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Spectral parameters of ground motion in different regions: comparison of empirical models

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Abstract

Fourier-amplitude spectrum is one of the most important parameters describing earthquake ground motion, and it is widely used for strong ground motion prediction and seismic hazard estimation. The relationships between Fourier-acceleration spectra, earthquake magnitude and distance were analysed for different seismic regions (the Caucasus and Taiwan island) on the basis of ground motion recordings of small to moderate ($3.5 \leq M_L \leq 6.5$) earthquakes. It has been found that the acceleration spectra of the most significant part of the records, starting from S-wave arrival, can be modelled accurately by the Brune's "ω-squared" point-source model. Parameters of the model are found to be region-dependent. Peak ground accelerations and response spectra for condition of rock sites were calculated using stochastic simulation technique and obtained models of source spectra. The modelled ground-motion parameters are compared with those predicted by recent empirical attenuation relationship for California. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Acceleration spectra; Scaling law; Attenuation relation; Rock sites; Stochastic simulation

1. Introduction

The design of buildings and structures in earthquake prone regions must be based on information relating to expected seismic effect expressed in terms of time domain quantities (maximum amplitudes of ground motion, periods, and duration) and spectral quantities (Fourier spectra and response spectra). Design of some critical facilities also requires time function of ground acceleration. Estimation of time domain and spectral parameters of ground motion are obtained either by empirical relations that connect these to earthquake magnitude, distance, and local soil conditions (source scaling and attenuation relations) or by means of mathematical modelling. At present, there is no doubt that these relations are different for different seismic regions, and "region and site-specific" models should be developed on the basis of available strong ground motion records.

One of the most important parameters describing strong ground motion during earthquakes is the Fourier-amplitude spectrum. Much effort has been devoted recently to the analysis of the frequency content of seismic ground motion in different seismic regions [4–8,10,12,15,19,21,26,29–31,34,36,37]. These assessments were based on data sets that include various numbers of records and used different models, but they allow identifying the features of seismic wave excitation and propagation, and to obtain estimates of strong ground motion produced by future earthquakes. It is, however, obvious that source scaling and attenuation models should be tested and updated, as new strong ground motion data become available. The purpose of this paper is to present recent results of ground-motion acceleration spectra parametrization by means of simple analytical expressions describing source and propagation for Caucasian region and Taiwan island.

2. Description of the model

There are two approaches to describe Fourier acceleration spectra as a function of magnitude, distance and local site condition. The first one is based on statistical analysis of empirical data to estimate an equation of regression [7,15,21,30,36]. A large number of frequency-dependent regression coefficients should be determined. It is necessary to possess information about local soil condition for every station, otherwise this regression will describe so-called "average soil".

In the second one, the spectrum is represented by simple analytical expressions describing source, propagation, and site effect, separately. Parameters of the expressions can be easily determined on the basis of empirical data, and it is

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not necessary to know detailed information on local soil conditions.

The general model of radiated spectra, describing the Fourier acceleration spectrum A at frequency f, can be expressed in the following way [9]

$$A(f) = (2\pi f)^2 CS(f)D(R,f)I(f) \tag{1}$$

where C is the scaling factor; $S(f)$ the source spectrum; $D(R, f)$ the diminution function, and $I(f)$ represents the frequency-dependent site response. The scaling factor is given by:

$$C = (\langle R_{\theta\phi}\rangle FV)/(4\pi\rho\beta^3 R^{\mathrm{b}}) \tag{2}$$

where $\langle R_{\theta\phi}\rangle$ is the radiation coefficient, F the free surface amplification, V represents the partitions of the vector into horizontal components, ρ and β are the density and shear velocity in the source region, and R is the hypocentral distance.

A commonly used source function $S(f)$ in the Brune's model [13] is

$$S(f) = M_0/[1 + (f/f_0)^2]. \tag{3}$$

For the Brune's model, the source acceleration spectrum at low frequencies increases as f^2 and approaches a value determined by f_0 (corner frequency) and M_0 at frequencies $f \gg f_0$. The value of f_0 can be found from the relation $f_0 = 4.9 \times 10^6 \beta(\Delta\sigma/M_0)^{1/3}$. Here $\Delta\sigma$ is the stress parameter in bars, M_0 is the seismic moment in dyne-cm and β in km/s. The level of the spectrum remains approximately constant for frequencies above f_0 until the cut-off frequency f_{max} is approached. The amplitude of the spectrum decays rapidly at frequencies above f_{max}.

