Chapter 2

Assessment of Seismic Hazard of Territory

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Additional information is available at the end of the chapter

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1. Introduction

The new complex method of seismic hazard assessment that resulted in creation of the probabilistic maps of seismic microzonation is presented in this chapter. 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 acceleration 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 hazard such as detailed seismic zoning (DSZ) based on the most advanced field research methods and analysis of every subject of

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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.

2. Assessment of seismic hazard. General and detailed seismic zoning

The seismic hazard of some territory represents a possible potential or a level of expected hazard, caused by geological structure features, tectonic movements, geophysical fields, macroseismical catalog, engineer-geological and hydrogeological structure etc. The adequate assessment of seismic hazard, at the same time is one of the important problems of engineer seismology. Unlike short-range and middle-range earthquake forecast, the involved assessment of seismic hazard, presented as seismic zoning maps, in fact is a long-ranged forecast of the earthquake strength and place.

One can mark out three types of analysis three consecutive stages of seismic zoning:

1. general seismic zoning – GSZ or SZ, is realized in 1:5 000 000 or 1:2 500 000 scale
2. detailed seismic zoning DSZ, was originally carried out for the most studied regions of perspective construction in 1:1 000 000, 1:500 000 scale or very rarely in 1: 200 000 scale.
3. seismic microzonation – SMZ, in 1:25 000 scale or greater, contained in engineer investigation system.

The results of seismic zoning have to be the appropriate map creation GSZ, DSZ and SMZ. DSZ differs from GSZ in investigation scale. At the same time, in DSZ process may and must be studied all potential sources of possible earthquakes, which may be not taken in account, e.g. they have relatively small seismic potential during GSZ analyzing. It has to be mentioned, that in the real conditions the consequences of seismic hazard generation with that types of sources may have, if not great, but noticeably negative effect. At the same time both types of zoning are very similar, nothing to say about minuteness.

The third stage or stage of seismic hazard assessment in SMZ type has absolutely other physical meaning, in spite of similar name with GSZ and DSZ. The SMZ using allows to take into account the seismic properties of site soils, including physicomechanical and dynamical properties of soil.

The SMZ map traditionally is a normative part of Building Codes, and regularly is revised. At the same time during the map design only huge geology-geophysical zones are taken into account, which the seismicity determined.

The assessment of seismic hazard of the site is carried out using necessity and probabilistic methods. The probabilistic analysis of seismic hazard assessment includes alternative models of seismic sources, the earthquake returne periods, the seismic signal attenuation and distance dependence, and much vagueness, caused by careless information of some parameters, and by random character of seismic events. In the necessity analysis of seismic hazard assessment the vagueness is not considered, only the extreme seismic effect is estimated on the real site, using near earthquake sources with fixed magnitudes. There are many domestic and foreign algorithms and programs for this purpose.

Practically all the previous maps of seismic zoning, from the first map (1937) in the former USSR till the last but one map (1978) were necessity. They not take into account the main characteristic of seismic regime of seism active territory, although in the middle of 40th S.V. Medvedev (Medvedev, 1947) proposed to bring in seismic hazard zones internal differentiation including the strong earthquake return periods and assumed constructions durability. Then U.V. Riznichenko created algorithms and programs for seismic "shakeability" estimation (Riznichenko, 1966). But all these progressive development of domestic seismologists, like their other ideas were not brought in use. (Seismic zoning of USSR territory, 1980). At the same time these ideas were brought in use abroad, after analogous paper of Cornel K.A. (Cornell, 1968). And then western countries begun to create seismic zoning map in exceeding (or nonexceeding) probability of seismic hazard in given times intervals.

The vagueness conditions, are always presented in nature, so the necessity method in the seismic zoning is incompetent. The seismic zoning process must use only probabilistic methods. The risk is always presented, but it must be estimated and reduced to minimum. These ideas are presented in the new more progressive maps of Russia general seismic zoning - GSZ -97. For the first time in Russia was proposed to use the probability map kit GSZ -97 for different constructions (Ulomov, 1995). General map GSZ -97 is presented on fig. 1.

