Assessment of seismic hazard of the territory of modern city (in example of Vladikavkaz)

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\textbf{ABSTRACT}

The new complex method of seismic hazard assessment that resulted in creation of the probabilistic maps of seismic microzonation is presented. To study seismicity and analyze seismic hazard of the territory the following databases are formed: macroseismic, seismologic databases and the database of possible seismic source zones (or potential seismic sources - PSS) as well. Using modern methods (over-regional method of IPE RAS - Russia) and computer programs (SEISRisk-3 – USA) in GIS technologies there were designed some probabilistic maps of seismic hazard for the Republic North Ossetia-Alania in intensity units (MSK-64) at a scale of 1:200 000 with exceedance probability being of 1\%, 2\%, 5\%, 10\% for a period of 50 years, which corresponds to recurrence period of 5000, 2500, 1000, 500 years. Moreover, first the probabilistic maps of seismic hazard were made in acceleration units for the territory of Russia. The map of 5\% probability is likely to be used for the large scale building, i.e. the major type of constructions, whereas the map of 2\% probability should be used for high responsibility construction only. The approach based on physical mechanisms of the source is supposed to design the synthesized accelerograms generated using real seismic records interpretation.

For each of the zoning subject the probabilistic map of the seismic microzonation with location of different calculated intensity (7, 8, 9, 9\*) zones is developed (the zones, composed by clay soils of fluid consistency, which can be characterized by liquefaction at quite strong influences, are marked by the index 9\*). The maps in accelerations units show the similar results.

The complex approach based on the latest achievements in engineering seismology, can significantly increase the adequacy or foundation for assessments and reduce the inaccuracy in earthquake engineering and construction.

Realization of investigations on mapping of seismic hazards such as detailed seismic zoning (DSZ) based on the most advanced field research methods and analysis of every subject of the Northern Caucasus separately on a scale of 1:200 000 gives the possibility to merge a bit unavailable, at first glance, schemes into geologically and geophysically quite reasonable map of DSZ for the Northern Caucasus with equal scale system of the source zones.

Special attention is also paid to possible earthquake consequences on the territory of the modern city, including geocological aspects, i.e. destructions of mining tailings and consequent pollutions.

\textbf{Seismic sources of the territory}

As a rule, today probabilistic assessment of seismic hazard is used all over the world for the identification of seismic loads for the engineering projects. The probabilistic approach is a more systematized method for the assessment of quantity, sizes and location of future earthquakes [1-4] than any other methods. Formal procedures for the probabilistic assessment include the determinations of spatio-temporal ambiguities for the expected (future) earthquakes. The computer
program EQRISK of McGuire became the main stage in the method development [5]. The program became widespread and is very popular up to present day. In this connection the probabilistic assessment of seismic hazard is often called Cornell McGuire’s method. The program includes integration on ambiguities distribution.

The Caucasian region is characterized by high intensity of dynamic geological processes [6] and hazards, connected with them, of both natural and man-caused character. The most clearly expressed among these hazards is seismicity, which is accompanied with wide range of secondary processes. Earth surface ruptures, activation of known earlier inactive faults, landslip phenomenon, collapses, avalanches, creep and subsidence of the earth surface, activation of surface structures, soil liquefaction and other hazardous phenomena can be noted among them.

The investigations on determination and parameterization of the seismic source zones in recent decades has been realized by V.P.Solonenko, V.S.Khromovskikh, E.A.Rogozhin, V.I.Ulomov, V.G.Trifonov, I.P.Gamkrelidze and others [7-17].

On basis of the results of the active faults study located southward of the Great Caucasian ridge, parameters of seismic source zones were chosen according to data of I.P.Gamkrelidze work [16] and to the north of the ridge they were chosen on data of E.A.Rogozhin and others (Rogozhin et al., 1995–2002). According to the results of the executed expert evaluation of seismic potential ($M_{max}$) the maps of seismic sources zoning of the territory of RNO-A (zones of possible seismic sources - PSS zones) were made up.