The function $D(R, f)$ accounts for frequency-dependent attenuation that modifies the spectral shape. It depends on the hypocentral distance (R), regional crustal material properties, the frequency-dependent regional quality factor Q, and f_{max}. These effects are represented by the equation

$$D(R,f) = \exp[-\pi f R/Q(f)\beta]P(f, f_{max}) \tag{4}$$

where $P(f, f_{max})$ is a high-cut filter. Two forms of the P filter are used—the Butterworth filter [9]

$$P(f) = [1 + (f/f_{max})^8]^{-1/2} \tag{5}$$

and filter proposed by Anderson and Hough [1]

$$P(f) = \exp(-\pi\kappa f). \tag{6}$$

The f_{max} filter produces more rapid spectral decay than κ (kappa) filter. There are different suggestions regarding the physical meaning of f_{max} or kappa. Some investigators [14,24,25] have suggested that it is a source effect, while the others [1,16,17] concluded that κ is a characteristic quantity associated with the peculiarity of the station site. In all probability, f_{max} and kappa have both source and site origins, because there are evidences of significant regional differences of these quantities [11,12].

3. Processing, initial data and results

Processing of the records consisted of visual inspection of every accelerogram, selection of the significant part of the record starting from S-wave arrival, and the computation of Fourier amplitude spectra for both horizontal components using 10% cosine window. The spectra were smoothed using a three-point running Hanning average filter (twenty consecutive smoothing were applied for raw spectra). The amplitudes of the spectra were tabulated at frequencies having a spacing of 0.1 log frequency units, since it is usual to model log amplitude versus log frequency.

3.1. The Caucasus region

A collection of ground-motion recordings of small to moderate ($3.5 \leq M_L \leq 6.2$) earthquakes has been obtained during the 1988–1991 strong ground motion network operation in the epicentral areas of the Spitak earthquake of 7 December 1988 ($M = 6.9$) and of the Ratchi earthquake of 29 April 1991 ($M = 7.1$) [2,3]. This region of the Caucasus still has a poor database for strong ground motion.

The data set used for the Ratchi area includes records of eight largest aftershocks ($3.5 \leq M_L \leq 6.2$) of the Ratchi earthquake, obtained at hypocentral distances up to 120 km. It has been found that ground motions at rock sites ($\rho = 2.7$ gm/cm^3, $\beta = 3.5$ km/s) from small events ($M \leq 4.0$) can be modelled accurately by the Brune source model using a stress parameter $\Delta\sigma$ of 150 bars and Butterworth filter with cut-off frequency $f_{max} = 6$–8 Hz [30]. At the same time, the empirical function developed for eastern North America by Atkinson [4] in the following form

$$S(f) = M_0\{(1-\epsilon)/[1 + (f/f_A)^2] + \epsilon/[1 + (f/f_B)^2]\} \tag{7}$$

gives a better fit to empirical data observed during larger events. The parameters ϵ, f_a, and f_b are the functions of moment magnitude M_w [18]: $\log \epsilon = 2.52 - 0.637\ M_w$; $\log f_A = 2.41 - 0.533\ M_w$; $\log f_B = 1.43 - 0.188\ M_w$. The use of trilinear form proposed by Atkinson and Boore [6] for the attenuation curve with $Q = 29.4[1 + (f/0.3)^{2.9}/(f/0.3)^2]$ is necessary to simulate spectra at long ($R > 70$ km) distances [30].

The data set used for the Spitak area includes records of the 1988 Spitak earthquake mainshock ($M_s = 6.9$), the major aftershocks ($4.0 \leq M_L \leq 5.0$), and the event of $M_L = 5.0$ that occurred toward the North from the Spitak area in Djavakhet upland (Georgia). From the comparisons between observed data and predictions, the Brune's ω-squared source model, with stress parameter varying from 50 to 200 bars, seems to provide satisfactory estimates of acceleration spectra (hard rock sites, $\rho = 2.7$ gm/cm^3, $\beta = 3.5$ km/s) at frequencies from 0.5 to 10–15 Hz for earthquakes in the study region of the Caucasus [32]. The same form of an elastic attenuation Q of spectral amplitudes with distance, as proposed for the Ratchi area, may be used in this region. It is necessary to note, that this form of $Q(f)$

