



Uniform approach to probabilistic site-dependent seismic hazard estimation

V.Yu. Sokolov

Geophysical Institute of Karlsruhe University, Karlsruhe, Germany

Yu.K. Chernov

Engineering & Geological Center, North Caucasus Branch, Stavropol, Russia

ABSTRACT: An integrated approach for evaluating site-dependent seismic hazard (SH) is presented. A probabilistic SH analysis in terms of Fourier amplitude spectra (FAS) of ground acceleration is performed to calculate Uniform Hazard Fourier (UHF) spectra for a given soil condition using spectral amplification functions. The spectral source scaling and attenuation models are developed on the basis of regional ground-motion data. The site amplification functions may be calculated using earthquake recordings and “hard rock” spectral models. The “dominant earthquakes” contributing the hazard are determined for a given return period in considered frequency range. The UHF spectra combined with strong-motion duration are used for generation of strong ground motion time series, so-called “Uniform Hazard Accelerograms”, which allow determining “Site&Region&Return period-dependent” ground motion parameters. When using FAS as an input parameter, it is possible to obtain the results in terms of Seismic Intensity (MM or MSK scales), Peak Acceleration, Response Spectra, and Characteristic Accelerograms. The described approach was applied for evaluating design input ground motion parameters and probabilistic microzonation for territories, which are characterized by different seismicity and tectonic settings: Taiwan, Central Asia, Caucasus, and Russian Far East region. Selected results are described in the paper.

1 INTRODUCTION

The rapid growth of large cities and industrial areas increase their vulnerability to natural disasters. Earthquakes, undoubtedly, are the most dangerous phenomena among the disasters. During the last decades large earthquakes caused massive loss of human life and extensive physical destruction throughout the world (Iran, 1990; Japan, 1995, Turkey and Taiwan, 1999; India, 2001, etc.). At the present state of knowledge, the proper level earthquake-resistant design seems to be the most effective way to prevent grave consequences of the earthquake. It requires determination of so-called “design ground motion” (design earthquake), which can be characterized by engineering ground motion parameters (peak amplitudes, Fourier and response spectra, intensity, acceleration time histories, etc.). The specification of design ground motion parameters is the goal of Seismic Hazard Analysis (SHA). The SHA procedures are based on ground motion attenuation relationships, which should take into account regional earthquake source and propagation path effects and local site response peculiarities.

At present, probabilistic approach to seismic hazard analysis (PSHA) is widely used for estimation of design ground motion parameters. PSHA produces integrated description of the influence from all damaging earthquakes at all possible locations with respect to a specific case. The procedure that is based on Fourier acceleration spectra (FAS) meets the requirements of earthquake engineering practice to estimate so-called “Site & Region & Return period - specific” strong ground motion parameters. The advantages of using FAS are as follows:

1. Various regional source scaling models and attenuation relations based on empirical data have already been developed, or may be easily established for the region under study. It seems to be possible to estimate the spectral model for condition of rock sites, even if there is no rock reference station available (Sokolov et al. 2001). It has been also shown, that the spectral models, which were developed using database from small and moderate earthquakes ($M < 6.5$), allow constructing the reliable spectra for the case of larger (up to $M = 7.5$) events in the region (e.g. Chernov 1989; Sokolov et al. 2002).

2. The variety of local soil conditions may be considered using soil/reference site spectral ratios. In this case, it is possible to use different site amplification functions, which depend on earthquake magnitude and distance, and to consider non-linear behaviour of the soil during strong excitation.

3. The term “site & region & return period - specific strong ground motion parameters” also includes seismic intensity as a useful and simple quantity describing the damage due to earthquakes. At present there is no doubt that seismic intensity, besides the amplitude, is an expression of the duration and frequency content of ground motion. The technique, which is based of the recently established relationships between intensity and the Fourier amplitude spectra (Chernov 1989; Sokolov & Chernov 1998; Sokolov 2002), allows evaluating absolute values of intensity directly using the site-dependent spectra.

Thus, when using the Fourier amplitude spectra as a basic input in seismic hazard analyses, it is possible to utilize a variety of the models and approaches. The more appropriate ones may be chosen depending on the quality and amount of the available data both for evaluation of the motion parameters as a function of magnitude and distance, and for consideration of local site conditions. The approach allows obtaining, simultaneously, the design engineering parameters of earthquake ground motion using a common ground-motion model. The purpose of the paper is to provide a short description of the method and to present selected result of the method utilization.