A new original method of more accurate ascertainment of the boundaries of seismogenic source (fault) active part and assessment of the potential of seismic source hazard has been worked out in recent years [18]. PSS zones are referred to the active fault systems, singled out on a basis of interpretation of the materials of remote sensing and geological data. Decoding of multispectral three-channel space images of Landsat–4/5 (resolution 30 m) and Landsat–7 (resolution 15 m) was realized. Extensive lineaments systems were identified with known faults, which were qualified on modern stage as active. The name of PSS zones was formulated on basis of faults and large settlements names. Morpho-kinematics of active faults is the base for qualification of seismic displacements kinematics in PSS zones. Hypocenters depth of expected earthquakes was calculated from the depth of fault plans, the depth on geophysical anomalies data and from the magnitude of expected events. Maximum magnitude of expected earthquakes (seismic potential, $M_{max}$) was assessed on the results of usage of the over-regional seismotectonic method of seismic hazard assessment, offered by G.I.Reisner. Usage of this method, foundation of which are described in the number of publications [19, 20], showed that the Northern Caucasus is the region of very high seismic hazard. In 2007 it was determined on data of field investigations that for the urbanized territories of RNO-A the most hazardous are Vladikavkaz, Mozdok, Sunzha and Tersk PSS zones (table 1), (Fig.1) [21, 22, 18].
Parameterization of seismic sources was made after creation of these maps, i.e. maximum possible magnitude $M_{\text{max}}$ for each seismic source was assessed. This is the most difficult problem in the process of parameterization of PSS zones. $M_{\text{max}}$ was determined on the data of number authors [14, 23, 18].

The second essential parameter, which characterizes expected earthquakes, is sources depth range, where the majority of seismic events with corresponding magnitude generate. According to the numerous investigations, Caucasus is the region with upper crust part location of seismic sources – their depth doesn’t exceed 20–25 km (deeper seismicity is observed in Tersk-Sunzha zone in the area of Grozniy city and in Caspian Sea). As sources distribution on depth for this region wasn’t executed, average value of depth (equal to 10 km) was taken for calculations (see Table 1).

Table 1

<table>
<thead>
<tr>
<th>№</th>
<th>PSS zone</th>
<th>Magnitude</th>
<th>H, km</th>
<th>Kinematics.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mozdok eastern</td>
<td>5.0</td>
<td>10</td>
<td>reverse faulting</td>
</tr>
<tr>
<td>1a</td>
<td>Mozdok western</td>
<td>4.0</td>
<td>5</td>
<td>strike-slip</td>
</tr>
<tr>
<td>2</td>
<td>Tersk</td>
<td>4.5</td>
<td>5</td>
<td>reverse faulting</td>
</tr>
<tr>
<td>3</td>
<td>Sunzha northern</td>
<td>6.1</td>
<td>15</td>
<td>reverse faulting</td>
</tr>
<tr>
<td>4</td>
<td>Sunzha southern (western branch)</td>
<td>6.5</td>
<td>15</td>
<td>strike-slip</td>
</tr>
<tr>
<td>4a</td>
<td>Sunzha southern (eastern branch)</td>
<td>6.1</td>
<td>15</td>
<td>reverse faulting</td>
</tr>
<tr>
<td>5</td>
<td>Vladikavkaz (western branch)</td>
<td>6.5</td>
<td>15</td>
<td>reverse faulting</td>
</tr>
<tr>
<td>5a</td>
<td>Vladikavkaz (eastern branch)</td>
<td>7.1</td>
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<tr>
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<td>Nalchik</td>
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<td>10</td>
<td>strike-slip</td>
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<tr>
<td>7</td>
<td>Mizur</td>
<td>6.2</td>
<td>15</td>
<td>strike-slip</td>
</tr>
<tr>
<td>8</td>
<td>Main ridge</td>
<td>6.2</td>
<td>15</td>
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</tr>
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<td>Side ridge</td>
<td>6.3</td>
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</tr>
<tr>
<td>10</td>
<td>Karmadon</td>
<td>6.5</td>
<td>15</td>
<td>reverse faulting</td>
</tr>
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</table>

**Seismicity of the territory**

For the assessment of ratio parameters between reiterations during the process of execution of a number of investigations on the international projects the earthquake catalogue was checked and specified. The seismicity in each source zone was analyzed on basis of catalogue usage: New Catalogue… 1982, Corrected Catalogue of Caucasus, Institute of Geophysics Ac. Sci. Georgia (in data base of IG), the Special Catalogue of Earthquakes for GSHAP test area Caucasus (SCETAC), 4-84

Corrected Catalogue of Caucasus contains data for more than 61000 of earthquakes, including 300 historical events [24, 25, 26 and 27], which happened during 2000 years. This catalogue was checked and corrected. Some hypocentral parameters of earthquakes were recalculated.

