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SEISMIC ZONING IN PRACTICE OF ASEISMIC CONSTRUCTION IN RUSSIA

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ABSTRACT

The new study of seismogeodynamics and seismic zonation for North Eurasia is based on the idea of a structural, dynamical and energy unity of the geophysical medium and the seismogeodynamic processes going on in it. A homogeneous seismogeological data base has been compiled for North Eurasia and a 3-D lineament-domain-focal model of earthquake source generation has been developed. A set of new General Seismic Zonation (GSZ) probability maps has been made for North Eurasia, including the Russian Federation and adjacent seismic regions.

The GSZ maps of Russia being accepted as the basis for the national Building Code. The probability of a possible exceedance of seismic intensity within 50 years shapes up as follows: 10 percent (map GSZ-A), 5 percent (GSZ-B), 1 percent (GSZ-C) and 0.5 percent (map GSZ-D). The GSZ-A map was recommended for the construction of residential, public and production buildings; the B and C-maps for the objects that should continue in service even during earthquakes and also for premises housing a large number of people; the GSZ-D map for such high-danger objects as nuclear power stations etc.

The Government has ratified the Federal Program - "Seismic safety of territory of Russia" (2002-2010). The purpose of this Program is the maximal increase of seismic safety of the population, reduction of social, economic, ecological risk in seismically dangerous areas of the Russian Federation, decrease of damages from destructive earthquakes by certification, strengthening and reconstruction of existing buildings and constructions, and also preparation of cities and other settlements, transport, power constructions, pipelines for strong earthquakes.

1. INTRODUCTION

Seismic zoning is among the most complex and extremely important problems of modern seismology. It is the foremost link in a complex chain of an estimation of seismic hazard and seismic risk. The study of seismicity and an adequate assessment of seismic hazard are important for practically all of the area of the Russian Federation, where regions of extreme seismic hazard that require the implementation of serious antiseismic measures, occupy over a third of the area of the Russia. Among these are the entire Far East, the south of Siberia and the North Caucasus. Local earthquakes in the European part of Russia also represent a certain seismic hazard. First of all, such are the Middle Urals, the land along the Volga, the Kola peninsula and adjacent areas. The basins of the Black and Caspian Seas, shelves of the Laptev Sea, the Sea of Okhotsk, Chukotka and Barents Seas which produce gas and oil are earthquake-prone areas, hence vulnerable. Long-lasting low-frequency vibrations of the Earth's surface propagating to great distances from large deep-focus earthquakes in the eastern Carpathians are capable of damaging high-cost engineering objects sensitive to such vibrations even at teleseismic distances.

Seismic hazard increases every year as economic assimilation of earthquake-prone areas is going on. It is also aggravated by uncontrolled human impact on the Earth's lithospheric shell (extraction of oil and gas, as well as of other mineral resources, construction of large hydro technical structures, burial of industrial waste and so on). Higher seismic risk is also caused by setting up atomic power plants and other ecologically hazardous facilities in earthquake-prone regions, because even insignificant earthquakes and the associated secondary damaging factors (landslides, rock falls, ground breakage and so on) can disrupt their normal operation.

As is known, the first step in decreasing the loss due to earthquakes is seismic zoning of earthquake-prone areas. It is one of the most complicated and very critical problems of modern seismology. Its scientific complexity consists, first of all, in the fact that it belongs to the category of predictions based on incomplete information, on meagre and not always successful experience and on methodological approaches that are not precisely enough defined. Therefore, each seismic zoning map formerly made for the former USSR area proved to be, to some extent, inadequate to actual natural conditions which, combined with low construction quality, has caused great material loss to the national economy and a loss of numerous human lives.

The map of General Seismic Zoning of the former USSR area (GSZ-78), in force since 1978, has also suffered the same fate (Shebalin, 1993; Ulomov, Strakhov, Giardini, 1993; Ulomov, 2000). During a relatively short period of time a series of damaging and catastrophic earthquakes occurred in the area concerned within zones whose seismic hazard was underestimated by 2-3 units of the macroseismic MSK-64 scale by this map. Among these are the Spitak (1988, Armenia) earthquake which resulted in tens of thousands of human lives, the Zaisan (1990, Kazakhstan), Racha (1991, Georgia), Susamyr (1992, Kirghizia), Khailino (1991, Koryakia, Russia) and the Neftegorsk (1995, Sakhalin, Russia) earthquakes. The Neftegorsk earthquake, when about 2000 persons were killed, resulted in total liquidation of this small town.

