13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2682

SCALING LAWS FOR FOURIER ACCELERATION SPECTRA IN FORMER YUGOSLAVIA

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SUMMARY

In this paper, empircal scaling of the Fourier spectral amplitudes of strong earthquake ground acceleration in former Yugoslavia is presented. The dependence of the individual spectral amplitudes of the Fourier acceleration spectrum on the magnitude, distance, local soil and geological conditions has been investigated through four different mathematical models. All models have been applied on seven different sets of data that differ between themeselves in respect to the values of one or both parameters of magnitude M and distance R.

The results obtained show that estimation of spectral amplitudes by using the applied approach of interval parametric analysis in respect to M and R parameters yields much better results than those that are obtained when estimation of spectra is made based on all data available in the M – R space. Also, results show that both the site geology and local soil conditions play a significant role in modifying the amplitudes of strong ground motion.

INTRODUCTION

For engineering purposes, the estimation of strong ground motion parameters during future earthquakes is one of the main reasons for recording, processing and analyzing data on strong ground motion recordings. A number of different parameters characteristic for the strong ground motion can be used for the needs of seismic design. The frequently used parameters in engineering practice are the peak acceleration, the peak velocity, the peak displacement, the response spectra and the Fourier spectra of acceleration, velocity and displacement. In these investigations, the Fourier acceleration spectrum has been used since it enables easy derivation of the other mentioned parameters through its multiplication by corresponding response factors of the instruments as to those parameters that are of interest for us.

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The magnitude, the distance and the local site characteristics are the principle variables that are used in estimation of future strong ground motion for engineering purposes. So, in these investigations, the dependence of the spectral amplitudes of Fourier acceleration spectrum on the magnitude, hypocentral distance, local soil and geological site conditions has been investigated by four different mathematical models. The first model (Model-1) has been used to explore the dependence of the spectral amplitudes on the magnitude and distance only. By successive introducing into Model-1 the parameters involving the effects from the local soil (Model-2) and local geology (Model-3) and the square of the magnitude (Model-4), the dependence of the spectral amplitudes on these parameters has also been explored. All the four models have been applied on seven different data sets that differ between themselves in respect to the values of one or both parameters of magnitude M and distance R.

The results obtained from regression analysis of the different data sets with Model-1 to Model-4 show that estimation of spectral amplitudes by using the approach of interval parametric analysis in respect to the M and R parameters yields much better results then those that are obtained when estimation of the spectra is made based on all data available in the M - R space.

The comparison of the spectra, estimated by application of each of the seven regression equations, derived based on the seven different data sets by Model-1 and the theoretical spectra evaluated with the ω-squared model by Boore [1] and the specific barrier model by Papageorgiou [2] does support our assertion that: a) the estimation of the spectrum for a specified value of magnitude will be much better if it is done based on a sufficient number of data obtained in a magnitude interval close to the specified value of magnitude than in the case when it is done based on all the data obtained within a wide magnitude interval and b) the near- and far-spectra are better estimated if the data on close earthquakes and those on distant earthquakes are considered separately.

Considerable is the effect of local soil upon the spectral amplitudes (Model-2). It shows a negligible dependence on the variation of the M parameter when the data on the close and distant earthquakes are jointly analyzed (I, II and III data set) and considerable dependence on the variation of both M and R parameters when the data on the close (VI, V and VI data set) and distant (VII data set) earthquakes are analyzed separately.

The effect of local geology upon the spectral amplitudes (Model-3) is also considerable. It points to a considerable dependence on the variation of parameter M when the data on the close and distant earthquakes (I, II and III data set) are jointly analyzed and even more significant dependence on the variation of both M and R parameters when the data on the close (IV, V and VI data set) and distant (VII data set) earthquakes are analyzed separately.

Important is also the effect of the parameter depending on the square of the magnitude over the spectral amplitude (Model-4). The comparison between the spectra estimated by Model-4 and those estimated by Model-3 shows that the effect of M^2 parameter is reflected by increase of the spectral values in spectra of greater magnitudes (M = 7 and 8) and decrease of the spectral value of lower magnitudes (M = 4, 5 and 6). However, with the exclusion of data on M < 4, there is a considerable drop in the effect of the square of magnitude upon the spectral amplitudes.

