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An Improved Technique for Determination of Seismic Hazard

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Abstract. The technique for estimating seismic hazard is described which has been applied in the calculation of seismic hazard for the set of new maps of the general seismic zoning GSZ–97 of the Northern Eurasia territory based on statistical simulation of the catalogue and of the information on the long–term characteristics of seismicity. The technique develops the ideas presented in the approaches of Yu.V. Riznichenko, V.I. Keilis–Borok and colleagues, and of C.A. Cornell. The main differences and advantages of the technique and the program codes realized in practice as compared to the techniques of the 60–70–ties are the following: the conditions are developed for taking into account various information on seismicity; the theoretically substantiated description of the field of incoherent radiation in the vicinity of an extended source is applied; the distribution of sources of finite dimensions over depth is accounted for; control is provided of the location of extended sources within the limits of the seismogenerating zone; the resulting set of maps of seismic hazard in terms of intensity with a certain recurrence period permits to obtain a probabilistic estimation of seismic hazard within the given territory and to provide for an identical degree of risk over whole territory.

The calculation of seimic hazard for the set of new maps of general seismic zoning of North Eurasia (GSZ–97) was performed by means of the technique described below; it consisted of the construction of maps of seismic hazard based on simulation of the catalogue of earthquakes. This simulation was bazed on information on the long–term characteristics of seismicity, represented by a model for the zones of generation of earthquake sources (the ESO zones) over the territory under investigation (see V.I. Ulomov's paper in the current review). Studies were performed within the framework of " Seismicity and seismic zoning of North Eurasia" whien is the components of the State scientific–technical program " Global changes in the environment and climate" [Ulomov, 1992; 1995; Gusev, Shumilina, 1995].

The technique develops and refines the GSZ methodology presented in the approaches of Yu.V.Riznichenko, V.I.Keilis–Borok with colleagues and of C.A. Cornell [Riznichenko, 1965; 1966; 1967; 1968; 1980; Keilis–Borok et al., 1973; 1980; Cornell, 1968]. The main limitations of these approaches are: the use of short series of seismic observations to describe the long–term characteristics of the seismic regime; application of the linearity hypothesis of the earthquake recurrence graph for its extrapolation into the area of maximum magnitudes; application of the concept of a source as a pointlike object in calculations; the fixation of sources at a given depth; the use of energy classes, instead magnitudes, as energy characteristics of sources; the failure to take into account the scatter in intensity valus for given magnitude and distance. The proposed technique and program for its implementation are free of these disadvantages.

As a basis for the GSZ map, the map is adopted of the calculated intensity I with a fixed return period T at each point on the map (once every T years on the average). This I value is denoted as I_T. The recurrence of intensity I events is the mean yearly number of earthquakes causing shaking of intensity $\geqslant I$; it is equal to $1/T$. A recurrence of once in T years, on the average, means that the probability of exceeding the intensity I_T during t years (i.e. that at least one such an event will occur) is equal to $P=1-\exp(-t/T)$, and $P=t/T$ when $t \ll T$. For example, P is approximately 10% (the precise value is 9.52) for $T=500$ years and $t=50$ years; $P \sim 5\%$ (the precise value is 4.88) when $T=1000$ years and $t=50$ years.

The map of the calculated intensity I_T (the seismic hazard map) is calculated from the long–range characteristics of seismicity in a region with the use of the regional dependence of intensity on magnitude and distance for an extended source.

1. Long–range Characteristics of Seismicity in a Region

The information on the long–term characteristics of seismicity is prepared in a special format, which permits to fixing the solution of experts (seismologists, geologists and so on), that determines (together with the attenuation model) the zoning map. As a rule, an expert's estimation is based on instrumental and historical catalogues of earthquakes, empirical recurrence graphs $\lg N(M)$; on geological data on the recurrence and maximum strength of earthquakes (primarily, the data on seismodislocations); on structural data (geology, tectonics and so on); on information relevant to regions–analogs. This list is not exhaustive, it can be extended for some regions.