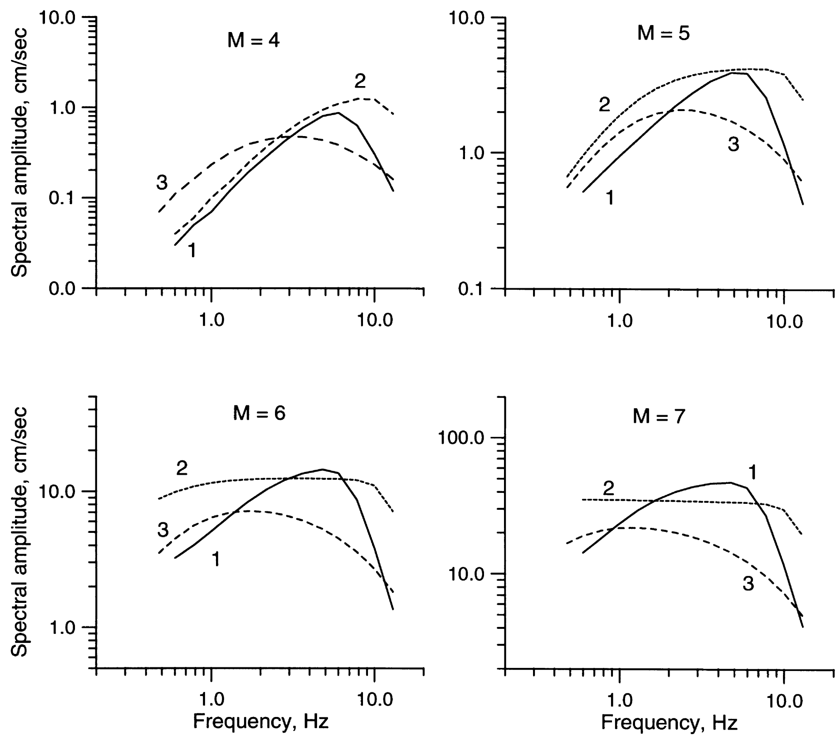

Fig. 1. Comparison of Fourier acceleration spectra (rock sites) calculated using ω-squared region-dependent models for different magnitudes M at hypocentral distance $R = 10$ km. (1) The Ratchi region; (2) the Spitak region; and (3) Taiwan area.

relationship fits a number of observations for the mountain territories [11]. The cut-off frequency f_{max} in Butterworth filter varies from 8 to 12–15 Hz depending on the site and event.

3.2. Taiwan island

The Taiwan data set includes 1380 horizontal components of ground acceleration recordings of 176 earthquakes ($4.5 \le M_L \le 6.5$) occurred since 1991 at epicentral distances up to 200 km. These records were obtained during the execution of Taiwan Strong Motion Instrumentation Program (TSMIP) [22]. It has been found [34] that the acceleration spectra of most significant part of the records, starting from S-wave arrival, for very hard rock sites ($\rho = 2.8$ gm/cm^3, $\beta = 3.8$ km/s) in Taiwan area can be modelled accurately by the Brune ω-squared source model with magnitude-dependent stress parameter $\Delta\sigma$, that should be determined using recently proposed regional relationships between seismic moment (M_0) and magnitude (M_L) [23]

$$\log_{10} M_0 = 19.043 + 0.914 M_L \quad (8)$$

and between $\Delta\sigma$ and M_0 [37]

$$\log_{10} \Delta\sigma = -3.3976 + 0.2292 \log_{10} M_0 \pm 0.6177. \quad (9)$$

Frequency dependent attenuation of spectral amplitudes with distance may be described using quality factor $Q = 225 f^{1.1}$ for deep (depth more than 35 km) and $Q = 125 f^{0.8}$ for shallow earthquakes, and kappa filter ($\kappa = 0.03$–0.04) may be used to modify the spectral shape. When considering geometrical spreading in the form $1/R^b$ (Eq. (2)) attenuation of the direct waves is described using $b = 1.0$ for $R_1 < 50$ km; for transition zone where the direct wave is joined by postcritical reflections from mid-crustal interfaces and the Moho-discontinuity ($50 < R_2 <$ 150–170 km) $b = 0.0$, and attenuation of multiply reflected and refracted S-waves is described by $b = 0.5$ for $R_3 >$ 170 km.