Wide spread usage of GSZ is caused by insufficient development of DSZ and distinct labor-intensiveness of its realization for researchers. Prof. Ulomov and his colleges use modern methods instead of ancient and out of date approach. In the same time the GSZ materials using sometime is impossible due impossibility to use more detailed information of regional and local materials including tectonical materials. The map generalization is enough for state overall planning, but is not enough for reliable estimation of real objects seismic conditions.

The process of Detailed seismic zonation is very complicated and expensive complex of geology tectonical, geophysical and seismical investigation for quantitative estimation of seismic effect in any site of perspective region (Aptikaev, 1986).

That type of investigation consists of all methods used in DSZ, but estimated quantitatively the source (background) seismic effects only on concerned site GSZ (more precisely for mean soil conditions or 2nd seismic category soils on site).

So, it is necessary to develop DSZ approach. The modern DSZ has clear and argumented content. There is huge Strong Motion Data Base with many records of soil velocity and acceleration, including South Caucasus Countries. Now, there are many modern computer programs, reliable digital velocity and acceleration registrators, now we may obtain many records of earthquakes. So, it is possible to realize DSZ purpose using reliable data. And, in spite of updating initial seismicity (UIS) for DSZ we have tye possibility to estimate site seismic hazard.

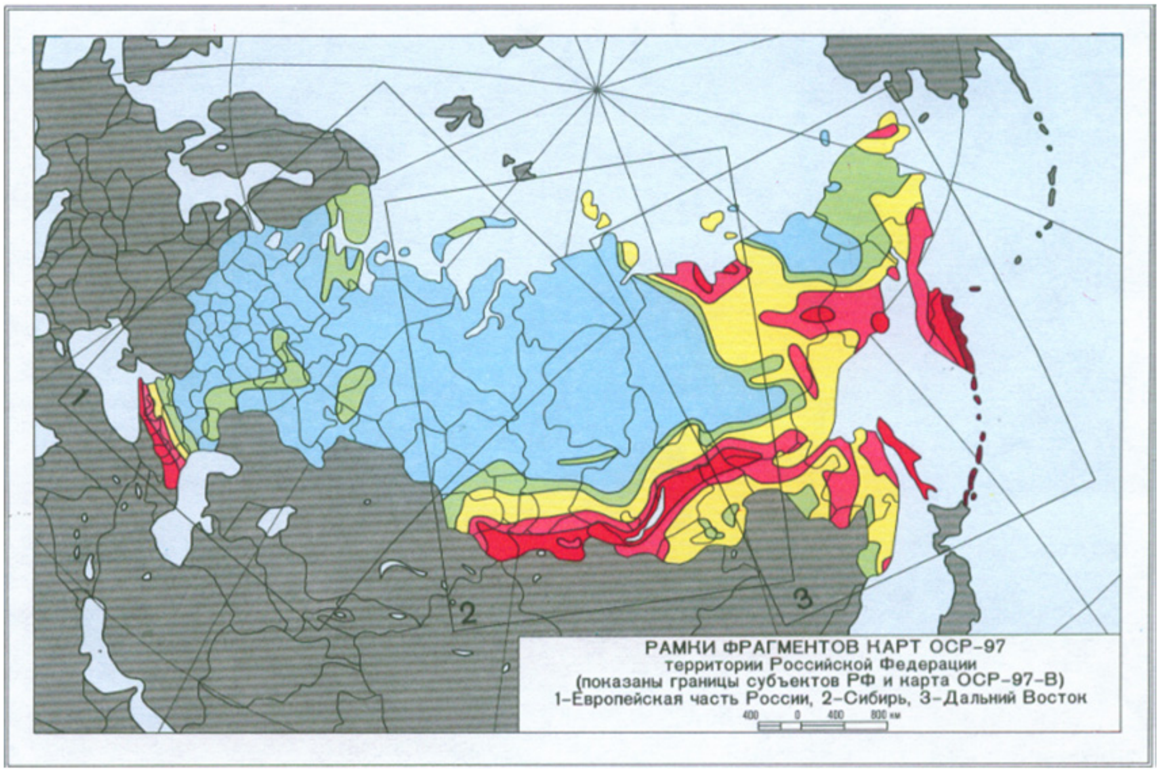


Figure 1. Map of General seismic zonation GSZ-97 of Russia

It must be told, that UIS-DSZ methodic always formed parallel with GSZ methodic, but the scale differs, and some additional methods.