2 DESCRIPTION OF THE METHOD

2.1 Seismic intensity and Fourier amplitude spectrum

The technique for estimating the seismic intensity (MM or MSK scale) on the basis of Fourier amplitude spectra of ground acceleration has been developed using more than 1100 recordings of earthquakes occurred throughout the world (Chernov 1989; Sokolov & Chernov 1998; Sokolov 2002). The method implies that the seismic intensity is determined by the level of ground motion spectral amplitudes in the frequency range of 0.4-13 Hz. The contribution of ground motion components to the ground motion severity is not the same at different frequencies. The corresponding empirical relationships between FAS in frequency ranges 0.3 – 13 Hz and each intensity level were developed in the following way. First, using the ground-motion recordings and reported intensity database, the average spectra and variances of the spectral amplitudes were evaluated for different intensities from IV MMI (MSK) up to IX MMI (MSK). The average spectra are further called as the spectra “assigned to a given intensity level”. The spectral amplitudes should be considered as random variables, and appear to be lognormally distributed. Thus, in order to estimate the intensity level I , it is necessary to calculate probability distribution function $F(i)=P [I \leq i]$, where i is the value of I in the range of interest. The following scheme is used.

The probability that the base 10 logarithm of the levels of Fourier acceleration spectra ($\log_{10} A$) at the frequency f_j within the considered frequency range will not exceed the values of $\log_{10} A_0$, which are assigned to this intensity level ($I = i$), is estimated as follows

$$P[x_j \leq a_{i,j}] = 1 - 1/(\mathbf{s}_{i,j} \sqrt{2\mathbf{p}}) \int_{x_{min}}^{x_j} \exp(-(a_{i,j} - x_j))^{1/2} / (2\mathbf{s}_{i,j}^2) dx \quad (1)$$

where $a_{i,j}$ and $\sigma_{i,j}$ are the mean and the standard deviation of $\log_{10} A_0$ at the frequency f_j assigned to the intensity $I = i$; x_j is the base 10 logarithm of the level of observed spectrum at frequency f_j ; x_{min} is

determined as $x_{min} = a_{i,j} - 5\sigma_{i,j}$. To take into account the influence of all considered frequencies, the probability $P[x_j \leq a_{i,j}]$ is calculated for every frequency, and the resulting probability $P[x \leq a_i]$ for the intensity i is obtained as

$$P[x \leq a_i] = \left(\sum_{j=1}^{j=n_f} [x_j \leq a_{i,j}] w_{i,j} \right) / \sum_{j=1}^{j=n_f} w_{i,j} \quad (2)$$

where n_f is the number of considered frequencies; $w_{i,j}$ is the weight, which depends on the variance $\sigma_{i,j}^2$. Obviously, when considering the condition of intensity $I = i$ not to be exceeded, it is necessary to take into account the larger intensities $I > i$. Therefore, the probability that the intensity level I will not exceed the given value i may be estimated as follows

$$P[I \leq i] = \prod_{i=1}^{i=12} P[x \leq a_i] \quad (3)$$

The desired value of instrumental intensity is estimated by the maximum of the first derivative of function P (Fig. 1). In practice the frequency range from 0.36 Hz to 13 Hz is considered. The spectral amplitudes, which should be assigned to intensities III and X-XII, were obtained by extrapolation from the nearest intensities (IV-V and VIII-IX).