A special format for the data on long–term seismicity involves dividing a territory (the areas, for which the GSZ map is to be compiled, and its borderbelt) into parts termed, here, conventionally–homogeneous zones. In choosing the boundaries of the zones, two factors are considered: homogeneity (given its seismic properties, the zone can be considered approximately homogeneous on the basis of geological, seismogeological and other data) and the lack of detailed knowledge (there are no well–grounded data to divide zone into parts with different seismicity properties). The density of epicentres is assumed to be uniform within the limits of the zone, and the distribution of events over depth and magnitude is considered similar over its area.

Here, by a " zone" we mean various seismogenerating structures: these include an areal zone —a " domain" (a polygon in map view), or a linear structure (a fault), or an inclined layer (such as a focal zone, for example, like the Pacific ocean focal zone).

For each zone we specify its boundary (geographic coordinates of the vertices of a polygon, or a linear fault, or of an inclined layer), the earthquake recurrence graph, the depths of the seismoactive layer, the information on the properties of extended sources (the orientation: the strike azimuth and the dip angle of a source).

The earthquake recurrence graph is constructed taking into account all the available information, both seismological (paleo–, historical and instrumental) and geological–tectonical. Here, the graph is not assumed to be linear, when it is extrapolated into the area of the maximum possible earthquake.

It is important that the zone determines the distribution of epicentres rather than of the extended sources themselves. Large sources can " penetrate" the boundaries of the zone. More precisely, each segment of the boundary of a zone should be specified as " penetrable" or " nonpenetrable" for each magnitude value.

Generally, the zones do not overlap in map view. The exception is the case when jne needs to represent complicated vertical structure of sesmisity. In sach a case, the zones located at different depths.

The most important difference between the proposed and traditional approaches is that the long–term and observed earthquake recurrence values are no longer automatically equal. It is up to the experts to construct the long–term graph lg$N(M)$ from the empirical data. Here, the factors should be taken into account of overstating the level (the contribution of aftershocks of large earthquakes) and of its underestimation (the short time of comprehensive observations and restricted data during a period of low seismicity). But it is most important to take into account the probable nonlinearity of the lg$N(M)$ graph around the $M_{\max}$ value. As a zero approximation one can introduce a fixed raising coefficient, which takes into account the expected difference between Gutenberg–Richter and characteristic–event types of recurrence graph.

The approach involving separate treatement of the observed and long–term recurrence allows us to calculate several versions of the I_T maps from identical initial seismological data and thus provides a clear basis for expert estimations aimed at definition of the official zoning map. Ideally, all the expert decisions should be made just at the stage of estimation of the long–range seismicity. An "expert" correction of the final I_T map itself is, in essence, meaningless.

2. The Intensity–Magnitude–Distance Relationship

The intensity–magnitude–distance relationship — $I(M, r)$ is modeled from the empirical data in a region. To approximate these data and to predict the intensity, the model of such a relationship is used that assumes the idea of an incoherent extended source [Gusev, 1984] in the form of a radiating rectangle with its long side parallel to the day surface. The source is characterized by the moment magnitude. The length and width of the rectangle and their relationship depend on the magnitude and the stress drop. The hypothesis of geometric and dynamic similarity of sources is applied for prediction of the parameters of the rectangular area from the moment magnitude; deviation from this hypothesis is also modeled: the scatter of stresdrop is modeled as a random value and the length–width relationship as a deterministic function of magnitude. The real scatter of intensity for a given magnitude is modeled at the point of observation on the basis of the hypothesis of a normal law for the error in the prediction of intensity according to the adopted calculation scheme. The value of the standard deviation of this law is given. The model takes into account saturation effects of the intensity near the source, the nonlinearity of the intensity–distance realationship $I(\lg r)$ and saturation of the magnitude for large M_0, i.e. the problem of overstating the intensity for small distances and the isoseismal ellipticity is modeled automatically within the near zone for the sources of large magnitudes.