The comparison of the spectra estimated by Model-1 through Model-4, derived based on the data recorded in the territory of former Yugoslavia, and the spectra estimated with the models developed by McGuire [3], Trifunac and Lee [4] and Trifunac [5], on the basis of data recorded in California, shows that for these two regions: 1. The attenuation of spectral amplitudes with distance is different for all the analyzed periods; 2. The extent of increase of all the spectral amplitudes with the increase in magnitude is different; 3. In the spectra estimated based on data obtained in former Yugoslavia, the maximum amplification between stiff soil and rock locations amounting to a value of about 2.5 is obtained for periods around T = 0.2 – 0.5 s, whereas in the spectra obtained by the McGuire [3] and Trifunac [4,5] models, the values of the spectral amplitudes at stiff soil and rock locations differ negligibly in the same period range; 4. The inclusions of the effects of site geology moreover increases the differences in amplification value for these two regions in all investigated period range.

THE STRONG MOTION DATA IN FORMER YUGOSLAVIA

The strong-motion accelerograph network was first installed throughout former Yugoslavia in the early 1970's as a result of the cooperative US-Yugoslav project. Since then, this strong-motion network has recorded hundreds of excellent strong-motion data. In 1983, a cooperative project was 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 process all strong-motion data recorded in free field during the period 1975 – 1983. The work on digitization and processing of 449 records was completed in 1987 by Jordanovski [6]. The resulting data consist of corrected acceleration time histories (Volume II) and response and Fourier spectra (Volume III) from more then 200 earthquakes. 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.

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. Classification of data in respect to site geology has been done in accordance with the classification given by Trifunac [7]. According to this classification, the recording stations are divided into three categories: $s_G = 0$ for basement rock, $s_G = 2$ for sediments and $s_G = 1$ for intermediate sites. The soil classification has been characterized by a soil parameter, s_L, which was assigned values 1 for deep soil sites, 2 for stiff soil and 3 for rock sites, as suggested by Seed [8]. Subsequently, this characterization was changed to 0 for rock sites, 1 for stiff soil sites and 2 for deep soil sites for convenience in regresion analysis. This database has been used recently to study the attenuation relationships for peak ground acceleration, velocity and displacement, as well as attenuation of spectral amplitude of the response spectra in former Yugoslavia by Manic [9,10,11].

THE MODELS AND THE REGRESSION PROCEDURE

We considered four regression models of Fourier spectral amplitudes in terms of earthquake magnitude, source-to-site distance, site geology and local soil conditions. The first model (Model-1) has been used to explore the dependence of the spectral amplitudes on the earthquake magnitude and hypocentral distance only. By successive introducing into Model-1 the parameters involving the effects from the local soil (Model-2) and local geology (Model-3) and the square of the magnitude (Model-4), the dependence of the spectral amplitudes on these parameters has also been explored. The equations used for the four models are as follows:

Model-1

$$\ln[FAS(T)] = b_0(T) + b_1(T)M + b_2(T)\ln R \tag{1}$$

Model-2

$$\ln[FAS(T)] = b_0(T) + b_1(T)M + b_2(T)\ln R + b_3^{(1)}(T)S_L^{(1)} + b_3^{(2)}(T)S_L^{(2)} \tag{2}$$

Model-3

$$\begin{aligned} \ln[FAS(T)] = {} & b_0(T) + b_1(T)M + b_2(T)\ln R + b_3^{(1)}(T)S_L^{(1)} + b_3^{(2)}(T)S_L^{(2)} \\ & + b_4^{(1)}(T)S_G^{(1)} + b_4^{(2)}(T)S_G^{(2)} \end{aligned} \tag{3}$$

Model-4

$$\begin{aligned} \ln[FAS(T)] = {} & b_0(T) + b_1(T)M + b_2(T)\ln R + b_3^{(1)}(T)S_L^{(1)} + b_3^{(2)}(T)S_L^{(2)} \\ & + b_4^{(1)}(T)S_G^{(1)} + b_4^{(2)}(T)S_G^{(2)} + b_5(T)M^2 \end{aligned} \tag{4}$$

In equations (1) to (4), FAS(T) is Fourier spectral amplitude for period T, M is magnitude, R is hypocentral distance, $S_L^{(1)}$ and $S_L^{(2)}$ are indicator variables for the soil condition s_L, defined as

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

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

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

$$S_G^{(1)} = \begin{cases} 1 \text{ if } s_G = 1 (\text{intermediate site}) \\ 0 \text{ otherwise} \end{cases}$$

$$S_G^{(2)} = \begin{cases} 1 \text{ if } s_G = 2 (\text{sediment site}) \\ 0 \text{ otherwise} \end{cases}$$

used to characterize the geological conditions at the site. The scaling functions $b_1(T)$ to $b_5(T)$ are constants at each period determined by the regression analysis.

