Paper No. 312. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

EMPIRICAL SCALING OF FOURIER AMPLITUDE SPECTRA IN RESPECT TO MAGNITUDE, DISTANCE, LOCAL SOIL AND SITE GEOLOGY IN FORMER YUGOSLAVIA

M. MANIĆ

Institute of Earthquake Engineering and Engineering Seismology, Section for
Risk and Disaster Management, University "St. Cyril and Methodius",
Skopje, Republic of Macedonia

ABSTRACT

There has been a great progress in the last twenty years in the study of strong earthquake ground motion and its engineering applications. New data and analyses have provided the basis for more reliable empirical estimates of strong ground motion parameters in future earthquakes. Also, recent trends in strong ground motion prediction are aimed at estimating the same probability level of exceedence of expected amplitudes of response and Fourier spectra across the whole range of frequencies of engineering interest, instead of only using peak ground amplitude values. In accordance with the mentioned, the purpose of this paper is to summarize the results on empirical scaling of Fourier amplitude spectra in respect to magnitude, distance, local soil and site geology for the territory of former Yugoslavia.

The procedure used for regression analysis of the spectral amplitudes in terms of magnitude (M), epicentral distance (D), local soil (S_s) and site geology (S_g) follows the commonly applied Ln-linearization of the exponential form of the ground motion model. The database containing 392 well-recorded horizontal components of 105 earthquakes with magnitudes between 3.0 and 7.0 utilized in the performed investigations were taken from the EQINFOS Strong Ground Motion Data Bank for former Yugoslavia.

The coefficient functions computed for the adopted regression models are all significant. It means that along with magnitude and attenuation with distance, both geological and soil conditions at the recording site play an important role in building up the amplitudes of strong ground motion.

KEYWORDS

predicted spectra, earthquake magnitude, epicentral distance, local soil, site geology, amplification factor.

INTRODUCTION

The primary purpose of this study is to examine a simple model for estimating Fourier amplitude spectra (FAS) of horizontal ground motion acceleration for known values of earthquake magnitude M, epicentral distance D, and local site conditions. For this reason, two ground motion models were developed and tested in this study: (1) Linear M model, and (2) Quadratic M model.

The data used in regression analysis have been recorded during 105 earthquakes with magnitudes between 3.0 and 7.0, mostly at shallow depths (< 25 km), and for small epicentral distances of less than 50 km. The majority of the records are from earthquakes with magnitudes of 3 to 6. (Manić, 1993). The geological and local site soil conditions have been specified for each recording site.

All the coefficient functions computed for the regression models are significant. The values of FAS calculated from strong ground motion records are log-normally distributed about the values estimated from the models. The accuracy of the models, as measured by the dispersion in observed values, is as good as the accuracy implied by the models investigated by McGuire (1978).

This preliminary study shows that along with the attenuation with distance, both the geological and local soil conditions at the site play a significant role in modifying the amplitude of strong ground motion. Stiff soils in respect to rocks amplify spectral amplitudes in the whole investigated period range, except for short periods up to 0.10 sec where the amplitude values are approximately the same. The amplification factor is the highest for periods ranging between 0.20 to 0.50 sec by value of about to 2.3. The spectral amplitude values for periods of less than 0.30 sec at sediments sites and intermediate sites are less than those recorded at basement sites. The deamplification factor amounts even to 2.5. For periods over 0.30 sec, the spectral amplitudes at the sediments and intermediate sites are larger than those at basement sites. The amplification factor is the highest for periods ranging between 0.5 to 1.2 sec and amounts to 2.5 for sediments sites.

DATA USED IN THE ANALYSIS

The data used in these investigations are taken from the EQUINFOS (Earthquake Data Information System) data bank on strong ground motion records from earthquakes that occurred on the territory of former Yugoslavia and neighbouring countries recorded by the Yugoslav network of SMA-1 instruments in the period 1975 - 1983 (Jordanovski et al., 1987). The data set selected for analysis contains 392 Fourier amplitude spectra (FAS) , defined from the horizontal components of 196 well recorded accelerograms during 105 earthquakes with magnitudes ranging between M = 3.0 - 7.0. The records are obtained at epicentral distances of D=0-340 km and the peak acceleration values range between 4.56 and 445.19cm/sec^2.