As a parameter suitable for prediction of the intensity, the integral of the square of an accelerogram, or the "Arias intensity", is applied [Arias, 1970]:

$$A = \int a^2(t)\mathrm{d}t \tag{1}$$

This is a modification of the approach of F.F. Aptikaev and N.V.Shebalin [Aptikaev, Shebalin, 1988]:

$$A_{\text{ash}} = a^2 d_{50} \tag{2}$$

Here, $a(t)$ is the accelerogram, a is the maximum acceleration, d_{50} is the duration of the part of the accelerogram with amplitudes exceeding 50% of the maximum.

The relationship between intensity and physical parameters of the oscillations of ground is accepted in the following form:

$$I = C_A \lg A + \text{const} \tag{3}$$

where $C_A = 1.667$ taking into account the usual relation $d\lg a / dI = \lg 2$ and in accordance with $I = 3.33\lg(ad_{50}^{0.5})$+const [Aptikaev, Shebalin, 1988].

The idea has been used of additivity of the energy contributions of elementary radiators — the components of a source forming the field in a receiver. It is assumed that the source is a limited area, the elements of which emit high–frequency (short–period) radiation independently (incoherently). This means that the energy contributions of different elements of the area are summarized in the receiver, and that at some receiver point

$$a^2(t) = \sum_{i=1}^{N} a_i^2(t) \tag{4}$$

$$A = \sum_{i=1}^{N} A_i \tag{5}$$

where $a_i(t)$ and $A_i = \int a^2(t)\mathrm{d}t$ are the accelerogram and the contribution to A, respectively, produced by the elementary radiator number i ($i = 1, 2, 3, \cdots, N$). The elementary radiator is assumed to be small and isotropic, then

$$A_i = E_i \Phi(r_i) \tag{6}$$

where $\Phi(r_i)$ is the attenuation function of damping, r_i is the distance from the elementary radiator to the receiver, and the value of E_i is the "energy" of the elementary radiator determined as A_i for unit distance. The energy E_i is proportional to the area S_i of the elementary radiator:

$$E_i = C_S S_i \tag{7}$$

Sources are considered to be geometrically similar. The relationship of the moment magnitude and the area from ref. [Kanamori, Anderson, 1975] is the following:

$$M_w = \lg S + C_{MS} \tag{8}$$

where $C_{MS} = 4.1$ when S in km^2 and is obtained on the basis of generalization of published data [Gusev, Mel′nikova, 1990].

For a far field zone of the source the following is assumed:

$$I = C_M M_W + \text{const} \tag{9}$$

For the calibration of relations (3) and (9) a certain reference empirical value of intensity I_B is used corresponding to a certain fixed "basic" combination $(M_w, r) = (M_B, r_B)$.

The absorption of seismic energy is modeled as a function of just a distance, neither variations in the absorption over the area (volume) nor its dependence on the azimuth (anisotropy) are considered. The model of attenuation is taken in the form:

$$\Phi(r) = r^{-2n} \exp(-r / r_Q) \equiv g(r, n, r_0) \tag{10}$$

$r_Q = cQ(f_1) / 2\pi f_1$, where c is the velocity of S–waves, f_1 is an average frequency, Q is the quality factor of the medium.

A more complex version of attenuation assumes two branches:

$$\Phi(r) = \begin{cases} g(r,\ n_1,\ r_{Q1}) & \text{for } r < r_c \\ g(r,\ n_2,\ r_{Q2}) & \text{for } r > r_c \end{cases} \tag{11}$$

As a result, the main formula for calculating the intensity I at a point at a distance r from the centre of the rectangular source involving N elementary emitters has the form:

$$I = I_B + C_M (M_w - M_{wB}) + C_A \left\{ \lg\left[(1/N) \sum_i^N \Phi(r_i) \right] - \lg\left[(1/N_B) \sum_j^N \Phi(r_{jB}) \right] \right\} \tag{12}$$