As our studies of 1991-1997 demonstrated, the GSZ-78 map was not actually "general", because it was prepared fragmentarily in different regions and republics of the former USSR using different techniques and on the basis of unsystematic seismological and seismogeological materials. All previous maps of seismic zoning for the former Soviet Union (1937, 1957, 1968, and 1978) were deterministic. The new studies cover the vast area of North Eurasia, including the Russian Federation, all the CIS countries, and also Estonia, Latvia, Lithuania, Romania, Transcaucasia, Central Asia, Northern Iran, Eastern Turkey, Afghanistan, Mongolia and North China. New methods were developed, and a set of three probabilistic maps of general seismic zoning - GSZ-97-A, GSZ-97-B, GSZ-97-C was prepared on the basis of the unified seismological and geological-geophysical database (Ulomov, 1994, 1997, 2000; Ulomov and Working Group, 1999). For the area of the Russian Federation the set of GSZ-97 maps was adopted as a standardizing document and included into the new edition of the national Building Code "Construction in seismic regions". It has replaced the GSZ-78 map. The GSZ-97-A map is in terms of peak ground acceleration (PGA), it has been incorporated into the world map of global seismic hazard (The Global…, 1999; Ulomov and Working Group, 1999).

Fixation of the huge file of initial and target data in a digital electronic form within the Geographical Information System is a distinct fundamental achievement of the GSZ-97 technology as compared with all previous techniques. It permits obtaining rapidly reference analytical information on all the parameters and to use the seismic hazard assessment materials for the preparation of different maps, as well as to estimating the seismic hazard and seismic risk.

2. MODEL OF EARTHQUAKE SOURCE ZONES

The identification of the zones of earthquake sources occurrence (zones of ESO) and the determination of seismicity parameters for them is the most complex and crucial part in seismic zoning work, because this determines the trustworthiness of all subsequent developments. According to our approach the basis for the model of ESO zones for seismic zoning is the dynamical Lineament-Domain-Focal (LDF) model (Figure 1). The LDF model contains four scales: a major region with an integral seismicity characteristic and its three main structural elements, namely, lineaments, which roughly represent the axes of the tops of 3-D earthquake-generating fault features and structured seismicity, and which form the backbone of the LDF model; domains, which cover the area without gaps and are characterized by diffuse seismicity; potential earthquake sources indicating the most dangerous segments and which are generally confined to lineaments.

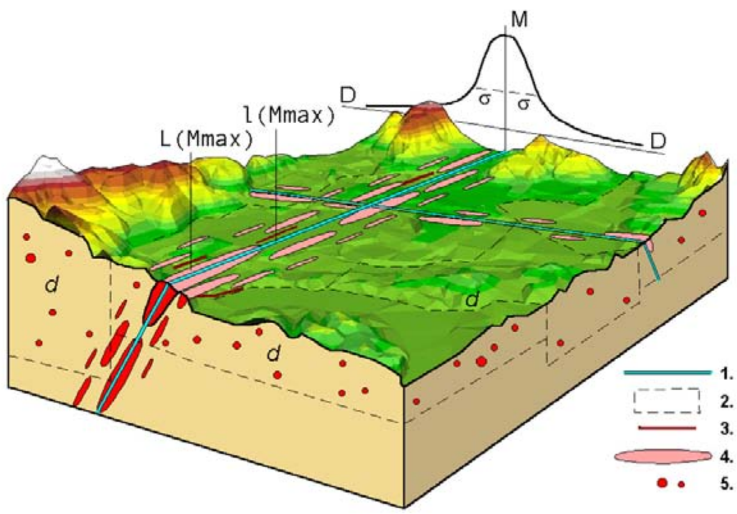

Figure 1. *Illustration of the LDF model of ESO zones:*
1 - axial planes of lineament structures; 2 - contours of three-dimensional domains; 3 - active faults, giving a fragmentary picture of lineament extension; 4 - earthquake sources with magnitude of M=7.0 and higher, deviating from the axial line of lineaments by value D inversely proportional to the M of earthquakes,
σ – standard deviation (see the plot in the background);
5 - earthquake sources of M=5.5 and lower, randomly dissipated in the domains.