Fig. 1 shows comparison of Fourier amplitude spectra of ground acceleration calculated for condition of hard rock sites for the study regions. It is seen that the amplitude and shape of the spectra are different and depend on the region. The spectra from Spitak region are characterized by the highest low-frequency amplitudes for magnitudes $M_L > 4.5$–5.0. The spectra from the Ratchi region reveal a "band-pass" character, and, for magnitudes $M_L > 6.0$, they are characterized by the largest amplitudes at intermediate frequencies ($f = 2$–5 Hz). The spectral amplitudes for Taiwan region are generally less than the Caucasian spectra in the whole considered frequency range, except low-frequency band ($f \le 2$–3 Hz) for small magnitudes ($M_L = 4.0$–4.5). These variations of spectral shape and amplitude reflect the style-of-faulting factor and regional properties of geological medium. The ground-motion spectra from intraplate earthquakes occurring in rigid and consolidated medium, (for example, eastern North America, or Central Asia (Turan Plate)) are characterized by the largest values of cut-off frequency f_{max} [10,11,15], and events of

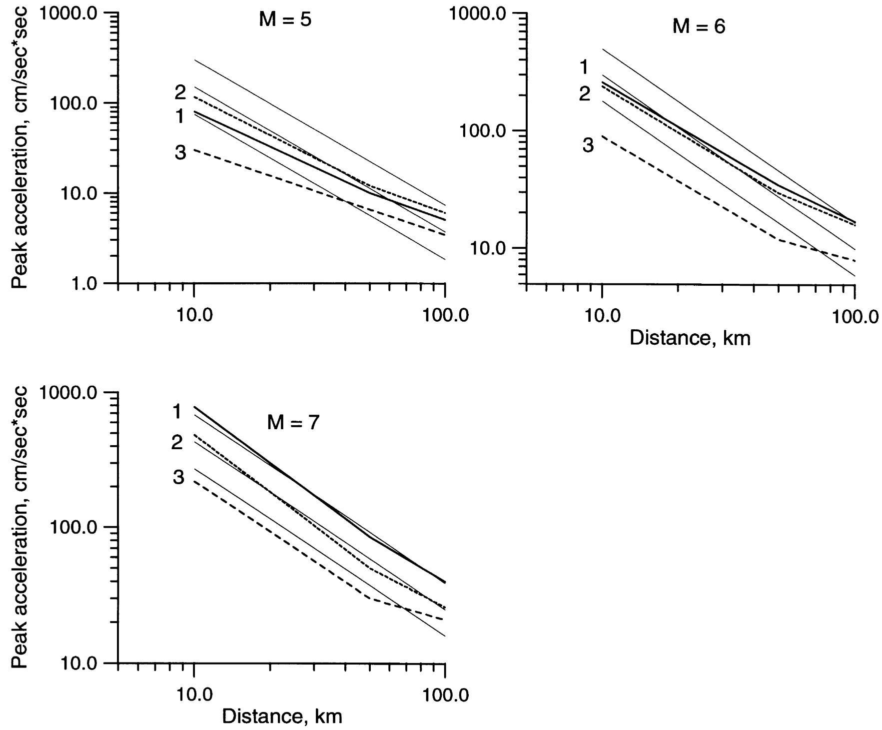

Fig. 2. Distribution of the maximum acceleration versus hypocentral distance (rock sites). Thick lines-maximum accelerations (averaged from 40 simulations) calculated using ω-squared spectral models and stochastic approach for the studied regions. (1) The Ratchi region; (2) the Spitak region; and (3) Taiwan area. Thin lines—mean-amplitude values ± 1 standard deviation estimated using recently developed empirical relationship for California [27].

dip–slip (reverse) faulting show the higher spectral amplitudes in high-frequency domain than those for strike–slip events [15]. In low-frequency domain this correlation is the opposite. But the style-of-faulting is not a single factor determining the spectral shape and amplitudes. For example, the earthquakes in the Ratchi area were deep-slip (reverse) events, and the most part of the earthquakes in the Spitak area were strike-slip or oblique-slip events. Earthquakes in the Ratchi area occurred in fractured carbonate and volcanogenic rocks, and events in the Spitak area occurred in rigid crystalline shales. Thus, the shape of the spectra in high-frequency domain (cut-off frequency f_{max}) should depend on the properties of the geological medium [14,24]. The spectral model for the Taiwan area reflects the features of different style-of-faulting earthquakes associated mainly with the subduction of the Philippine Sea plate beneath the Eurasian plate.