For the purpose of including the local effects upon the spectral amplitudes in the analysis, all the data have been classified in respect to the characteristics of the local geology and local soil conditions. The classification in respect to local geology has been performed in the same way as described by Trifunac and Brady (1975). So, all the data recorded at places of basement rock are coded by $S_g=0$, while those recorded on sediments are coded $S_g=2$. Those recorded on complex geological structure that cannot be identified as $S_g=0$ or 2 are indicated by $S_g=1$. A similar classification of data has been performed also in respect to the local soil characteristics (after the procedure of Seed et al. 1976). All the locations with soil thickness of d<10m over deposits with shear velocity of Vs≥800m/sec have been identified as 'rock' locations and coded by $S_s = 0$. Soils with a thickness of d = 15m to 75m, on deposits with Vs≥800m/sec have been identified as 'stiff soil' locations and indicated by $S_s=1$, whereas those of d>100m have been identified as 'deep soil' locations and indicated by $S_s = 2$. The selected data set does not contain records that could be coded by $S_s=2$.

The same classification of data has also been used in the studies for correlation of the values of Mercalli-Cancani-Sieber (MCS) intensity scale with the recorded peaks of strong ground motion in Yugoslavia (Trifunac et al., 1991), and empirical scaling of response spectra for the same region (Lee and Manić, 1994)

MODELS FOR ESTIMATION OF FOURIER AMPLITUDE SPECTRA

The earthquake ground motion recorded at a certain location could be considered as a combination of three dominant effects: radiation from the source RS ($T=2\pi/\omega$), attenuation along the transmission path TS ($T=2\pi/\omega$)

and local amplification at the recording site AS ($T=2\pi/\omega$). Therefore, the parameters characterizing ground motion GM ($T=2\pi/\omega$) could be generally expressed as follows:

$$GM(T) = RS(T)*TS(T)*AS(T) \tag{1}$$

For mathematical modeling of the above relation, one usually starts with the expression for determination of the amplitude of a harmonic wave in an infinitely elastic half-space.

$$A = A_0 * e^{(aM+cR)} * R^b \tag{2}$$

where A is the amplitude of motion observed at distance R, M is the earthquake magnitude, A_0 is the amplitude of motion corresponding to the distance of 1km from the source, whereas a, b and c are constants that have to be defined in the analyses. The logarithm of the above expression results in:

$$\ln A = \ln A_0 + aM + b\ln R + cR \tag{3}$$

where the expression blnR represents attenuation from the geometric propagation of the wave front, whereas cR indicates material friction, i.e., inelastic attenuation.

The above equation in the given form (Dahle et al., 1990); modified form, by adding of a term for the local soil (Benito et al., 1992), or elimination of the term for the inelastic attenuation and addition of a term for local soil and/or local geology (McGuire, 1978; Herraiz and Benito, 1992; Manić, 1993), has been used for derivation of empirical attenuation models for different parameters that characterize strong ground motion in function of period or frequency.

In these investigations for analysis of the dependence of the Fourier amplitude spectra FAS(T) on the parameters characterizing the earthquake intensity, the transmission mechanism and the local amplification, adopted are two modified forms of equation (3) that are used to express the linear and quadratic dependence of spectral amplitudes upon magnitude.

$$\begin{aligned} \ln[FAS(T)] = {} & b_1(T) + b_2(T)M + b_3(T)\ln(D + D_0) + \\ & + b_4^{(1)}(T)S_S^{(1)} + b_4^{(2)}(T)S_S^{(2)} + b_5^{(1)}(T)S_G^{(1)} + b_5^{(2)}(T)S_G^{(2)} \end{aligned} \tag{4}$$

$$\begin{aligned} \ln[FAS(T)] = {} & b_1(T) + b_2(T)M + b_3(T)\ln(D + D_0) + \\ & + b_4^{(1)}(T)S_S^{(1)} + b_4^{(2)}(T)S_S^{(2)} + b_5^{(1)}(T)S_G^{(1)} + b_5^{(2)}(T)S_G^{(2)} + b_6(T)M^2 \end{aligned} \tag{5}$$