The structural ESO zone elements (lineaments, domains, and potential sources) are classified by maximum possible magnitude M_{max}, as are the earthquakes, at intervals of 0.5 magnitude units. The magnitude M_{max} is assessed by all accessible and reasonable techniques: from the dimensions of interacting geoblocks, the width of zones of dynamical influence emanating from major seismogenic features, the length and segmentation of earthquake-generating faults, from archeological and historical evidence, the configuration of the frequency-magnitude relation, the extreme values in the plot of strain buildup in seismogenic features, the positions of potential earthquake sources likely to produce the maximum magnitude, and also from the dimensions of paleo-seismodislocations.

In order to identify the structures generating seismic waves and to estimate their seismic potential, it is important to use the mapping of the sources of earthquakes with various magnitudes in accordance with their size and orientation rather than the mapping of abstract “point” epicenters as is commonly done. The size and orientation of source are determined from the distribution of aftershocks, coseismal ruptures, maximum isoseismic lines, focal mechanisms, geodetic measurements, analysis of tectonic events, and so on.

Seismic lineaments (l_{Mmax}) serve as the main carcass for the LDF model of ESO zones and represent in a generalized form the axes of the upper edges of the three-dimensional and relatively clearly defined (concentrated) seismic active structures at the Earth's surface. They trace the geoblock boundaries, which are characterized by the most contrast tectonic activity. Lineaments and their segments are characterized by the magnitude of the maximum possible, within their limits, earthquake M_{max}; by their length and width due both to their tectonic nature and the errors in determining their dislocation; by the depth of bedding of the upper, h_{min}, and lower, h_{max}, edges of the plane of seismogenic structure; by the strike azimuth; by the dip angle; by the type of predominant displacements (shear-fault, overthrust, normal fault and so on).

Domains (d_{Mmax}) are volumetric areas less pronounced as far as structure is concerned or inadequately studied seismogenic zones characterized by “quasi-homogeneous” tectonics and relatively weak seismicity. They embrace layers of thickness from h_{min} to h_{max} kms. Unlike lineaments, domains do not intersect each other, and they cover all the investigated territory without breaks and superposition. An apparent intersection is characteristic of domains belonging to different depth layers, i.e. in the subduction zones and their relict on the continents.

Potential Sources of earthquakes identified by various methods (from dislocations, from the dominant distances between epicenters, by methods of pattern recognition, and so on) are, as a rule, confined to seismolineaments, and their dimensions are related to the magnitude of the maximum possible earthquakes. Potential sources have the same parameters as the respective lineaments.

According to the LDF model, as was pointed out above, each lineament that can generate earthquakes of M_{max} also includes lineaments of smaller ranks, down to $M = 6.0$ inclusive, because these also produce (with some deviations across the feature) earthquakes of lower magnitudes as well. Events of $M_{max} \leq 5.5$ generally belong to domains. Potential earthquake sources have definite magnitudes (usually $M_{max} \geq 7.0$) and most frequently occur on lineaments.

Since the actual earthquake sources do not occur strictly along lineament axes, but deviate from these in some way, it is possible to calculate the mean deviations. The lower the magnitude, the farther the sources may stray from the relevant lineament axis (see Figure 1.). According to the LDF model, the top of the associated sources reach (but do not go beyond) the top of the consolidated crust, although the earthquake sources themselves and the associated hypocenters involve a greater scatter in depth of focus, since the depth distribution of larger earthquakes is controlled by the vertical extent of the source planes.

The resulting characteristics of seismicity behavior and the scatter of earthquake sources are further used in subsequent work to model a predicted (virtual) seismicity, to calculate repeat times of intensity in seismic zoning. Disregarding for the moment the type of geodynamical fault movement (strike slip, thrust, normal faulting, etc.), it is possible to assume that in a first approximation all faults of one and the same rank in a region, accommodate the geodynamical stress and strain built up there, on an “equitable” basis. This justifies the procedure whereby seismological parameterization of the ESO zones has the rate of seismic events with respective magnitudes in the region distributed in direct proportion to lineaments length.