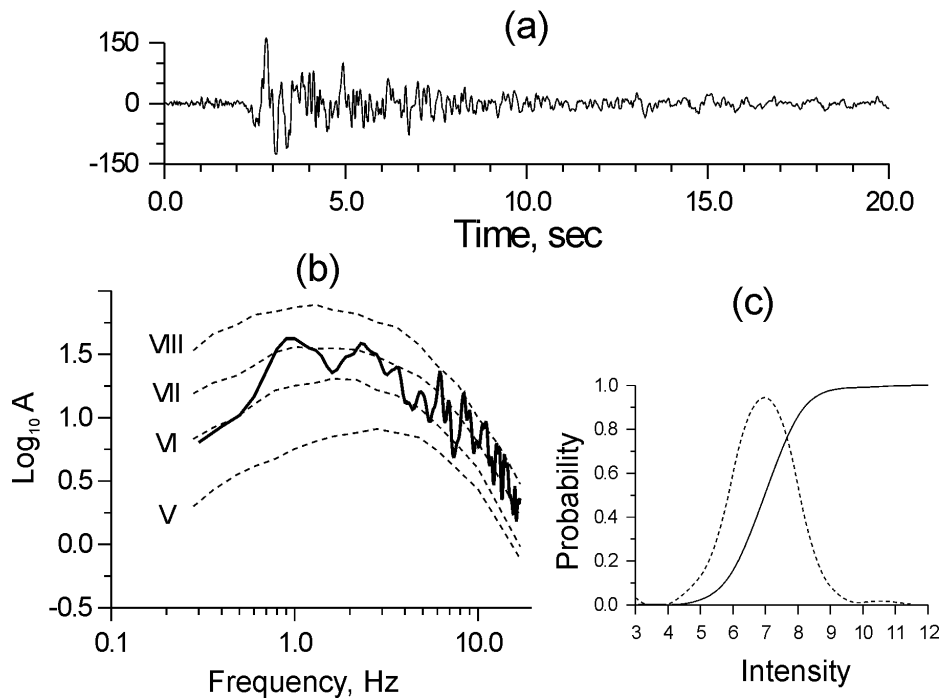


Figure 1. Seismic intensity estimation on the basis of Fourier amplitude spectrum of ground acceleration. The case of the 1977 (M 7.4, H=100 km) Vrancea (Romania) earthquake, st. Incerc (Bucharest). a – acceleration record (cm/sec²), E-W component; b – comparison of the spectrum of real record (solid line) and the average spectra (dashed lines) for various intensities (V-VIII); c – probability function of intensity not to be exceeded (solid line) and first derivative of the function (dashed line). Instrumental intensity is about MMI 7.0.

Besides the SHA in terms of MM (MSK) intensity, the technique may be used for compilation of so-called “Instrumental Intensity Map” showing the overall distribution of the intensity after a large earthquake (Sokolov & Wald, 2002).

2.2 Probabilistic seismic hazard analysis on the basis of FAS

The method is based on the well-known Cornell’s approach to probabilistic seismic hazard assessment, which incorporates the influence of all potential sources of earthquakes and the activity rate assigned to them. However, our technique and computational scheme differ somewhat from the classical one and, therefore, it is necessary to describe the principal statements (see also Chernov 1989).

For a given earthquake occurrence, the probability that a ground motion parameter X will not exceed a particular value x can be computed using the total probability theorem, that is

$$P [X \leq x] = P [X \leq x | Y] P [Y] \quad (4)$$

where Y is a vector of random variables (earthquakes of magnitude M and distance R) that influence X . Assuming that M and R are independent, the probability of not to be exceeding can be written as

$$P [X \leq x] = \int_0^1 \int_0^1 P [X \leq x | m, r] f_M(m) f(r) dm dr \quad (5)$$

where $P [X \leq x | m, r]$ is obtained from the predictive relationship, $f_M(m)$ and $f(r)$ are the probability density functions for magnitude and distance, respectively. When performing PSHA using classical scheme, it is necessary to determine the source-to-site probability distributions for source zones. In our scheme we do not use the probability density function $f_M(m)$ and $f(r)$, and consider every potential earthquake as a *separate event*. Thus, equation (4) may be rewritten as

$$P [X \leq x] = P [X \leq x | Y(m_1, r_1)] \cdot P [X \leq x | Y(m_2, r_2)] \cdot \dots \cdot P [X \leq x | Y(m_N, r_N)] \quad (6)$$

where $Y(m_i, r_i)$ is the potential earthquake with magnitude $M_{\min} \leq m \leq M_{\max}$ and distance $R_{\min} \leq r \leq R_{\max}$. To characterize the source areas, a combination of so-called “fault” and “area-source” models are used. The possible earthquakes are specified by geometry (in three dimensions) and a function describing rupture area as a function of magnitude. At the same time, the earthquakes occur within the areas (source zones) which are characterized by maximum possible magnitude M_{\max} . Thus, the active fault is considered as a narrow source zone rather than a line. Instead of cumulative magnitude-recurrence model which determines number N of events with a magnitude m larger than M , an alternative model is used and N is defined as the number of events with a magnitude $m = M \pm \Delta m$.