In the above equations, FAS(T) is the spectral amplitude (cm/sec) of horizontal ground acceleration for period T, M is magnitude, D is epicentral distance in km, whereas D_o is constant by which the attenuation is modulated at distances close to the fault where low geometrical attenuation is expected (Campbell, 1981). $S_S^{(1)}$ and $S_S^{(2)}$ are variables indicating the local soil effect S_s, defined as:

$$\begin{gathered} S_S^{(1)} = \begin{cases} 1 & \text{if } S_S = 1 \text{ (stiff soil)} \\ 0 & \text{otherwise} \end{cases} \\ S_S^{(2)} = \begin{cases} 1 & \text{if } S_S = 2 \text{ (deep soil)} \\ 0 & \text{otherwise} \end{cases} \end{gathered} \tag{6}$$

while $S_G^{(1)}$ and $S_G^{(2)}$ are variables indicating the effect of local geology S_g, defined as:

$$\begin{gathered} S_G^{(1)} = \begin{cases} 1 & \text{if } S_g = 1 \text{ (intermediate site)} \\ 0 & \text{otherwise} \end{cases} \\ S_G^{(2)} = \begin{cases} 1 & \text{if } S_g = 2 \text{ (sediments site)} \\ 0 & \text{otherwise} \end{cases} \end{gathered} \tag{7}$$

The frequency-dependent coefficients $b_1(T)$ to $b_5(T)$ in the Linear M model in equation (4), i.e., $b_1(T)$ to $b_6(T)$ in the Quadratic M model in equation (5) are unknown quantities that are defined by the multilinear regression analysis of spectral amplitudes.

RESULTS FROM REGRESSION ANALYSIS OF DATA WITH ADOPTED MODELS

The final results from the regression analysis of spectral amplitudes with the adopted models, given in equations (4) and (5) the frequency-dependent coefficients $b_i(T)$ and hence the empirical equations for scaling of FAS(T) are directly dependent on the input data set. Therefore, for the purpose of investigating into the nature and the extent of the effect of the input data on the results and particularly their dependence on the magnitude range M to which the data belong, they have been analyzed using three different data sets for each of the adopted models. The first data set contains 392 FAS obtained from magnitudes in the range of M=3.0-7.0. The second data set contains 270 FAS from M=4.0-7.0, and it is obtained from the first data set with excluding the data recorded from magnitudes M<4.0. The third data set contains 144 FAS from M=5.0-7.0 and is obtained from the previous data set by eliminating the data obtained from magnitudes M<5.0.

The values of the coefficients $b_i(T)$ defined by regression analyses of the three data sets by using the Linear M model and the Quadratic M model are shown in Fig. 1 and 2. These Figs show that irrespective of the model used, the values of coefficients $b_i(T)$ defined from different data sets are considerably different among themselves. These differences are particularly emphasized in the values of $b_i(T)$ defined from the first set and $b_i(T)$ defined from the second and the third set of data.

All the coefficients are variable in respect to period. The trends of coefficients $b_3(T)$, $b_4^{(1)}(T)$, $b_5^{(1)}(T)$ and $b_5^{(2)}(T)$ defined with the Linear M model and the Quadratic M model are almost identical. However the differences among the values obtained from different data sets for the same period are smaller in the Quadratic M model. Figures 1 and 2 show that the values and the trends of coefficients $b_1(T)$ and $b_2(T)$ defined by the first and the second model are quite different and incomparable between themselves.

Figures 3 and 4 illustrate the effects of different input data sets, the influence of the local conditions, and the epicentral distance on the values and the shape of FAS defined by the Linear M model. Similar results have been obtained by using the Quadratic M model.

To define which of the models fits better to the data, performed is a statistical analysis of residuals $\varepsilon(T)$, defined as

$$\varepsilon(T) = \ln FAS(T) - \ln \widehat{FAS}(T) \tag{8}$$

where lnFAS(T) is the observed spectral amplitude, whereas $\ln \widehat{FAS}(T)$ is spectral amplitude defined by using the regression equation of one or the other model. Besides, the residual distribution has been analyzed in order to verify the hypothesis of the method: median zero and constant sigma. The obtained values of standard deviation $\sigma_{\ln FAS(T)}$ of the residuals for both models and the three analyzed data sets are insignificantly different. This is illustrated in Fig. 5 and 6 showing the observed and the evaluated spectra (median and 80 per cent confidence interval) from an earthquake with M=6.1, for both locations which are approximately at the same epicentral distance, but with different soil and geological conditions.