4. Discussion

The obtained source scaling and attenuation models allow a satisfactory prediction of the peak ground acceleration for rock sites and, combining with generalized soil amplification curves, for soil sites from earthquakes of magnitudes 4.0–4.5 $\le M_L \le$ 6.5 and distances up to about 200 km [30–34]. The stochastic simulation technique introduced by Boore [9] was used to generate synthetic time histories of ground motion. One of the most important parameters of used stochastic predictions is the duration model, because it is assumed that most (90%) of the spectral energy given by Eq. (1) is spread over a duration $\tau_{0.9}$ of the accelerogram. The frequently used duration models are the following:

$$\tau_{0.9} = \tau_0 + bR \tag{10}$$

where τ_0 is the source duration and bR represents a distant-dependent account for dispersion [12];

$$\log_{10}\tau_{0.9} = 0.207M_s + 0.264 \log_{10} R - 0.65 \pm 0.19 \tag{11}$$

for rock sites, and

$$\log_{10} \tau_{0.9} = 0.178M_s + 0.4 \log_{10} R - 0.48 \pm 0.24 \tag{12}$$

for soft soil sites [28]. Atkinson and Boore [6] for eastern North America used the following parameters: $\tau_0 = 1/(2f_0)$ (f_0 is the corner frequency), and b is 0.16 for $10 \le R \le 70$ km; -0.03 for $70 \le R \le 130$, and 0.04 for $R \ge 130$ km. Wen and Yeh [38] studied strong motion duration for Taiwan region. They obtained the following relationship for ground acceleration

$$\tau_{0.9} = 0.430 \exp(0.504M_L) \pm 2.749 \tag{13}$$

for the whole data set including alluvium site and rock site records. Unfortunately, they did not present the relationships between the duration and distance, although have mentioned that the duration has a slight tendency to increase with distance up to about 80 km.

It has been found, that Atkinsons and Boore's duration model should be used for calculating strong ground parameters in the Caucasus regions (the Ratchi and the Spitak areas) [30,31], and regional Wen and Yeh's model gives a better fit to empirical data for Taiwan region [34]. Fig. 2 shows comparison between maximum amplitudes (A_{max}, averaged from 40 simulations) of synthetic accelerograms obtained on the basis of the described spectral models. The characteristics of peak ground acceleration distribution versus distance (mean values and ± 1 standard deviation limits) estimated for rock sites using recent ground motion attenuation relationship [27] for California earthquakes are also shown in this figure. This empirical relationship was obtained by Sadikh et al. using closest distance to vertical projection of the rupture R_{CLS}. To make these data dependent on the hypocentral distance R_{HYP}, the source depth $H = 10$ km is used supposing that $R_{CLS} = R_{EPC}$ (R_{EPC} is the epicentral distance), $R_{HYP} = (R_{CLS}^2 + H^2)^{1/2}$. It is seen from comparison that maximum amplitudes of ground acceleration for hard rock sites in the Taiwan area are constantly less than those calculated for the Caucasus and California. When this paper passed the review process, a magnitude $M_w = 7.6$ ($M_L = 7.3$) earthquake struck central Taiwan on September 21, 1999 [35]. This shallow thrust event provided a wealth of modern digital data for seismology which allow to refine the regional source scaling and attenuation relationships in the nearest future. The preliminary results [35] show that the average horizontal PGAs from the earthquake recorded at distances less than 20 km are about 30% below the median PGAs based on commonly used attenuation in California.

The maximum amplitudes for the Ratchi region are larger, in average, than those for the Spitak region for magnitudes $M > 6$. It corresponds to the results of recent study of peak ground acceleration for the Ratchi region on the basis of empirical data [29]. At the same time, the mean-amplitude values of maximum acceleration estimated for the Ratchi and the Spitak regions are within ± 1 standard deviation limits for the Californian peak ground acceleration. Therefore, bearing in mind the scatter of the data, it is not possible to say that there is significant difference between the whole set of the Californian and Caucasian peak ground acceleration data for condition of rock sites.

The comparisons between 5% damped response spectra (hard rock sites) calculated for magnitudes $M = 5$, 6, and 7, and hypocentral distances 10, 50 and 100 km are shown in Figs. 3–5. The spectral amplitudes in low-period domain ($T < 0.5$–0.6 s) for the Ratchi region are large, in average, than those for the Spitak region and Taiwan area for magnitudes $M = 6$–7. The ground motions in Taiwan area are characterized by the lowest spectral amplitudes than those from the Caucasin regions and California for distances less than 50–60 km. As in the case of PGA comparison, mean-amplitude values of response spectra estimated for the