Let us assume that the level of seismic hazard is controlled by the total influence of all earthquakes that may occur in the region under study, and that the characteristics of ground motion expected during an earthquake of given M and R are lognormally distributed with standard deviation σ_x . Then, for a single earthquake ($N = 1$) of $M = m$ and focus depth $H = h$ occurred at distance $R = r$ the probability that ground motion parameter will not exceed a given value may be estimated as follows:

$$P_{N(M=m;R=r;H=h)=1} [X \leq x] = \frac{1}{\sigma_x \sqrt{2p}} \int_{x_{\min}}^x \exp\{(x-a)^2 / 2\sigma_x^2\} dx \quad (7)$$

where a is the mean value of $\log_{10} X$ (X — ground motion characteristic) for an earthquake of given M and R ; and x_{\min} is of sufficiently small value ($x_{\min} \approx a - 5\sigma_x$). Let us also assume that value a_R represents ground motion parameter for “reference”, for example - hard rock, site. Thus, for a non-reference site, parameter a in equation (7) may be determined as $a = a_R + \Psi'$, where Ψ' is a site coefficient. If the parameter a represents the Fourier amplitude spectra at a given frequency, then the local site effect can be described by the frequency-dependent site/reference spectra spectral ratios. To consider the uncertainty of the site response, the spectral amplification should be described as a random variable.

$$P_{N(M=m;R=r;H=h)=1} [X \leq x] = \sum_{\Psi_{\min}}^{\Psi_{\max}} \left\{ \left[\frac{1}{\sigma_x \sqrt{2p}} \int_{x_{\min}}^x \exp\{(x-a)^2 / 2\sigma_x^2\} dx \right] P [\Psi' = \Psi_k] \right\} \quad (8)$$

where $P [\Psi' = \Psi_k]$ is the probability that the spectral amplification equals Ψ_k . After taking into account distribution of earthquakes along depth $h_{\min} \leq h \leq h_{\max}$ and earthquake recurrence, and considering all earthquakes of $M_{\min} \leq m \leq M_{\max}$ that may produce significant effect at a given distance $R = r$, we have the following

$$P_{N(R=r) \geq 1} [X \leq x] = \prod_{M_{\min}}^{M_{\max}} P_{N(M=m;R=r) \geq 1} [X \leq x] \quad (9)$$

The final expression that takes into account all distances from $R = R_{\min}$ to $R = R_{\max}$ is as follows:

$$P_{N \geq 1} [X \leq x] = \prod_{R_{\min}}^{R_{\max}} P_{N(R=r) \geq 1} [X \leq x] \quad (10)$$

Here R_{max} is the maximum distance at which the earthquake of $M = m$ may produce significant effect. The technique described above has been used for the probabilistic region- and site-dependent seismic hazard assessment of various regions in the former USSR (Caucasus, Central Asia, Sakhalin Island) (Chernov 1989; Sokolov 2000) and Taiwan island (Sokolov et al. 2001).

To make the results of probabilistic seismic hazard assessment clearer and more useful for engineering purposes, the so-called deaggregation procedure is used. The hazard is represented by a single, or several earthquakes of certain M and R (so-called “dominant earthquakes”) that determine the motion in a given frequency range. Ground-motion parameters for engineering purposes can be obtained (generated or selected) for these (M, R) pairs. The approach for generating ground motion time series, so-called “hazard compatible” or “Uniform Hazard Accelerograms”, on the basis of Uniform Hazard (UH) Fourier spectra determined for a given return period (probability of exceedance) has been proposed recently (Sokolov 2000). The approach uses the concept of “dominant earthquakes”. It can be seen from equations 9 and 10 that the total probability of ground motion parameter X not to be exceeded is determined by multiplication of probability functions for different M and R values. The “dominant earthquake” should be characterized by the largest value $(1 - P_{(M=m; R=r)} [X \leq x])$. Therefore, it is possible to determine the influence (relative contribution) on Fourier spectra hazard from every (M, R) pair taking into account return period. Note that the distribution of the earthquake depths and occurrence of the events have been already taken into consideration. The UH Fourier spectra of ground acceleration are weighted accordingly the contribution of "dominant" earthquakes to spectral amplitude at a given frequency to produce “characteristic” spectra, which represent influence from “dominant earthquakes”. These “characteristic” spectra are used for generation of ground motion time series, or "dominant earthquake compatible" accelerograms. The stochastic technique (Boore 1983) combined with correspondent duration model was applied. Summation of these accelerograms produces the UH Fourier spectrum-compatible accelerogram, or Uniform Hazard accelerogram. Peak ground acceleration and response spectra that are determined using these time functions are, in essence, the hazard-compatible estimations. Figure 2 shows the scheme of the approach.