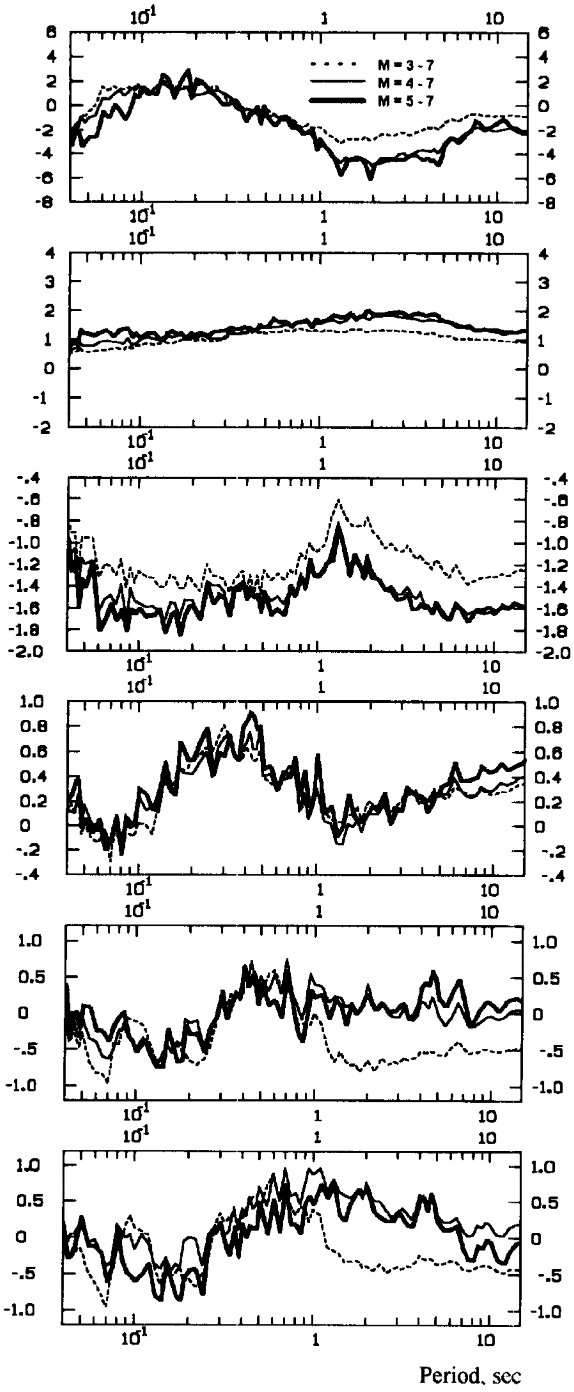

Fig. 1. Coefficient function $b_1(T)$ through $b_5(T)$ for Linear M model

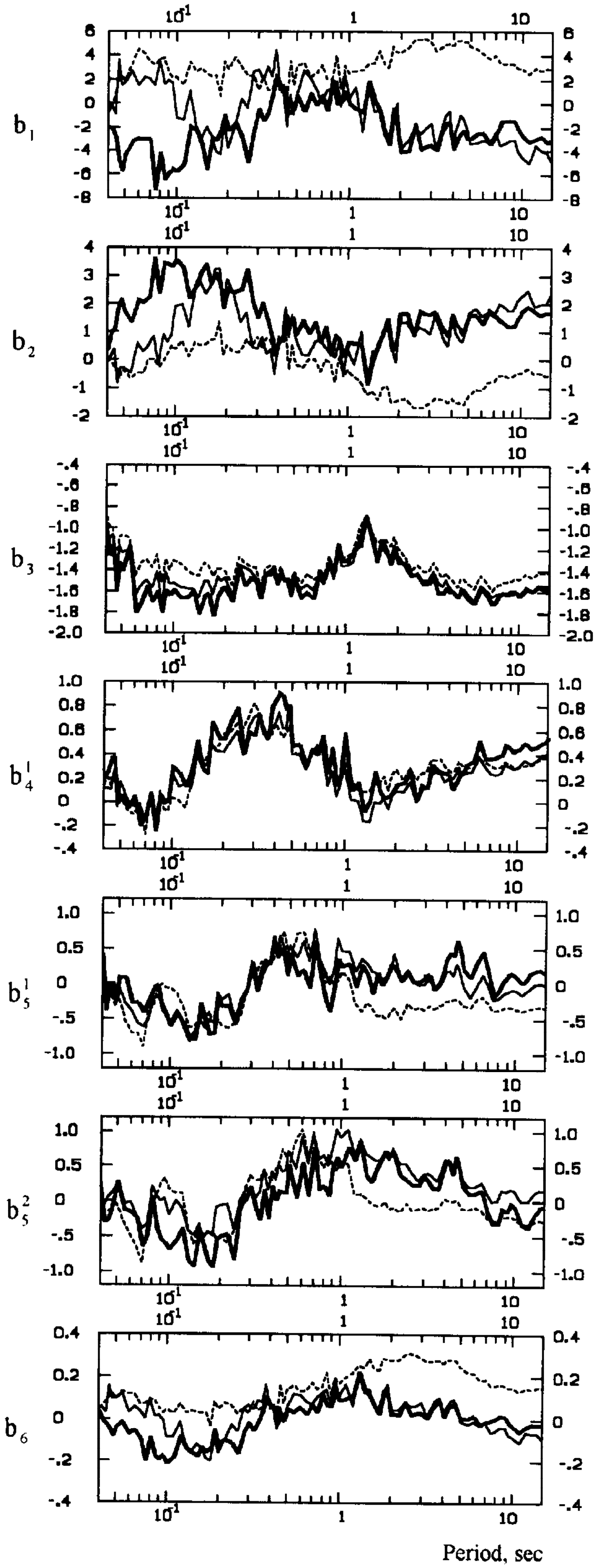

Fig. 2. Coefficient function $b_1(T)$ through $b_6(T)$ for Quadratic M model

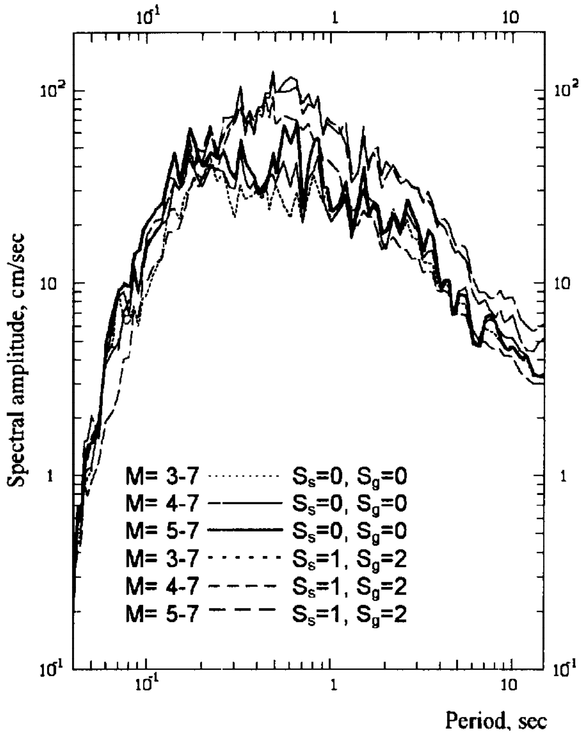

Fig. 3. Comparison of estimated FAS(T) from different data