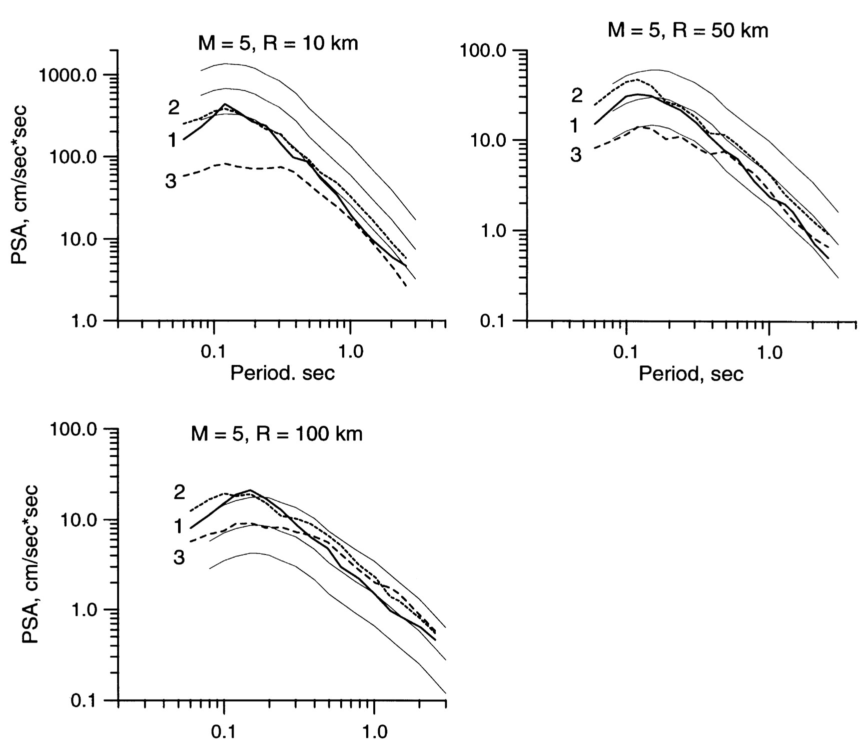

Fig. 3. Comparison of 5% damped response spectra calculated for earthquake of magnitude $M = 5$ and different hypocentral distances R (rock sites). Thick lines—response spectra (averaged from 40 simulations) modelled using ω-squared spectral model and stochastic approach for the studied regions. (1) The Ratchi region; (2) the Spitak region; and (3) Taiwan area. Thin lines—mean-amplitude values ± 1 standard deviation estimated using recently developed empirical relationship for California [27].

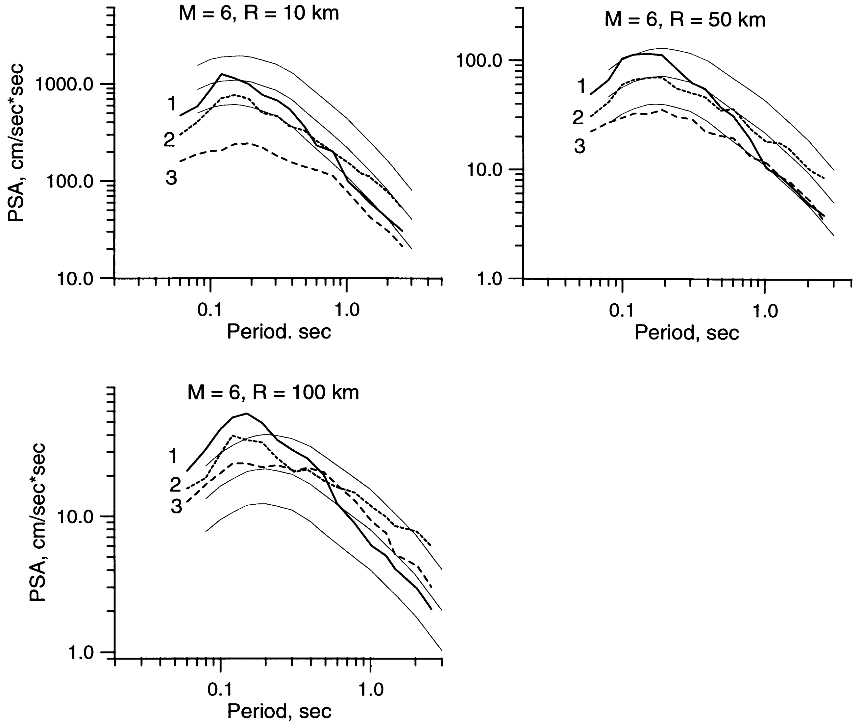

Fig. 4. Comparison of 5% damped response spectra calculated for earthquake of magnitude $M = 6$ and different hypocentral distances R (rock sites). Thick lines—response spectra (averaged from 40 simulations) modelled using ω-squared spectral model and stochastic approach for the studied regions. (1) The Ratchi region; (2) the Spitak region; and (3) Taiwan area. Thin lines—mean-amplitude values ± 1 standard deviation estimated using recently developed empirical relationship for California [27].