3. ILLUSTRATION OF THE METHODOLOGY

Figure 2 illustrates an example of the sequence of creation of LDF model and virtual seismicity map for the Caucasus and adjacent area. Lineaments are identified by cluster analysis of the space-time distribution of “chains” of earthquake sources of corresponding magnitudes, as well as from the geophysical fields (especially from their gradients; for example see Figure 2a, b, c), from palaeoseismodislocations, cosmic photographs, from the similar historic-tectonic development in the Cenozoic era (predominantly in the upper Pleistocene and Holocene), from activity in the Quaternary period, from the close values of velocity gradients of neotectonic movements and from other signs of recent and modern geodynamics.

Figure 2d shows the observed earthquake sources of different magnitudes and sizes L_M. In accordance with the new map legend, sources of earthquakes with M≥7.0 (M≥6.8) are shown as ellipsoids in “natural” sizes and orientation (Ulomov, 1974). The large L and small W axes of the ellipsoids, as well the conventional diameters L' of spheres for weaker sources:

M≥6.8: $\log L = 0.6M - 2.5$; $\log W = 0.15M + 0.42$; M≤6.7: $\log L' = 0.24M - 0.16$.

LDF model shown on the Figure 2e. Here are shown the lineaments with $M_{max} = 8.0\pm0.2$; 7.5 ± 0.2; 7.0 ± 0.2; 6.5 ± 0.2; 6.0 ± 0.2 and domains having different $M_{max} \leq 5.5$.

Figure 2f shows an example of predicted seismicity for the region obtained by computer generation of virtual earthquake sources based on a synthetic catalog generated in accordance with the LDF model in this region and with their mean long-term seismic regime.