All the four models have been applied on seven different data sets that differ in respect to the values of one or both parameters of magnitude M and hypocentral distance R. Thus, the first data set contains all the data available for regression analysis, i.e. 406 horizontal Fourier spectra which are obtained from earthquakes with M = 3.0 – 7.0 and at epicentral distances D = 0 – 340 km. The second data set (M = 4.0 – 7.0 and D = 0 – 340 km) contains 284 data, and it is obtained when data with M < 4.0 are excluded from the first data set. The third data set (M = 5.0 – 7.0 and D = 0 – 340 km) contains 158 data, and it is obtained when data with M < 5.0 are excluded from the second data set. Based on such defined data sets, with different lower limit of magnitude value (M = 3, 4 and 5) and constant upper limit of magnitude value (M = 7), the influence of different M on the values of regression coefficients has been explored. The fourth (M = 3.0 – 7.0, N = 330), the fifth (M = 4.0 – 7.0, N = 208) and the sixth (M = 5.0 – 7.0, N = 84) data set consists only near-field data, i.e. they are obtained when data recorded at epicentral distances D > 50 km are excluded from I, II and III data sets. Finally, the seventh data set (M = 5.0 – 7.0, N = 76) consists only of far-field data, i.e. data recorded at epicentral distance D > 50 km. Based on VI, V, VI and VII data set, the influence of different distance intervals (D ≤ 50 km and D > 50 km) to the values of regression coefficients has been explored.

THE RESULTS FROM REGRESSION ANALYSIS WITH MODEL-1 TO MODEL-4

The results obtained from the regression analysis of the different data sets with Model-1 to Model-4 show that estimation of spectral amplitudes by using the approach of interval parametric analysis in respect to M and R parameters yields much better results then those that are obtained when estimation of the spectra is made based on all data available in the M - R space (Fig. 1 and 2).

Our analysis shows that the amplitudes and the shapes of average Fourier amplitude spectra are different in former Yugoslavia from those recorded in the western U.S. At all frequencies (Fig. 3), the rate of growth of spectral amplitudes with magnitude is different for these two regions. Also, in the high frequency range, the spectral amplitudes in western U.S. decay faster with frequency than in Yugoslavia. This may be explained by the different value of the quality factor Q in former Yugoslavia and western U.S. This plausible, but not unique interpretation, is in good agreement with several other studies which all point in the same direction, Manic [9,10,11], Trifunac [12] and Lee [13].

If differences in the spectral shapes and amplitudes for former Yugoslavia and western U.S. can be supported further by other independent data in the Balkan, the consequences will be important for site specific analysis 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 based on strong motion data in western U.S., and as this investigation suggested, this may not be feasible due to the regional differences in Q, overall wave amplitude attenuation and magnitude scaling differences.