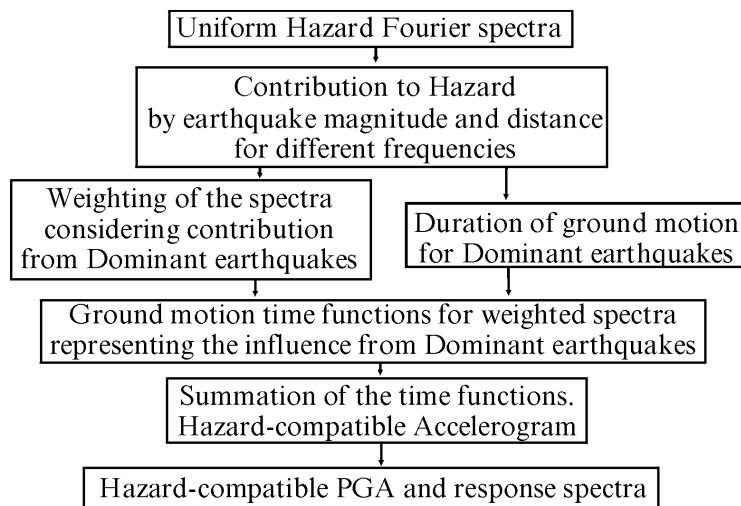


Figure 2. Scheme of probabilistic seismic hazard assessment in terms of Peak Ground Acceleration (PGA) and Response Spectra on the basis of Uniform Hazard Fourier Acceleration Spectra.

3 SELECTED RESULTS OF THE APPROACH APPLICATION

The approach shortly described above has been developed in order to meet one of the urgent needs of earthquake engineering, namely: including of local site effect into seismic hazard maps. The technique allows compilation of probabilistic (return period-dependent) microzonation schemes in terms of various design input ground motion parameters. Till present, the approach was applied for territories located in the Caucasus (Sokolov 2000), Central Asia (Chernov 1989; Sokolov & Chernov, 2001) and Taiwan (Sokolov et al. 2001). In this paper, we shortly describe probabilistic microzonation of the city

of Tashkent - the capital of Republic of Uzbekistan (Central Asia). It can be considered as a typical case, which includes estimation of ground motion parameters and seismic intensity.

The city is situated in the transition zone from Tyan-Shan mountain range to Turan platform (Fig. 3a). For its long history the city was affected by many earthquakes, and maximum observed seismic intensity was up to MSK VIII (the earthquake of 1966, $M=5.3$). Uniform Hazard Fourier Acceleration Spectra were calculated, using source spectra (Fig. 3b) and attenuation model, for the nodes of the grid with 5 km x 5 km spacing covering the territory. Every cell is characterized by a model of soil column. Figure 3c shows the generalized scheme of Quaternary deposits over the city area. We considered 9 typical soil models, and the numbers of the soil model are shown on the cells. The influence of different local soil conditions on seismic ground motion are characterized by “typical soil”/“reference soil” spectral amplification ratios (Fig. 3d), which were calculated for S-wave using 1-D linear model.