2.1. The Simulated Catalogue

The simulated earthquake catalogue (as proposed by [Shapira, 1983a; 1983b]) is compiled from the given long–term characteristics of seismicity in a region by (Monte–Carlo) simulation [Ventzel, 1964; Forsait, 1980]; its duration must be adequate for reliable estimation of I_T. Each event in the catalogue is characterized by moment magnitude, length, width, the azimuth of the strike and the dip angle of the source area; by the geographic coordinates and by the depth of the source center. One can treat the simulated catalogue like with the usual observed catalogue: to construct recurrence graphs, maps of the projections of the source areas onto the surface (the analog of the map of epicentres with point source), the vertical cross–sections of the focal zones and so on. Such constructions allow us to be sure that the simulated catalogue reflects well the seismicity characteristics in the region.

2.2. The Intensity of Shaking

The intensity of shaking at the nodes of the grid covering the region under investigation is calculated for each event of the model catalogue from the intensity–magnitude–distance relationship applying formula (12).

As a result of processing the complete catalogue of the net, the histogram of intensity $N(I_i)$ is accumulated each node. Here, the I axis is discretised with a bin size equal to 0.25. The values of $N(I_i)$ are accumulated for each bin:

$$I_i = 3.125 + (i - 1) \times 0.25; \qquad (i = 1, \cdots, 36) \tag{13}$$

Next we calculate of the cumulative histogram $N_S(I_i) = \Sigma N(I_j)$ (summing over $j \geqslant i$). Then the histogram $N_S(I_i)$ is divided by $N_p = T_{\max} / T$ (the number of periods of duration T); as a result the cumulative histogram $n_S(I_i)$ is obtained for the given time T. The intensity I_T for $n_S = 1$ is read from it. This is the intensity, the recurrence of which at a given point is once in T years.

Estimations of the accuracy of the value of I_T are also made. To do this, the histograms $n_S(I_i) - \sigma_i$ and $n_S(I) + \sigma_i$ are constructed, where $\sigma_i = \sqrt{n_S(I_i)} / N_p$ is the root–mean–square deviation of the value $n_S(I_i)$. From each of these histograms the values of I_T are also read out for $n_S(I_i)$

$\pm\sigma_i = 1$, which determine the left and the right boundaries of the interval characterizing the accuracy of calculating of the I_T value. The dimension of the interval for I_T depends on $T_{\max}/T$,. a tenfold increase of this ratio reduces the error interval by a factor of three. In our practice, the ± 0.1 accuracy of I_T value is provided by the duration of catalogue equal to $100T$.

The calculation error of the Monte–Carlo method is known to be less than the errors related to the uncertainty of the initial data. The problem of estimation of the effect of the uncertainty in the initial data on the results of the I_T calculation is, naturally, of utmost interest. But this problem has not been analysed at this stage, because it demands development and realization of the dediceted approach and technique.

From the values of I_T at the nodes of the grid obtained in a described way, the map of seismic hazard (represented by I_T value) —is prepared.

2.3. The Main New Features and Advantages of the Technique

The main new features and advantages of the technique and programs proposed and realized here, as compared to the techniques of the 60–70–ties are the following:

- the capability is developed for incorporating various information on seismicity (structurization of the seismicity field, the nonlinearity of the recurrence graph, and so on) and on sources (dimension, orientation, the relieved stress, and so on), which was formerly ignored;
- the theoretically substantiated description of the field of incoherent radiation in the vicinity of an extended source is applied, which has allowed to solve the problem of overstating the intensity in the case of small distances and to automatically model the ellipticity of isoseimals within the zone nearest to the sources of large magnitudes;
- the depth distribution of sources of finite dimensions is taking into account;
- the location of extended sources within the limits of a given zone–area is controlled, and the effects related to the location of extended sources of large magnitudes at linear structures, the lengths of which are comparable to the dimensions of these sources, are taken into account correctly;
- the resulting set of maps of seismic hazard in terms of intensity with a certain shake recurrence period allows us to make a probabilistic estimation of seismic hazard within the given territory and to provide the uniform of risk within the limits of the map with the recurrence period given.