Threshold of magnitude for the whole catalogue and a and b values of the reiteration law were determined for large tectonic zones, as their calculation for certain PSS zones was impossible because of data absence. Value of b of the reiteration law is determined by formula of Gutenberg-Richter. For each PSS zone (both linear and square) frequency of earthquake origination was referred to the separate faults or PSS zones taking into account accuracy in epicenter determination.

Because of the shortage of data about accuracy of location determination average model was accepted. This model supposes that mistakes have normal distribution with standard deviation equal to 3–4 km.

**Design of seismic hazard maps**

Earthquake effect was assessed on basis of two different parameters usage: macroseismic intensity and peak ground acceleration (PGA). Macrosiesmic intensity (MSK-64 scale) traditionally was used for the seismic zoning in USSR. It is shown in the paper [28], that macrosiesmic field parameters, which are determined in the catalogue of strong earthquakes, give average values, which describe macroseismic field for moderate earthquakes and far from the epicenter well. In the above mentioned work the parameters are determined for strong earthquakes and relative close distances.

On the other hand, instrumental data of strong motions on Caucasus and neighboring regions allows using PGA and spectral law of acceleration attenuation for the analysis of seismic hazard. In recent years PGA is used actively for seismic hazard assessment of the whole Caucasus (Project ISTC 2006) [29], certain countries [30; 31 and 32], cities and regions [32, 33 and 34].

Comparison of the attenuation correlations for peak horizontal acceleration in Caucasus with similar correlations for the other regions, in particular with models of West and North America shows a good accordance. It is obvious, that attenuation in Europe is lower than in Caucasus and neighboring region. Predicted peak values in near zone are higher than corresponding values, obtained with the help of the other European models [35].

The maps of seismic hazard, which determine exceedance probability of fixed value of impacts during different exposition time, were made up for the territory of RNO-A in the form of set of maps for macroseismic intensity at return period of 50 years with exceedance probability 2%, 5% and 10% in scale 1:200 000 (fig. 2).

Computer program SEISRISK III, developed in 1987 by Bender and Perkins [36] was used for the calculations. The map of observed maximum intensity was compared with the maps of different periods of exposition and the most real map was chosen on a basis of the analysis of differences between the observed and calculated maps. According to these criteria the map of 5% probability with exceedance probability of 50 years can be recommended for seismic zoning of the territory of RNO-A.

The analysis of maps shows that main seismic hazard is connected with the faults or PSS zones, which are close to Vladikavkaz city (Fig.1 and Fig. 2).

The scientists from Vladikavkaz in collaboration with the colleagues from the Institute of Physics of the Earth of RAS not only offer to use large-scale maps but also decided to continue investigations and cover the whole Northern Caucasus in scale 1:200000. So, maps of seismic
hazard can be made up in scale 1:200 000 for the Republics of Chechnya, Ingushetia, Kabardino-Balkaria, Stavropol and Krasnodar areas and the other territories. Taking into account, that faults and other peculiarities of the territory exist out of any boundaries, including state boundaries, it is possible to make unusual but quite physically proved single general map of detailed seismic zoning of the territory of Northern Caucasus in scale 1:200000, moreover, one can make them for different exposition times and accordingly for different probabilities. So, created maps of detailed seismic zoning of RNO-A conform to earthquake realization once in 500 years, 5% - in 1000 years and 2% - in 2500 years. The level of seismic hazard grows with the time increase etc. Essentially, the long-term maps of expected intensities locations are that of described maps of detailed seismic zoning. Indeed, that evacuate people from the hazardous territory before expected earthquake is impossible, but it is real to prevent population burring under destroyed or, to be more precise, differently damaged buildings, which is formed on basis of such maps. The more educated society is the less seismic risk, i.e. economic and social losses. So, the priorities are clear.