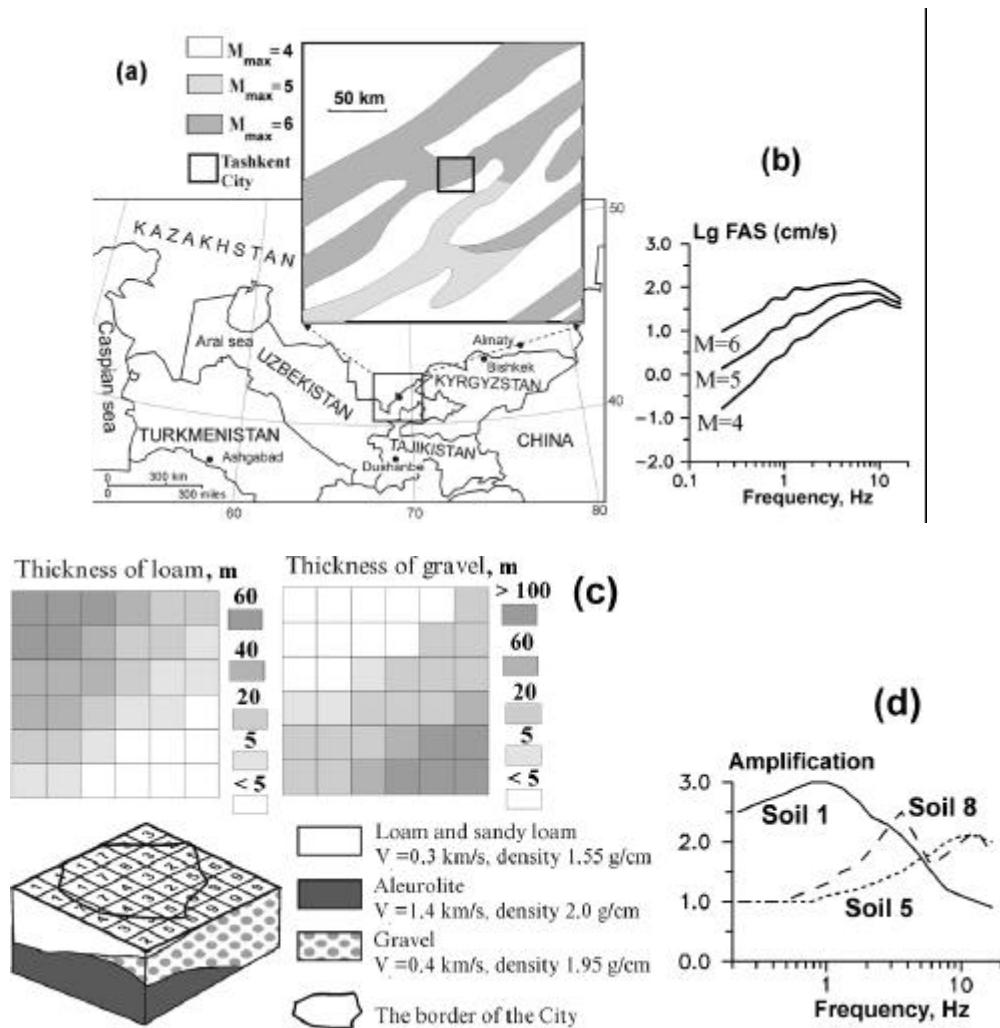


Figure 3. Input data for probabilistic microzonation of Tashkent city. a) Scheme of seismic source zones in the Tashkent region. b) Source (near-field) spectra of ground acceleration (FAS) evaluated for the region. c) Generalized scheme of soil conditions within the territory of the city. Numbers in the cells indicate soil types. Cell dimension is 5 km x 5 km. d) Averaged spectral amplification ratios for several soil types. Soil 1 – deep (thickness more than 50-60 m) loam; soil 8 – shallow (thickness about 20 m) loam; soil 5 – shallow (thickness 5-10 m) loam over gravel (thickness about 40-60 m).

Figure 4 shows the relative contribution to Fourier spectra hazard by earthquakes of magnitude M and distance R for various return periods at different frequencies. The hazard for small return period ($T = 100$ years, 40 % probability of exceedance in 50 years) is determined by nearby earthquakes of $M = 4$ and $M = 5$ for high frequencies ($f > 3-4$ Hz). The earthquakes of $M = 6$ are “dominant” for low and intermediate frequencies. The hazard is completely determined by nearby events of $M = 6$ for return periods more than 500 years.

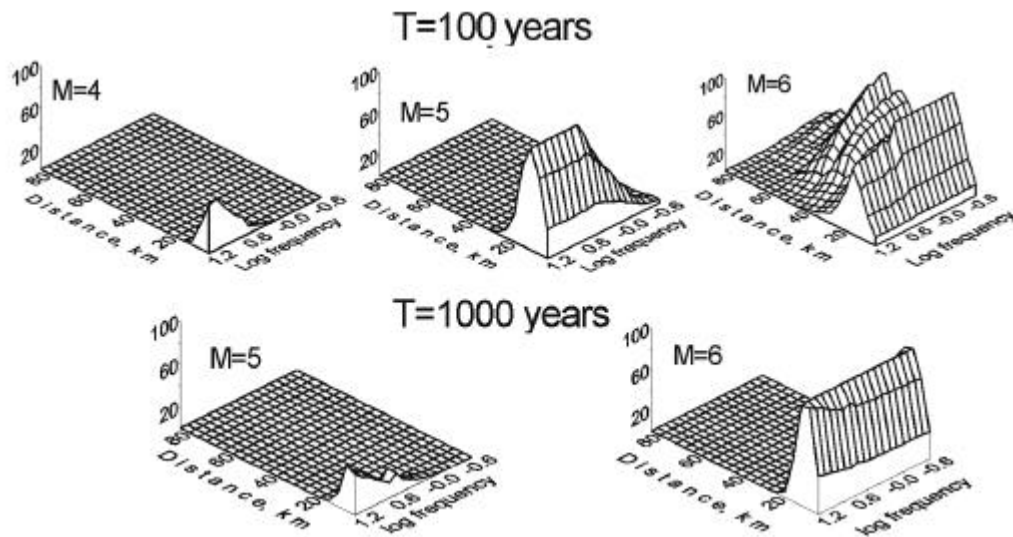


Figure 4. Relative contribution (percentage) to Fourier spectra hazard by earthquakes of magnitudes M versus ground motion frequency and earthquake distance for various return periods T .