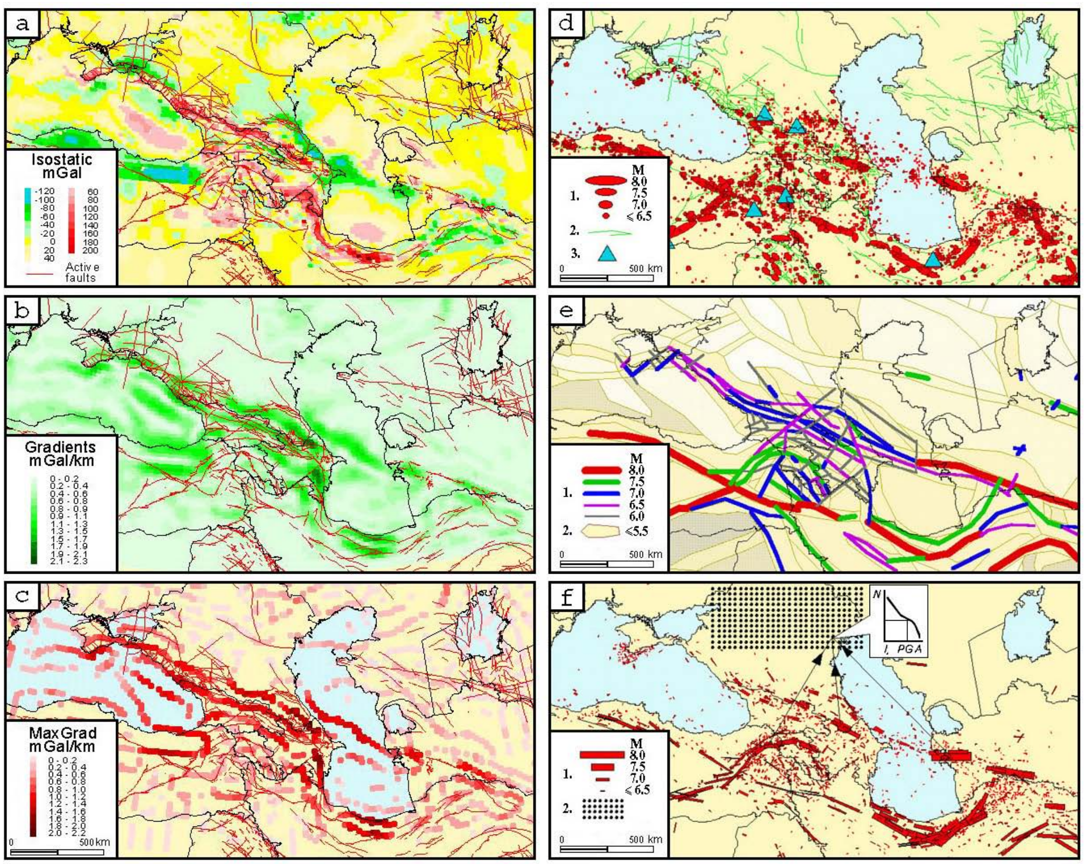

Figure 2*. Earthquake source model construction for the Caucasus and adjacent area.*
a - Isostatic gravimetric anomalies (IGA) and active faults; b - Gradients of IGA; c - Maximum of IGA Gradients; d - Observed seismicity: 1 - earthquake sources of different M, 2 - active faults, 3 - volcanoes; e - LDF model: 1 - Lineaments of different M_{max}, 2 - Domains; f - Virtual seismicity: 1 - earthquake sources of different M, 2 - grid and the scheme of seismic effect calculation.

The virtual seismicity map shows the synthesized sources as the projections of the horizontally extended rectangles onto the Earth's surface. The rectangle size is related to the magnitude of possible earthquakes (in the given case, M≥5.0). The width of the rectangles depends on the fault plane dip angle. To take into consideration the great number of statistically dependent factors, the technique is applied for Monte-Carlo calculations based on the extended in time random catalogue of earthquakes. The two maps of Figures 2d and 2f look similar, demonstrating that the LDF model of ESO is realistic.

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. The calculation of strong ground motion is carried out for each node of grid with size 25×25 km^2 (or other, depending on scale of a map and desirable detail) covering the region and adjacent area. For each node of grid ("receivers") a histogram of intensity occurrence is made, these data being the basis for subsequent mapping of earthquake hazard and related tasks (see Figure 2f).

The fragments of General Seismic Zoning maps of Northern Eurasia shown in the Figure 3d, e, f is based on the recent advances in the field of seismology and seismic zonation.