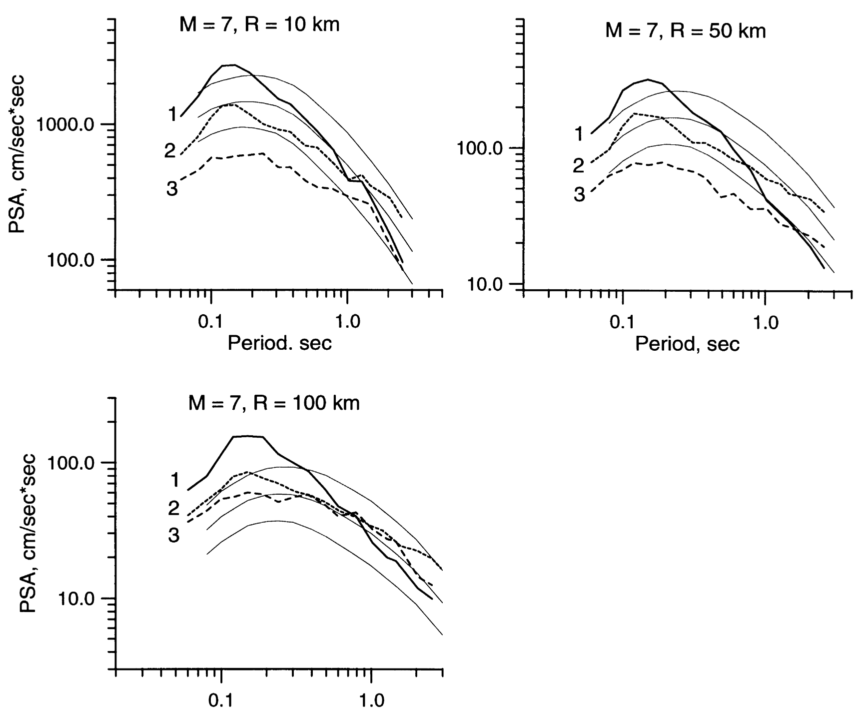

Fig. 5. Comparison of 5% damped response spectra calculated for earthquake of magnitude $M = 7$ and different hypocentral distances R (rock sites). Thick lines—response spectra (averaged from 40 simulations) modelled using ω-squared spectral model and stochastic approach for the studied regions. (1) The Ratchi region; (2) the Spitak region; and (3) Taiwan area. Thin lines—mean-amplitude values ± 1 standard deviation estimated using recently developed empirical relationship for California [27].