The resulting microzoning maps in terms of MSK intensity are shown in Figure 5a. The intensity values are constantly large (up to 2 points of MSK scale) on thick layer of soft sandy loam (north-western part of the territory), while the thick gravel deposits (south-eastern part) are characterized by the smallest intensity values. It is necessary to note that in this study we do not take into account the possibility of liquefaction of saturated sandy loam deposits or subsidence of soft soil during strong vibration. This effect should increase expected intensity when considering relatively long return period, and, therefore, taking into account the large and nearby earthquakes. However the problem of quantitative account for non-linear phenomena in soft and saturated soils when estimating seismic hazard in terms of seismic intensity is still to be resolved.

The distribution of resulting peak ground acceleration (PGA) estimated for various return periods (PGA hazard) is shown in Figure 5b. It is seen that PGA values are constantly large on shallow (thickness < 30 m) sandy loam deposits in north-eastern part of the territory, and the deep gravel (south-eastern part) is characterized by the lowest PGA values. It is necessary to note, that the area of the highest PGA (north-eastern part of the city) do not coincide with the area of the highest seismic intensity (north-western part). Analysis of calculated Uniform Hazard Response (UHR) spectra shows that standard curve dictated by Building Codes seems to overestimate the seismic load for the oscillator periods more than 0.4-0.5 sec. The spectral amplitudes depend on site characteristics (Fig. 5c). Therefore the single design curve and seismicity coefficient (PGA value) proposed by the Building Code for generalized soil condition are not adequate for the whole territory of the city, and should be considered as the "very conservative" ones (Fig. 5d). On the one hand, an increased level of conservatism implies a greater margin of safety or resistance against earthquakes. On the other hand, the cost of the construction increases with increasing of the safety, and careful consideration of balancing of all aspects of design and engineering are needed to minimize the possible loss.

As a concluding remark, it is necessary to note that the procedure, using the same ground motion model (FAS), allows us to estimate different design ground motion parameters including intensity in terms of macroseismic scales (MMI or MSK), which is still widely used for loss estimation.

REFERENCES:

- Boore, D.M. 1983. Stochastic simulation of high-frequency ground motions based on seismological model of radiated spectra. *Bull. Seism. Soc. Am.*, 73, 1865-1894.
- Chernov, Yu.K.1989. *Strong ground motion and quantitative assessment of seismic hazard*. Tashkent, Fan Publishing House (in Russian).
- Sokolov, V.Yu. 2000. Hazard-consistent ground motions: generation on the basis of Uniform Hazard Fourier

Spectra. *Bull. Seism. Soc. Am.*, 90, 1010-1027.

Sokolov, V.Yu. 2002. Seismic intensity and Fourier acceleration spectra: revised relationship. *Earthquake Spectra*, 18, 161-187.

Sokolov, V.Yu. & Chernov, Yu.K. 1998. On the correlation of seismic intensity with Fourier amplitude spectra. *Earthquake Spectra*, 14, 679-694.

Sokolov, V.Yu. & Chernov, Yu.K. 2001. Probabilistic microzonation of the urban territories: a case of Tashkent city. *Pure and Applied Geophysics*, 158 (12), 2295-2312.

Sokolov, V.Yu. & Wald, D.J. 2002. Instrumental Intensity Distribution for the Hector Mine Earthquake: a Comparison of Two Methods. *Bull. Seism. Soc. Am.*, 92 (in press).

Sokolov, V.Yu., Loh, C.-H. & Wen, K.-L. 2000. Empirical study of sediment-filled basin response: a case of Taipei city. *Earthquake Spectra*, 16, 681-707.

Sokolov, V.Yu., Loh, C.-H. & Wen, K.-L. 2001. Site-dependent input ground motion estimations for the Taipei area: a probabilistic approach, *Probabilistic Engineering Mechanics*, 16, 177-191.

Sokolov, V.Yu., Loh, C.-H. & Wen, K.-L. 2002. Comparison of the Taiwan Chi-Chi earthquake strong motion data and ground motion assessment based on spectral model from smaller earthquakes in Taiwan. *Bull. Seism. Soc. Am.*, 92.