On basis of the given maps it is necessary to make up the maps of seismic microzonation(SMZ) of cities and large settlements of each certain subject of the Federation with the usage of the most modern standard methods and tools, but in scale 1:10 000. The probabilistic maps of SMZ were first developed in the Center of Geophysical Investigations of Vladikavkaz Scientific Center RAS and RNO-A. Such maps of SMZ are direct and reliable base of earthquake-proof design and object construction.

![Fig. 2. Probabilistic map of seismic hazard (DSZ) in the intensities (MSK-64) with the exceedance probability 5% (a) и 2% (b) for RNO-A territory and adjacent areas (Zaalishvili, 2006).](image)

Created on the above mentioned methodology set of the maps allow to provide equal degree of risk within the territory, covered by each of these maps and is intended for earthquake-proof construction and measures for seismic risk reduction for different categories of responsibility degree and durability [18]. We offer to use the maps of 5% probability for the mass, i.e. major construction, the maps of 2% probability for construction of objects of enhanced responsibility. At the same time, it is necessary to remember that the given maps are the essential base for SMZ and creation of corresponding maps.

Besides, it is necessary to note that at usage of the traditional units of macroseismic intensity the boundaries between different zones are characterized by sharp changes, which obviously do not correspond to the real situation of monotonous change of intensity for homogenous soil conditions of the investigated territory. No doubt, it will form evident inaccuracies at the assessment of the level of seismic hazard of this or that territory. The practical usage of artificial intensity subdivision, for example, in the form of 7.2 or 8.3 points is not validated enough from the theoretical point of
So, firstly, it is not usually explained how these fractional assessments are obtained and, secondly, the following transition to the acceleration units (obviously, according to foreign data, as there are no acceleration records for forming reliable correlation in Russia), undoubtedly, forms considerable inaccuracy and it is hardly ever physically proved because of the formality of the parameter of «intensity» itself.

On the other hand, at seismic influence assessment at earthquake-proof design engineers use the acceleration values, (strictly speaking, conveniently) corresponding to specified intensities. Thus, it’s assumed that design acceleration $a = 0.1\, \text{g}$ corresponds to the intensity 7 earthquake, $0.2\, \text{g}$ – to the intensity 8, $0.4\, \text{g}$ – to the intensity 9 etc. At the same time, network of digital stations dislocated on the Southern Caucasus installed in source zones of Spitak (Armenia, 1988), Racha (Georgia, 1991), Barisakho (Georgia, 1992), Baku (Azerbaijan, 2000), Gouban (Georgia, 1991), Tbilisi (Georgia, 2002) and other earthquakes collected seismic records for formation of database of accelerations for Caucasus. It makes possible to design maps of the seismic hazard independently in units of PGA. Such maps for the territory of RNO-A for exposition of 50 years with exceedance probability 2%, 5% and 10% in scale 1:200 000 were created (Fig. 3). It is obvious that at changing of smothering step it is possible to obtain smooth variations of accelerations directly used as design impacts.

In contrast to the maps of general seismic zoning (GSZ) with a scale of M 1: 8000000 and, at the best, with the scale M 1:2500000 obtained maps of both types on a scale 1:200000 can be referred to the DSZ type maps.

![Fig. 3. Probabilistic map of seismic hazard (DSZ) in accelerations (PGA) with exceedance probability 5% (a) and 2% (b) for RNO-A territory (Zaalishvili, 2006).](image)

Thus, these materials allow assessing seismic hazard on a detailed level, according to the known formulas to calculate the macroseismic field of seismic effects on a scale that may provide a reliable basis for SMZ.

In the next stage we should carry out SMZ. It should be noted that as a basis the maps of different probability of exceedance will be used and as the initial intensity, the value of which corresponds directly to the intensity of the sites, composed by average soils or characterized by average soil conditions and, therefore, the maps will be referred to the 7, 8 or 9 points (and similarly for acceleration). The zones, composed by clay soils of fluid consistency, which can be characterized by liquefaction at quite strong influences, are marked by the index 9*. Intensity calculation here supposes the usage of special approaches in the form of direct taking soil nonlinearity into account [37, 38]. The usage of relevant methods and techniques of SMZ will allow to obtain the correspondent maps of SMZ.

Thus for maps with probability of exceedance 2%, 5% and 10% one can obtain
corresponding maps of SMZ with probability of exceedance 2%, 5% and 10%, i.e. probabilistic maps of SMZ (Fig. 4).