sets for D=10km, M=6.5, at a sites with S_s=0 (rock), S_g=0 (basement rock), and S_s=1 (stiff soil), S_g=2 (sediments).

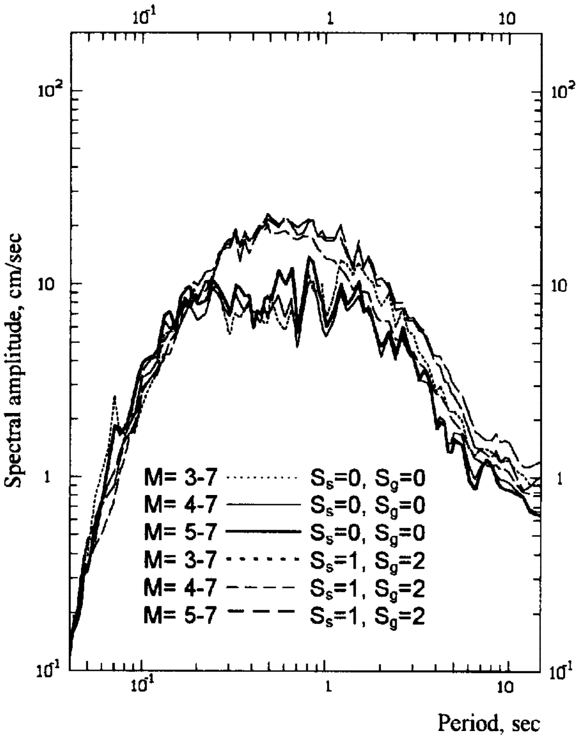

Fig. 4. Comparison of estimated FAS(T) from different data sets for D=50km, M=6.5, at a sites with S_s=0 (rock), S_g=0 (basement rock), and S_s=1 (stiff soil), S_g=2 (sediments).