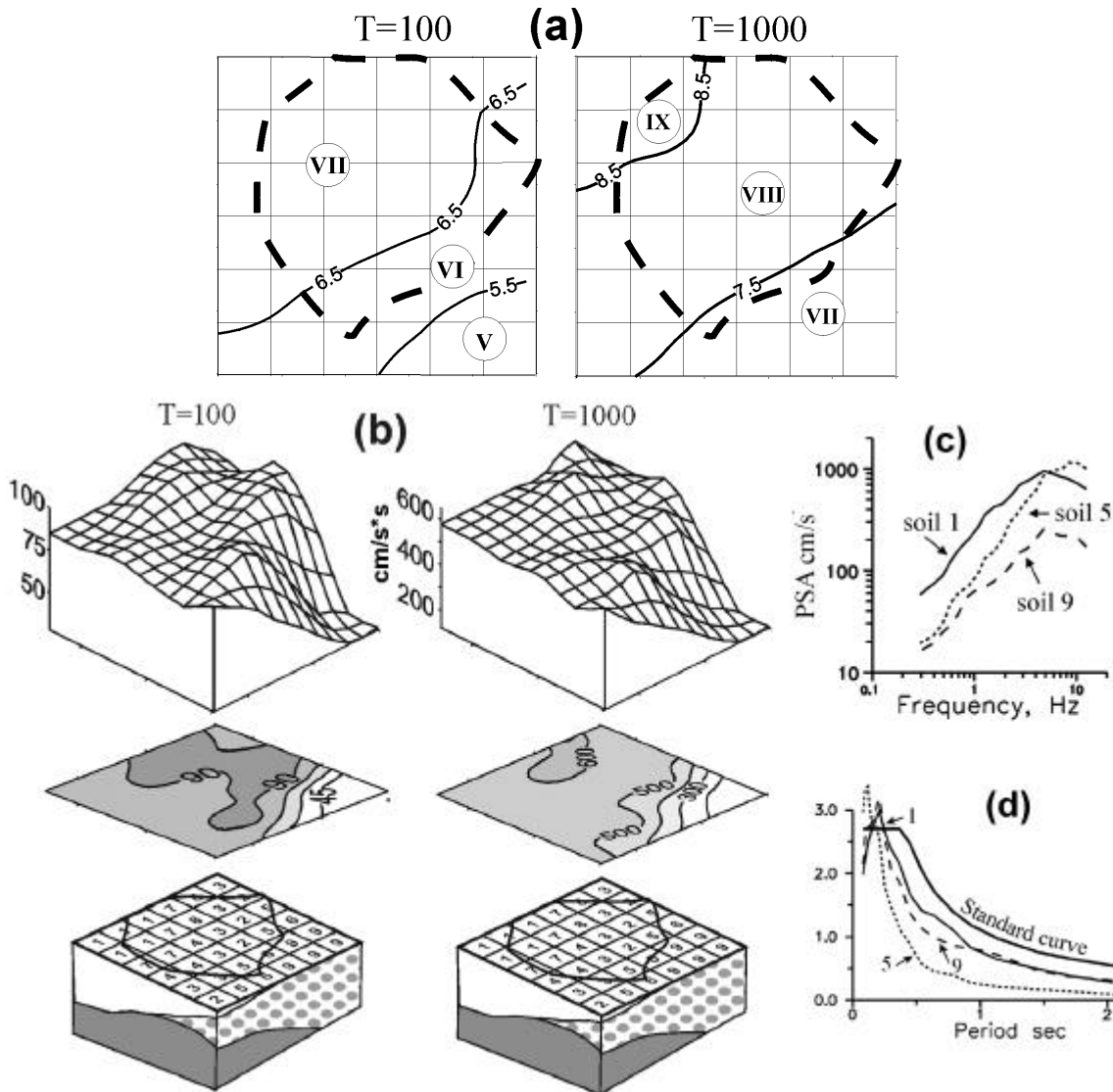


Figure 5. Probabilistic microzonation of Tashkent city. a) MSK intensity schemes for various return periods T (years). Dashed lines show the border of the city. b) Schemes of distribution of peak ground acceleration (cm/sec^2) along the studied territory calculated for different return periods T . c) Uniform Hazard Response (5% damping) and Design (d) spectra (return period $T=500$ years) estimated for typical soil conditions.