Fig. 4. The maps of seismic intensity microzonation for probabilities of 5% (a) and 2% (b) for the central part of Vladikavkaz city territory (Zaalishvili et al., 2010).

Such maps of SMZ except of mentioned developments are also based on materials of local network of seismic observations “Vladikavkaz”. Network was organized for the first time on the urbanized territory of the Northern Caucasus in July 2004. Stations are located on the sites with different typical for the city soils (clays of medium-hard and liquid consistence, gravels with filling material of less than 30% and more than 30%, and their assembly).

It must be noted that usage of the maps with high time exposition i.e. maximal magnitude (maximal intensity) for given territory (for return period of 50 years and exceedance probability 2% or 1%) physical nonlinearity of soils necessarily must be taken into account with the help of developed tools [37, 38, 39].

Unlike small-scale M 1:8 000 000 seismic hazard map of the territory of Russia (GSZ) maps of DSZ in scale 1:200 000 allow taking into account features of specific seismic sources (faults) directly. But the main thing is that such scale zoning is suitable for quite large territories. So it’s seen that alignment of faults of different constituent entities of the Russian Federation of Northern Caucasus make a good sense (Fig. 5).

In recent years a new instrumental-calculate method is developed in the Center of Geophysical Investigations. Complex of mentioned developments that have no analogues and the other world achievements along with close collaboration with colleagues from various countries allowed to enlarge range of solving tasks and physical foundation of final results.
Fig. 5 The mosaic of maps of hazardous potential seismic sources on the territories of the Northern Caucasus (model of the future joint map).

**Geoecological aspects**

In addition to their direct destructive effect, an earthquake could cause an environmental catastrophe in territories where there are industrial enterprises producing or processing hazardous chemicals.

Estimation of losses from earthquakes, made by global data from the insurance company Munich Re, show that the number of events with severe consequences throughout the world during the period 1986-1995 has increased comparing with 1960s in 3.2 times and volume losses rose 15.4 times [40]. The analysis of the reasons for the increase in losses testify that this is not a random phenomenon – these are irreversible consequences of rapid population growth, industry, infrastructure, commercial and economic activity in the major cities and industrial centers located in the seismoactive regions.

The products of extraction and processing of wastes posted in cramped conditions causes environmentally the tense situation in the regions and contribute to the degradation of the natural environment [41]. Environmental capacity of mountain biosphere systems compared to lowland areas is limited, therefore, technological intervention in a mountain landscape requires a balanced approach [42].

According to seismic hazard maps of the Republic territory for the important objects, we may refer tailing dumps as such objects, located in southern part of Republic located within a 9-degrees intensity zone (Fig. 2 b).

Even at intensity of 5 degrees depending on type of underlying soils tailing dumps (mining waste) will be affected. At moderate seismic impacts the volume of tailings material that contains heavy metals and their salts, and is often watered will be deformed by elastic waves, and noticeable changed, accelerating the leaching of minerals. This will increase the amount of penetration of toxic substances into the soil, which will increase the area of contamination. Toxic substances temporary "conserved" in bottom sediments, such as of river Ardon will increase the contamination of the territory, even though most of the substances will be moved to the estuary polluting it.

It is known that even moderate earthquakes may cause large losses from so-called secondary hazards (e.g., landslides or fires) and therefore the seismic risk from earthquakes repeatedly exceeds. During strong earthquakes leaching mining waste will increase significantly, and the effects generated by such a secondary threat, can without a doubt, many times exceed the losses from primary sources.

For the assessment of pollution, the development of neoplasms among the inhabitants of the
mountainous territory (as a closely related parameter) has been studied. The morbidity was studied depending on distance from the metallurgical enterprises and the tailings dumps, located in the north-eastern part of the city. Scattering halo of heavy metals from factories is detected on an area of about 40 km², in which the metal content is much higher than the average concentration.

Special database had developed for processing and analysis of neoplasms data (Fig. 6). Generate database options included the place of residence, gender, age of the patient, the patient's body lesion localization (brain, larynx, stomach, thyroid, colon, skin, blood, lymph nodes, liver, kidney, prostate, etc), only 17 titles. The patients were divided into several groups by age 18-20, 20-29 years, 30-39 years, 40-49 years, 50-59, 60-69 years, 70 years of age or older.