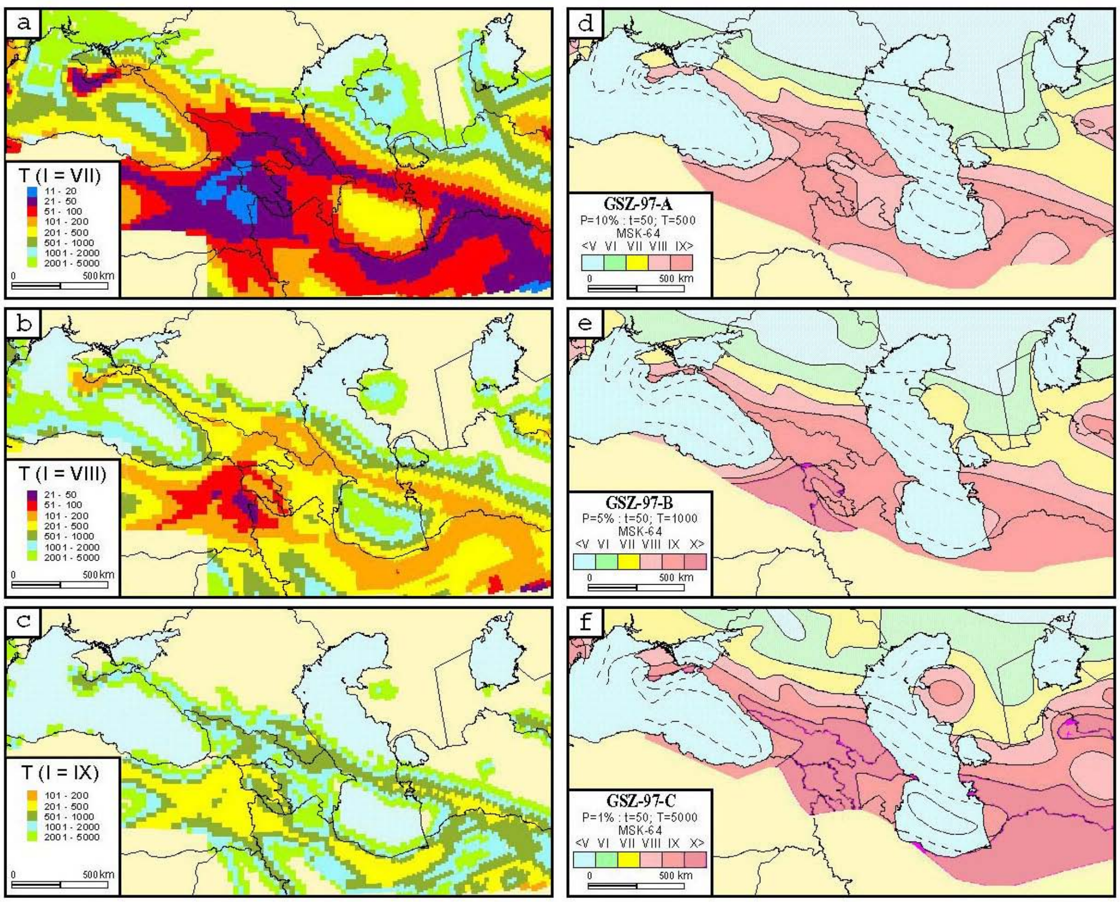

Figure 3. *Seismic hazard assessment for the Caucasus and adjacent area.*
Return periods (years) for different intensity in 25×25 km squares of the grid within the Caucasus and adjacent *area: a - recurrence of VII; b - of VIII, and c - of IX of MSK-64 seismic intensity. Fragments of GSZ maps of Northern Eurasia: d - GSZ-97-A, e - GSZ-97-B and f - GSZ-97-C maps for the region, corresponding to mean return periods T = 500, 1000, and 5000 years.*

4. SEISMIC ZONATION OF THE RUSSIAN FEDERATION

The general seismic zoning maps of the territory of Russia (Figure 4) compiled in 1991–1997 allow to assess the extent of seismic hazard for objects of various service life periods and categories of responsibility at three levels reflecting the rated intensity of jolts expected within a given area at an assigned probability during a definite time span. Thus, according to GSZ-97, the probability of a possible exceedance of earthquake intensity within 50 years shapes up as follows: 10 percent (map GSZ-97-A), 5 percent (GSZ-97-B) and 1 percent (GSZ-97-C), which corresponds to the mean periods of 500, 1,000 and 5,000 years for the recurrence of such effect. The seismic effect prognosticated by these maps is coupled to average ground conditions in keeping with the present construction standards and rules (Building Code) operating in earthquake-prone districts. The set of GSZ-97 (A, B, C) maps was endorsed by Russia's State Building Committee for use in construction throughout this country. The GSZ-97-A map was recommended for the construction of residential, public and production buildings; the other two maps (GSZ-97-B and GSZ-97-C) – for the erection of objects that should continue in service even during earthquakes and during work to eliminate their aftereffects (power and water supply, fire stations, communication facilities, transportation routes) and also for premises housing a large number of people (hospitals, schools, kindergartens, railway stations, air terminals, theaters, roofed-in markets, stadiums and like structures) and for buildings higher than 16 stories.