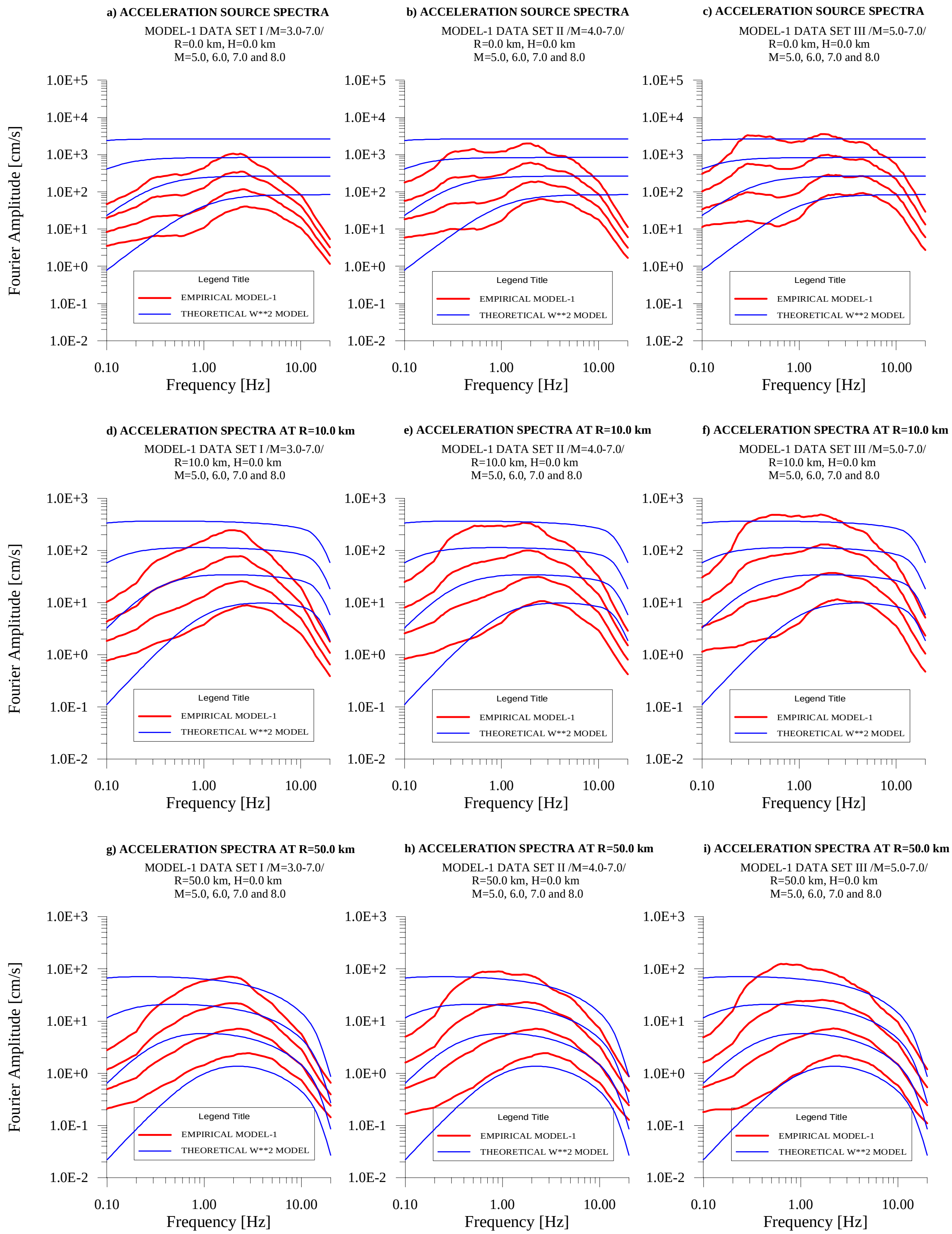

Figure 1. Comparison of empirical Fourier acceleration spectra estimated based on I, II and III data set with Model-1 and theoretical Fourier acceleration spectra estimated with ω^2-model by Boore [1], for M = 5, 6, 7 and 8, R = 0.0, 10.0 and 50.0 km and H =0.0 km.

