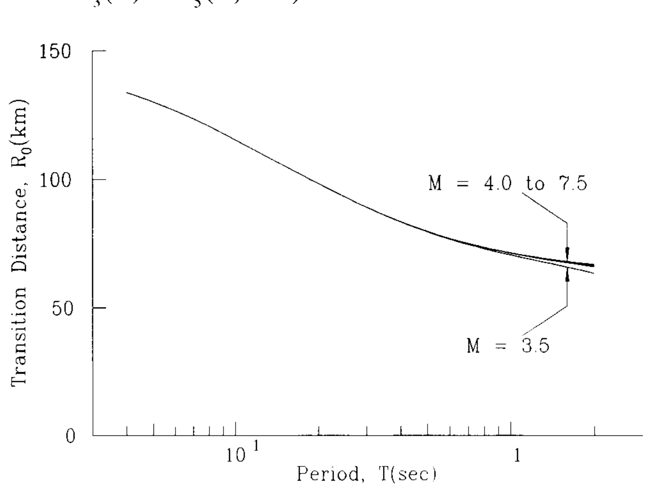

Fig. 4 – Dependence of the transition distances R_0 on T.

where Δ_1 is the distance (Eq. (3)) corresponding to $\mathcal{D}_1$ = 32 km and Δ is for distance $\mathcal{D}$ = 42 km. The terms in the bracket in Eq. (16) above correspond to the estimated Fourier amplitude for M = 6.3, $\mathcal{D}$ = 42 km and s = 0.

To study the trends of the attenuation function in the four period bands: [.04, .08], [.085, .18], [.42, .85] and [.9, 2.] (in seconds), it is convenient to modify the data in each period band to correspond to the central period of the group, respectively .05, .12, .55 and 1.4 sec. Thus, if the amplitude $MFS(T)$ is in the i^{th} group with central period T_i, it is modified to $MFS_i(T_i)$ corresponding to period T_i by

$$\log_{10}\widehat{MFS}_i(T_i) = \log_{10}\widehat{MFS}(T) + \delta\log_{10}\widehat{MFS}_i(T), \quad (17)$$

where $\delta\ \log_{10}\widehat{MFS}_i(T)$ is the estimated «correction» from period T to the central period T_i, given by

$$\delta\log_{10}\widehat{MFS}_i(T) = \log_{10}\widehat{MFS}(T_i) - \log_{10}\widehat{MFS}(T), \quad (18)$$

with $\log_{10}\widehat{MFS}(T_i)$ and $\log_{10}\widehat{MFS}_i(T)$ respectively, the estimated logarithms of Fourier amplitudes at periods T_i and T using Eq. (11) at the site with modified magnitude M, site condition s = 0 and component v = 0. The averages of all the resulting amplitudes in each of the five period bands are shown in Figure 3.

Figure 4 presents the variation of R_0 (transition distance in equation (10)), plotted versus period T.

Discussion and conclusions

Table I shows that the recorded strong motion data in Yugoslavia is relatively abundant between magnitudes 3 and 5, and for distances between 10 and 30 km. For $M > 5$ and for hypocentral distances $\mathcal{D} > 100$ km, the data is very sparse. One of the consequences of this is that the terms $b_1(T)$, $b_4(T)$ and $b_5(T)$ in Eq. (11) become sensitive to the magnitude range which is used in the regression analysis, and thus to the distribution of data with respect to magnitude. To investigate this sensitivity we repeated the entire regression analysis, but using only the data for $M \geq 3.5$, 4.0, 4.25 and 4.5, and found that the coefficients $\mathcal{A}_0(T)\, b_2^{(1)}(T), b_2^{(2)}(T)$ are all stable and change only very little from one regression to the next. In Fig. 2, we show $\mathcal{A}_0(T)$ for the Yugoslav data, for $M \geq 4.25$. With this and larger cut-off magnitudes, $b_1(T)$ fluctuates around zero, while $b_5(T)$ is small, but negative for all T considered. This leads to the saturation of strong motion amplitudes with progressively increasing magnitudes in the manner which is consistent with the observed trends in the western United States data, and in agreement with the physical consequences associated with scaling of near-field strong ground motion.

Larger $\mathcal{A}_0(T)$ for the Yugoslav data, relative to the short period amplitudes of $\mathcal{A}_0(T)$ for the western United States (for periods shorter than .1 to .3 sec) could be interpreted by slightly larger Q in Yugoslavia (at least for the areas where strong motion data has been recorded) than in the western United States. This is in agreement with the conclusion of the analysis and the comparison of M_L^{SM} in California and in Yugoslavia, which suggested the same trends (Lee et al., 1990).

The strong motion data in Yugoslavia is not adequate, by itself, to constrain the selection of the functional forms for the frequency dependent attenuation models. Therefore, this work should be interpreted to mean only that the assumed frequency dependent attenuation equation (Eq. (11)) is not contradicted by the data and that it can describe the trends in the data quite well. At least two or three fold increase in the number of recorded accelerograms in the strong motion data base, and better and more uniform coverage of the entire magnitude and hypocentral distance are required before one can hope to finalize the empirical description of this attenuation. Assuming the present rate of seismicity this may require at least additional 20 to 30 years to gather such data.

Nevertheless, the results of this work clearly show that there is difference in how high and low frequencies attenuate with distance and that this difference is significant. Thinking in terms of $\mathcal{A}_0(T)$ as representing exponent n in Δ^n, it is seen that n changes from about –.6 to –.8 for long periods ($T \sim 2$ sec), to –1.5 to –1.7 for the short periods (T =.04 to .05 sec). Clearly, fitting the attenuation of strong ground motion with fixed n (independent of period), cannot be justified.

Analyses of this type should be extended to other European countries, where sufficient number of strong motion data is available, and parallel studies on the regional variations of Q should be performed. Only after the physical causes of all differences between $\mathcal{A}_0(T)$ for different regions can be explained, it may become possible to relate the parameters of the frequency dependent attenuation of strong ground motion to the regional geologic and tectonic setting.

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