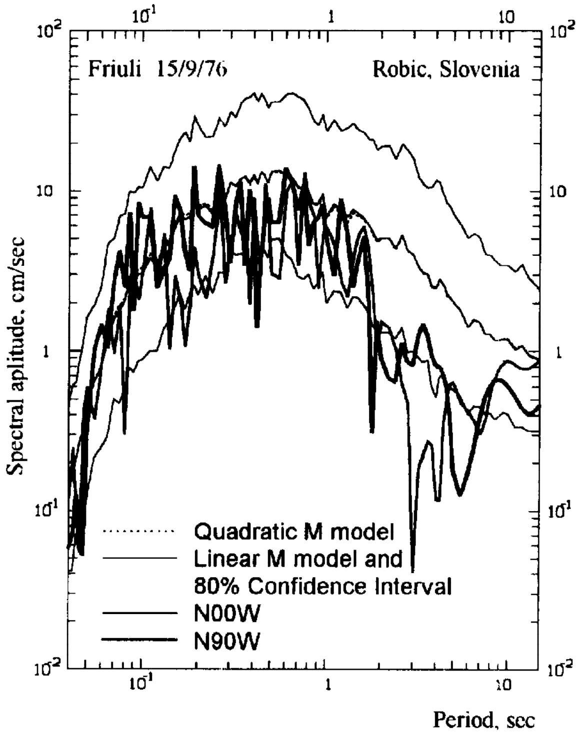

Fig. 5. Observed FAS(T) of horizontal ground acceleration at Robic in 1976, compared to median and 80 per cent confidence interval spectra for M=6.1, D=25.5km, S_s=0 and S_g=1.

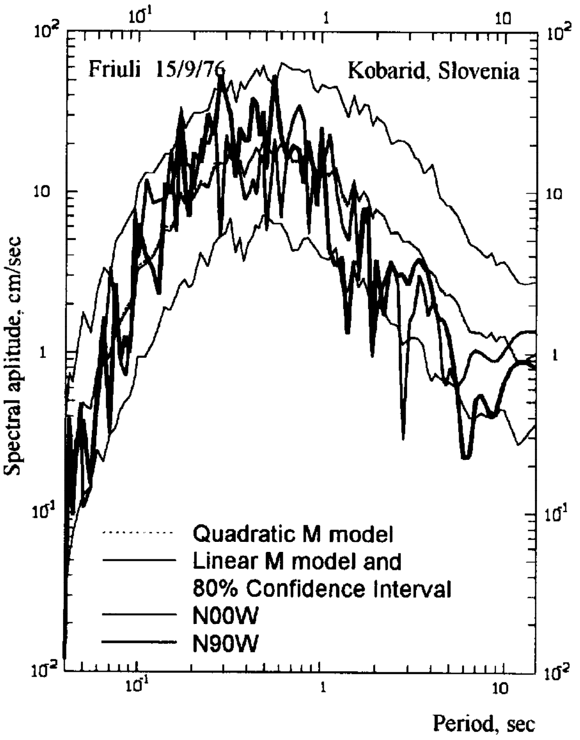

Fig. 6. Observed FAS(T) of horizontal ground acceleration at Kobarid in 1976, compared to median and 80 per cent confidence interval spectra for M=6.1, D=30.6km, S_s=1 and S_g=2.