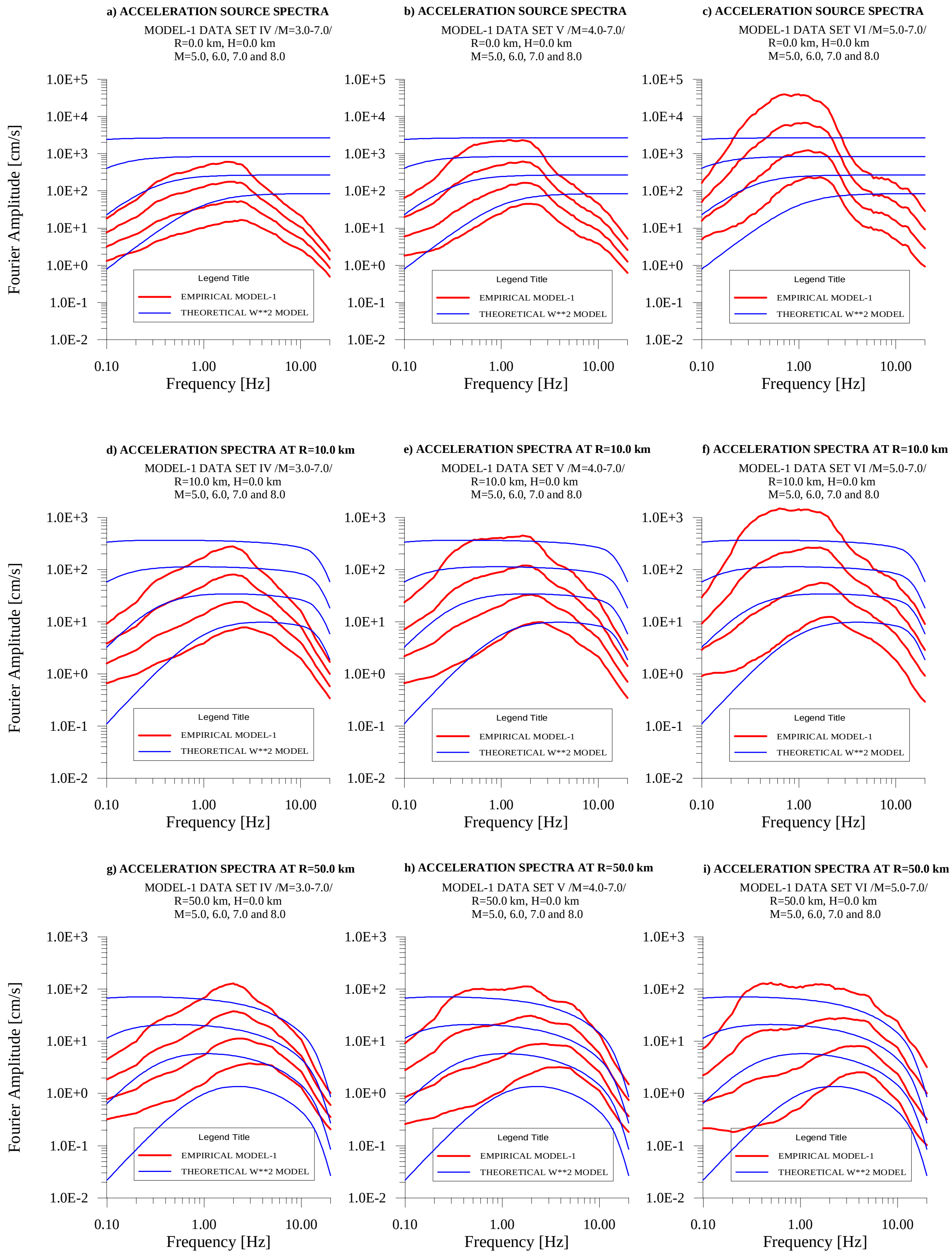

Figure 2. Comparison of empirical Fourier acceleration spectra estimated based on IV, V and VI data set with Model-1 and theoretical Fourier acceleration spectra estimated with ω^2-model by Boore [1], for M = 5, 6, 7 and 8, R = 0.0, 10.0 and 50.0 km and H =0.0 km.