We also took into account the direction of the winds rose for the influence of air flow on the spread of contaminants and their possible influence on the oncomorbidity of the population.

Figure. 6. Dialog window of cancer database of Vladikavkaz City population

Exploring the relationship of distance to sources of pollution, one can conclude that the number of cases per unit area decreases with increasing distance from the industrial sites and tailings dumps (Fig. 7).

Figure. 7. Dependence of blood diseases per unit area on the distances from industrial sites.
In addition to the specified curve was built dependency’s according to all age groups, localizations and sex. Markers were installed directly on the background contamination of territories with well-defined localizations (blood, bladder and thyroid) (Fig.8).

Figure. 8. Dependence of the lymph cancer cases number from the distance to the industrial objects per unit area.

Unlike other localization (brain) (Fig. 7) kind of curve background contamination (Fig. 8) is a classic case of the Poisson distribution.

Using generally accepted methodology for spatial limits of patient care clinics were obtained values of morbidity for different years, as well as an average over several years, which was delivered on the map (Fig. 9).

Analysis of these maps for different age groups, as well as the types of localization, leads to the conclusion that particular areas of air currents and the proximity of buildings and constructions of industrial enterprises "Electrozinc" and "Pobedit", including tailings dump form the largest negative contribution for the age group of 18-20 years. It should be noted that such impact is also most pronounced for cancer patients with well-defined localizations (blood, bladder and so on).

When sufficiently strong earthquake can occur secondary emission of harmful substances into the environment due to the collapse of tailings dump, violation of its integrity, soil contamination, groundwater, rivers and air masses that can cause a drastic increase in morbidity.
Conclusions

1. New complex method of seismic hazard assessment providing probability maps of seismic microzonation (which are the basis for earthquake-proof construction) is introduced. Undoubtedly such approach significantly increases physical validity of final results.

2. For seismicity investigation and seismic hazard analysis the next databases were created: macrosesimic, seismological, zones of possible earthquake sources. On the bases of different data analysis (seismological, geological, geophysical, etc.) set of probability maps were created for return period of 50 years and exceedance probability 2%, 5% and 10%.

3. Earthquake effect is assessed on basis of two different parameters: macroseismic intensity (MSK-64) and peak ground acceleration (PGA). Borders of zones of both units (intensity and acceleration) are in a good accordance. Map of accelerations is characterized by continuous values and make it possible to plot borders in different intervals what is impossible for traditional approach.

4. Developed set of maps allows providing equal risk level at the borders of territories of each map and intended for earthquake-proof construction and developing of actins for seismic risk reduction for different extent of responsibility and durability.

5. It is proposed to use the map of 5% probability for the mass, i.e. the main construction, and map of 2% probability for high responsibility construction.

6. For each of the probabilistic maps seismic microzonation maps with allocation of zones with different designed intensity (7, 8, 9, 9*) are developed. Similar maps in accelerations units show similar results.

7. Considered procedures on the level of possible seismic sources zones exploration, maps of detailed seismic zoning and seismic microzonation may differ from presented here.

8. Ability of realization of investigations on mapping of seismic hazards such as detailed seismic zoning (DSZ) based on the most advanced field methods of research and analysis for each of the subjects of the Northern Caucasus separately on a scale of 1:200 000 will subsequently bind together in a few achievable, at first glance, but geologically and geophysical quite reasonable one
map DSZ of entire Northern Caucasus, where equal scale source zones will be merged into a one network of source zones.

9. This will allow carrying out more purposeful work on seismic microzonation of territories (SMZ) not formally, but taking into account the peculiarities of a particular region based on the use of some most advanced SMZ methods and techniques for creating probability SMZ maps - the immediate basis of earthquake-proof design and construction.

10. The map of morbidity neoplasms of Vladikavkaz territory was built.

11. The closest correlation characteristics of airflow entering at the tailings dump and extend the scope of contamination of toxic substances on the territory of the city, observed with cancer sick to 20 years of age group and number of cancer locations for all age groups (thyroid, blood, bladder).

12. When sufficiently strong earthquake could occur a hazardous waste and substances emission in the environment which adversely affect human health and the environment as a whole.

References


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