CONCLUSIONS

Both analyzed models Linear M model and Quadratic M model fit equally well to the data. Both models show that the final results, the values of the spectral amplitudes in the expected spectra, are very much dependent on the input data set. The FAS values defined on the basis of data from M=3.0-7.0 are lower in respect to those obtained from data on M=4.0-7.0 even for a factor greater than 2 for a great number of investigated periods. Somewhat less expressive are the differences among the values obtained from M=4.0-7.0 and M=5.0-7.0. These relations hold for an epicentral distance of D=10km. With the increase in epicentral distance, the differences are decreased so that at distance of D=50km they are between 10 to 30 per cent. However, since we are interested in the strong ground motion close to the causative fault, the importance of the magnitude of data to be used for spectra evaluation, particularly from earthquakes of stronger magnitudes, becomes evident.

The obtained values of coefficient $b_4^{(1)}(T)$ point that for periods of up to 0.10 sec, the spectral amplitudes at stiff soil and rock are approximately the same, or somewhat higher for rock. For the remaining period range, the spectral amplitudes at stiff soil are larger than those at rock. The maximal value of the amplification factor ranges from 2.0 to 2.5 for periods ranging between 0.20 and 0.50 sec.

Both coefficients of the effect of local geology $b_5^{(1)}(T)$ (intermediate sites) and $b_5^{(2)}(T)$ (sediments sites) show that the spectral amplitudes observed at such sites are considerably lower than those at basement rock sites for periods less than 0.30sec. The deamplification factor amounts even up to 2.5. For periods of 0.30 to 0.75sec, the spectral amplitudes at intermediate and sediments sites are larger than those at basement sites. For periods of up to 7.0sec the sediments sites generally prove to have amplification properties for M=4.0-7.0 and M=5.0-7.0, and low deamplification properties for M=3.0-7.0. For the same period range, the intermediate sites generally show deamplification properties for M=3.0-7.0 and low amplification properties for M=4.0-7.0 and M=5.0-7.0.

This preliminary study points to the fact that evaluation of spectral amplitudes from expected magnitudes at a certain location should be done in future on the basis of a sufficient number of data per classes of magnitudes centered about the magnitude values for which the spectra are estimated.

REFERENCES

Benito, B., D. Rinaldis, V. Gorreli and A. Paciello (1992). Influence of the magnitude, distance and natural period of soil in the strong ground motion. *Proc. Tenth World Conf. Earthquake Eng.*, 773-779.

Campbell, K.W. (1981). Near-source attenuation of peak horizontal acceleration. *Bull. Seism. Soc. Am.*, **71**, 2039-2070.

Dahle, A., H. Bungum and L.B. Kvamme (1990). Attenuation models inferred from interplate earthquake recordings. *Earthquake Eng. Struct. Dym.*, **19**, 1125-1141.

Herraiz, M. and B. Benito (1992). Analysis of frequency dependence of some strong motion parameters for different soil conditions. *Proc. Tenth World Conf. Earthquake Eng.*, 1049-1055.

Jordanovski, Lj.R., V.W. Lee, M.I. Manić, T. Olumceva, C. Sinadinovski, M.I. Todorovska and M.D. Trifunac (1987). Strong earthquake ground motion data in EQUINFOS: Yugoslavia, Part I. Rep. No. **87-05,** *Dept. Civil Eng., Univ. Southern California.*

Lee, V.W. and M. Manić (1994). Empirical scaling of response spectra in former Yugoslavia. *Proc. Tenth Europe. Conf. Earthquake Eng.*, 2567-2572.

Manić, M. I. (1993). Influence of the local soil and geological site conditions on the spectral amplitude of recorded strong ground accelerations (in Macedonian). Macroproject Seismology, Report IZIIS **93-08**, *Inst. Earthquake Eng. and Eng. Seism., Skopje.*

McGuire, R.K. (1978). A simple model for estimating Fourier amplitude spectra of horizontal ground accelerations. *Bull. Seism. Soc. Am.*, **68**, 803-822.

Seed, B.H., C. Ugas and J. Lysmer (1976). Site-depended spectra for earthquake-resistant design. *Bull. Seism. Soc. Am.*, **66**, 221-243.

Trifunac, M.D. and A.G. Brady (1975). On the correlation of seismic intensity scales with the peaks of recorded strong ground motion. *Bull. Seism. Soc. Am.*, **65**, 139-162.

Trifunac, M.D., V.W. Lee, M. Zivcic and M. Manić (1991). On the correlation of Mercalli-Cancani-Sieberg intensity scale in Yugoslavia with the peaks of recorded strong earthquake ground motion. *Europe. Earthquake Eng.*, **V(1)**, 27-33.