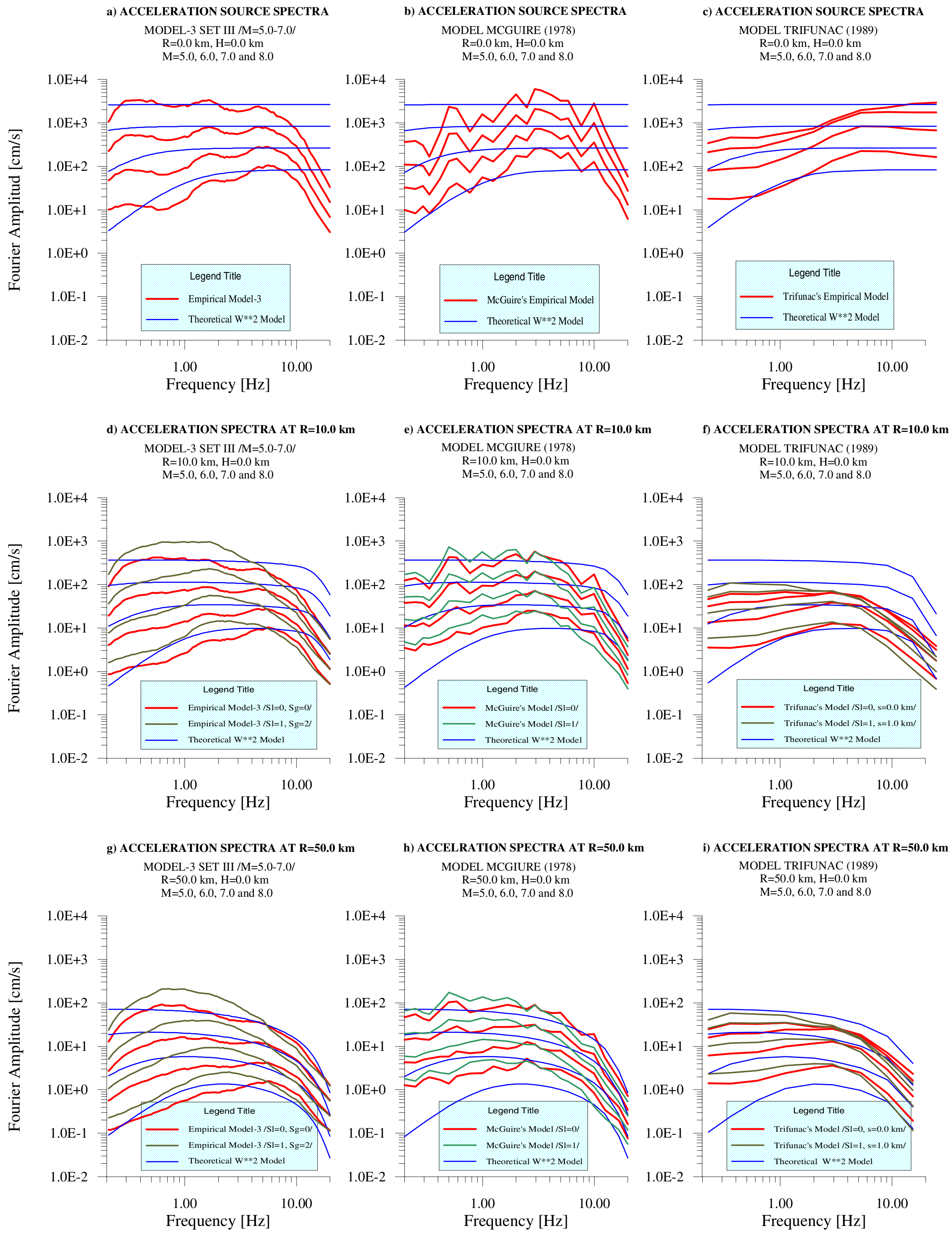

Figure 3. Comparison of empirical Fourier acceleration spectra estimated with Model-3 (Fig. 3a,d,g), McGuire's model (Fig. 3b,e,h) and Trifunac's model (Fig. 3c,f,i) for M = 5, 6, 7 and 8, R = 0.0, 10.0 and 50.00 km and H = 0.0 km. Also the theoretical spectra of an ω^2-model proposed by Boore [1] are shown for comparison.

The strong motion database used in this study comes mainly from five regions in former Yugoslavia, which were seismically active between 1975 and 1983, when this data was recorded. These regions are «Friuli», «Banja Luka», «Macedonia», «Montenegro» and «Kopaonok». 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 five regions is to small to investigate these differences in detail.

CONCLUSION

In the foregoing, we presented the models described by Equation (1) to (4) that can be supported by the strong motion data in former Yugoslavia. We found that the all models lead to scaling coefficient functions, which are significantly different from zero. However, based on the results from testing the significance of Model-1 to Model-4, we have concluded that the best estimation of the spectra is obtained with Model-3, in which spectral amplitudes depend on M, R, S_L and S_G.

This study shows that due to the regional difference between the western U.S. and former Yugoslavia, it is not feasible to use directly the empirical scaling models developed for California for estimating of spectrum amplitudes in southeastern Europe. It might become possible to do so only when all the observed differences have been explained in terms of measured regional parameters, and when the functional form of these differences is fully explained and calibrated.

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