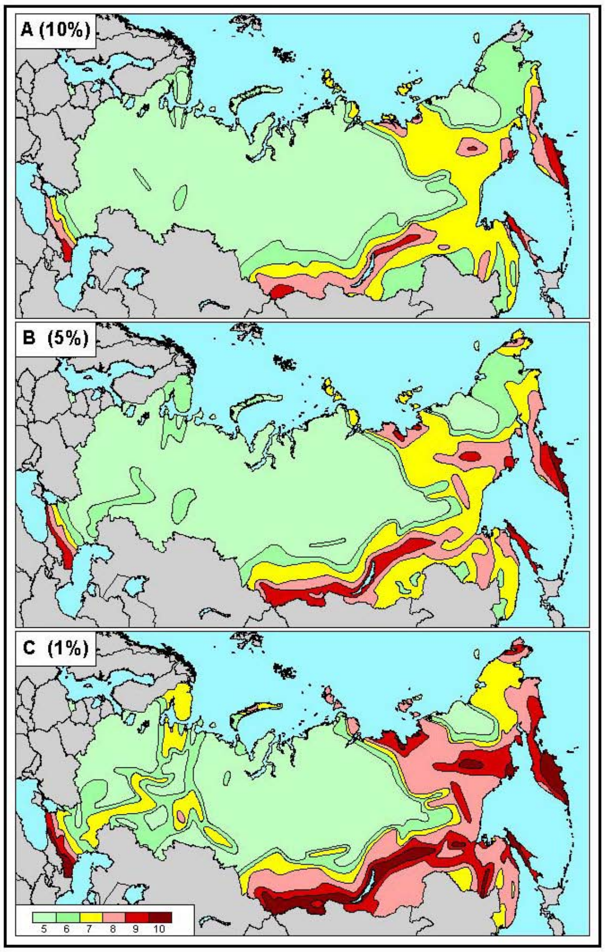

Figure 4*. The maps of General Seismic Zoning (GSZ-97) of Russia's territory recommended by the Russian Academy of Sciences and by the State Building Committee for the building industry. GSZ-97-A-map for10%, B-map for 5% and C-map for 1% probability of exceedance within 50 years.*

The GSZ-97 set is supplemented with maps indicating the recurrence periods for jolts of different intensity (see Figure 3a, b, c); this is likewise important for the practice of antiseismic construction because multiple seismic shocks may cause mechanical damages which, if accumulated, can size ably reduce the strength of structures and, consequently, affect their resistance to subsequent quakes.

5. CONCLUSION

Thus for the first time ever we have been able to do the job of seismic zoning for all of Northern Eurasia, including its level lands and shelves of its border and inland seas. We have seen that a large part of the Russian Federation's territory is subject to stronger seismic tremors than it was believed earlier. There is a 1 percent probability of VI intensity jolts occurring in half of the nation's territory within 50 years. The same probability value holds for violent and disastrous quakes of VIII–IX intensity and higher in a third of Russia's territory. Given the 10 percent risk of a possible excess of seismic intensity within 50 years (i.e. using the GSZ-97-A), the extension of such areas, even though it shrinks by about 20 percent, still remains large enough. Judging by this map, nearly 30 percent of Russia's territory can be hit by VII seismic intensity. About 10 percent of the total area is under extremely dangerous zones of VIII–IX and IX–X intensity.

Among the most seismic active regions are the Far East, southern Siberia and northern Caucasus. According to the GSZ-97-C map (the more so, the GSZ-97-D map), VI–VII intensity zones of European Russia pose a definite threat to high-risk construction projects as well; here, too, antiseismic preventive measures are imperative. Such zones cover the Middle Urals and adjacent districts, the Azov Sea and the Volga areas, the Kola Peninsula and contiguous territories. Besides, the locally induced seismic activation in the oil-mining districts of Tatarstan and in the ore-mining and processing enterprises of the Perm Region in the Urals can also cause some damage to the national economy. Next, the long low-frequency tremors of IV–V intensity, which propagate over vast distances from the deep seated foci of major earthquakes in the eastern Carpathians, are capable of damaging high-rise structures even at a very great distance from the epicenters, as far as the Moscow Region. There is a heightened risk of atomic power stations and other nuclear objects built in seismically active districts – even minor tremors can interfere with their normal operation.

The problem of providing seismic safety is thus a complex one, demanding interdepartmental solutions and coordination, the estimation and forecast of, not only direct, but also of consequential loss implementation of a great number of multi-level tasks. In this context, the Government of the Russian Federation has approved the Federal Program “Seismic safety of the Russian area” (2002 - 2010). The GSZ-97 maps are its basis. The goals of the program are as follows: enhancement of the seismic safety of population, reduction of the social, economic and ecologic risk in the earthquake-prone regions of the country. Providing earthquake resistance for existing buildings also belongs to the priority goals together with the realization and introduction into practice of advanced methods and technical facilities creating a legal basis for the provision of seismic safety of population.

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