References

Aptikaev F.F., Shebalin N.V., 1988. Improvement of correlations between the level of macroseismic effect and dynamical parameters of the ground motion. Investigations on seismic hazard. Moscow, Nauka, pp. 98–107. (Problems of engineering seismic hazard, Issue 29).

Arias A.A., 1970. A measure of seismic intensity. In: Seismic esign for Nuclear power plants. Cambrige a.o., M.I.T. Press, pp. 433–483.

Cornell C.A., 1968. Engineering risk in seismic analysis. Bull. Seism. Am. 54, pp. 1583–1606.

Forsait Dj., Mal′kom M., Mouler K., 1980. Computer methods of mathematical calculations. Moscow, Mir, p. 280.

Gusev A.A., 1984. Descriptive statistical model of radiation of the earthquake source and its application to the estimation of a strong movement. Volcanology and seismology. Numb. 1, pp. 3–22.

Gusev A.A., Mel′nikova V.N., 1990. Relationships between magnitudes: average–world and for Kamchatka. Volcanology and seismology, Numb. 6, pp. 55–63.

Gusev A.A., Shumilina L.S., 1995. Certain aspects of the technique of general seismic zoning. Seismicity and seismic zoning of North Eurasia, Issues 2–3, Moscow, OIPE RAS, pp. 289–300.

Kanamori Y., Anderson D.L., 1975. Theoretical basis for some empirical relations in seismology. Bull. Seismol. Soc. Amer., 65. pp. 1073–1095.

Keilis–Borok V.I., Kronrod T.L., Molchan G.M., 1973. Algorithm for the estimation of seismic hazard. Computational seismology. Moscow, Nauka, Issue 6, pp. 21–43.

Keilis–Borok V.I., Kronrod T.L., Molchan G.M., 1980. Calculation of seismic hazard. Seismic zoning of the territory of USSR. Chapter 9, Moscow, Nauka, pp. 69–82.

Riznichenko Yu.V., 1965. From the activity of sources of earthquakes to the seismic vulnerability of the Earth′s surface. Reports of AS USSR. Physics of the Earth. Moscow, Nauka, Numb. 11, pp. 1–12.

Riznichenko Yu.V., 1966. The calculation of seismic vulnerability of the points of the Earth′s surface from earthquakes in the surrounding area. Reports of AS USSR. Physics of the Earth. Moscow, Nauka, Numb. 5, pp. 16–32.

Riznichenko Yu.V., Zakharova A.I., Seiduzova S.S., 1967. The maps of seismic vulnerability. Reports of AS USSR. Moscow, Nauka, Vol. 174, Numb. 4, pp. 830–832.

Riznichenko Yu.V., 1968. Seismic activity and seismic vulnerability. Seismic zoning of USSR. Moscow, Nauka, pp. 112–120.

Riznichenko Yu.V., 1980. Seismic regime and seismic activity. Seismic zoning of the territory of USSR. Chapter 7, Moscow, Nauka, pp. 47–58.

Ulomov V.I., 1992. Program for investigations of seismicity and seismic zoning in North Eurasia. GNTP "Global changes of environment and climate". Moscow, IPE RAS, p. 21.

Ulomov V.I., 1995. On the main aspects and recommendations for the construction of a new map of seismic zoning of the territory of Russian Federation. Seismicity and seismic zoning of North Eurasia. Issues 2–3, Moscow, OIPE RAS, pp. 9–26.

Shapira A., 1983a. Potential earthquake risk estimations by application of a simulation process. Tectonophysics, Vol. 95, Numb. 1 / 2, pp. 75–89.

Shapira A., 1983b. A probabilistic approach for evaluating earthquake risk, with application to the Afro–Eurasian junction. Vol. 91, Numb. 3 / 4 , pp. 321–334.

Ventzel E.S., 1964. Probability theory. Moscow, Nauka, p. 625.

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