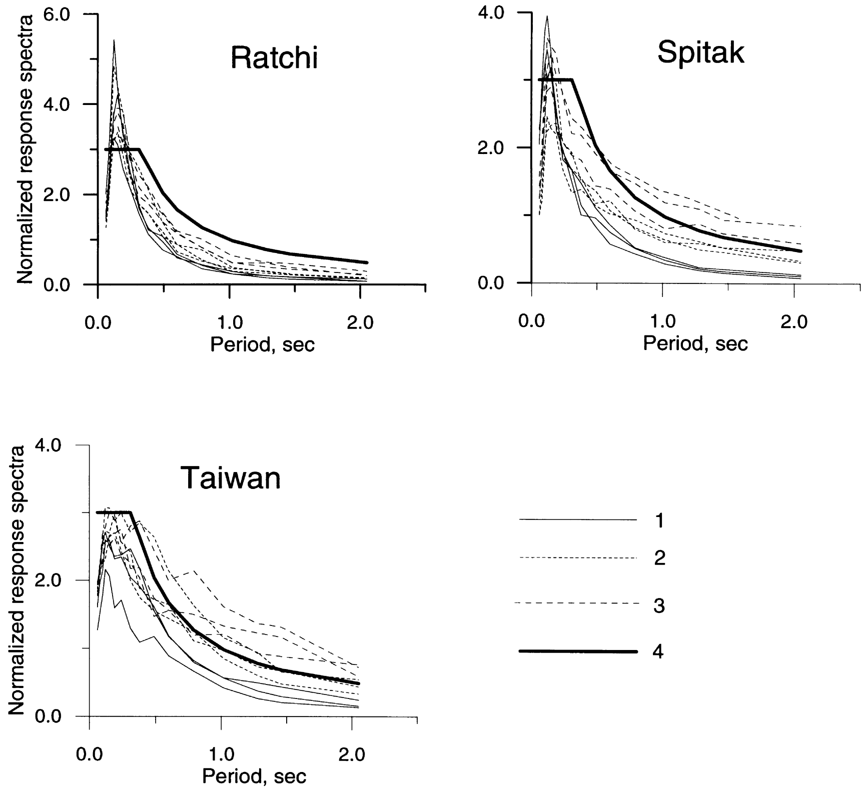

Fig. 6. Comparison of the normalized response spectra and Building Code "design" spectra for rock site. Simulated response spectra (values averaged from 40 simulations) were calculated for earthquakes of different magnitudes: (1) $M = 5$; (2) $M = 6$; and (3) $M = 7$ and hypocentral distances (10, 50 and 100 km) using ω-squared spectral models and stochastic approach for the studied regions. Building Code design spectrum (4) represents rock and stiff soil sites and is used for design of buildings in the former Soviet Union and, therefore, in the Caucasus region.

Ratchi and the Spitak regions are within ± 1 standard deviation limits for the Californian response spectra, at least for magnitudes up to $M = 6.0$–6.5 and distances up to 50 km. Fig. 6 shows the comparison of normalized (divided by the maximum amplitude of acceleration time function) response spectra and "design" response spectrum proposed by the Building Codes [20] for the whole territory of the former USSR and, therefore, for considered regions of the Caucasus. The "design" spectrum, or so-called "dynamic factor", corresponds to soil category *T*-Rock and stiff soils. The lateral seismic force depends on the "dynamic factor" and on the so-called "seismic zone factor" (peak ground acceleration assigned to considered region). The "design" spectra used in the Codes were determined as an envelope of a set of normalized response spectra obtained for earthquakes of various magnitudes and distances. Because of possible variation of ground motion characteristics in different regions, the envelope reflects the features of the region producing the major part of the record used in the analysis. For example, most of the strong motion data used for constructing of the USSR Building Codes were obtained from strike–slip earthquakes occurred in the western US. It is seen from the comparisons (Fig. 6) that normalized response spectra for the Ratchi area are less, in general, than the Code "design" spectrum for periods $T > 0.4$–0.5 s, and normalized spectra for large ($M = 7$) and distant ($R > 50$ km) events for the Spitak area are larger than the Code "design" spectrum. It is possible to conclude that the shape of "design" spectra, proposed in the Building Codes for rock and stiff soil sites in the considered regions of the Caucasus, should be admitted as a satisfactory one. However, the "design" spectrum for the Ratchi area is a conservative one. There is no "design" spectrum for rock sites in the Taiwan region [20], but the lateral force in Taiwan's Codes is determined by period-dependent "seismic force" coefficient than can be determined considering local (and regional) conditions. The comparison of the normalized response spectra calculated for the Taiwan region and the Caucasus shows that the ground motions for rock sites in the Taiwan region are characterized by the higher ratio between the low-frequency and high-frequency part of the spectra.

5. Conclusion

The principal results derived from this study of the features of strong ground motion excitation and propagation are the evidence that source scaling may differ in the various parts of the world and even within a seismic region. These peculiarities must be taken into account when evaluating design input ground motion. Available ground motion recordings should be used to estimate parameters of the model for strong-motion prediction and probabilistic seismic hazard assessment. At the same time, a special study is necessary to verify whether available ground motion attenuation relationships can be applied in any specific region.

In this paper, the spectral models derived only for rock sites are described. The local site effects (frequency-dependent function $I(f)$ in Eq. (1)) may considerably modify the shape and amplitudes of the spectra and, therefore, the design parameters. One of the advantages of described spectral models is the ability to evaluate site response characteristics in terms of spectral ratios between spectra of earthquake recordings and modelled "hard rock" spectra [33]. Besides local site response, the spectral ratios include effects of source rupture peculiarities and inhomogeneous propagation path. Therefore, the variability of the empirical amplification functions reflects regional peculiarities of seismic waves excitation and propagation, as well as intrinsic variability in the site response itself (by virtue of different incidence angles, lateral soil heterogeneity, etc). The combination of regional source scaling and attenuation models with local site response characteristics allows to obtain "site and region-specific" design parameters both in deterministic (scenario earthquake) and probabilistic approaches.

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