There are some methods that may be used in GSZ and DSZ for seismic generic structures (SGS) identifications, it is identification of zones of danger earthquake appearance (Nesmeianov, 2004).

2.1. Seismogeological method

Using the first epicentral zone investigation in the end of XIX and beginning of XX centuries Abich G. and Lagorio A.E. find out the dependence between earthquake and tectonic structures. Mushketov I.V. writing about Vern earthquake 1887 year, told that Turkestan earthquake is connected with discontinuous disturbance (Mushketov , 1889). He wrote earthquakes "culminate on the boundary of the most huge and new disturbance" (Mushketov, 1891). Besides, he wrote that some groups of earthquakes are connected with lines, transversal to common stretch of rugosity, e.g. connected them with transversal structures in modern terminology. K.I. Bogdanovich analyzing Kebi earthquake (1911) consequences in the North Tien Shan, introduced new term – seismotectonic element, and for the first time proved the seismic shock migration inside seism active zone.

So, seismogeological method was able to connect strong earthquakes with tectonic structures. Those bonds later were named as geological seismicity criterion and were used in other methods.

2.2. Seismotectonical methods

Seismotectonical method was introduced in the end of 40th years of XX century by Gubin I.E. when investigate Garm region on the Pamirs - Tien Shan border. He connected earthquakes with discontinuous zones some tenth km wide. He wrote, that "seismogenity degree" is stable all over the zone, "seismicity degree" may be ascribed to other similar zones, "if this structures, using geological data, are connected by mutual evolution process with equal intensity". This method (Gubin seismotectonics law) says, that in a given geological medium in the active structures of the same type and size, maximum earthquakes, originate from the rock displacement along the active rupture, have equal magnitudes and sources. Seismotectonical method accents on geological seismicity criterion – the velocity of young rupture displacement.

2.3. Seismostructural method

Seismostructural method developed in the mid-50's, by V. Belousov, A. Goriachev, I. Kirillova, B. Petrushevsky, I.A. Rezanov, A.A. Sorsky, but most fully reflected in works of B. Petrushevsky. Earthquakes associated with large structural complexes-blocks allocated by using the historical-structural analysis and discontinuous joints.

Large-scale analysis blocks allowed to associate with them (and the underlying faults) varied range of depths of earthquakes (most profound on the articulation of the Pacific with Eurasian and the American continents). Picture of the strong earthquakes focuses with different three-dimensional structures of the Earth's crust was further developed in the works of G.P. Gorshkov (Gorshkov, 1984). However, this promising direction needs to be fleshed out.

2.4. Tektonophysical method

Tektonophysical method developed in the second half of the 50-ies by M.V. Gzovsky. The method connects the earthquake with the maximum tangential stresses area, which is in conjunction with the maximum gradients of average speeds of tectonic movements and breaks. The energy of the earthquake was put by M.V. Gzovsky in dependence on a number of factors. But a precise calculation is impossible because the mechanical properties of the Earth's crust and its viscosity in Maxima tangential stresses can be evaluated only in qualitative terms.

2.5. Method of allocating quasihomogeneous zones

In the late 50-ies started to be developed method of allocating quasihomogeneous zones of earthquakes for one or all geological and geophysical criteria, some of which have tectonical nature. However, these criteria have not been effective in a number of regions.

Since the choice of number and encoding parameters and their combinations are endless, equally infinite may be variants of map M_{max}. In connection with this were analysed practically all existing geologic-structural, seismic and geophysical maps for the territorial zoning using seismotectonic capacity (combined geological criteria reflecting the characteristics of the medium properties and the intensity of tectonic process), described in conventional units on a reference site. Based on mathematical patterns is forecasting of magnitude Mmax with reference site to the rest territory. Let's note the approach developed by Reisner and Ioganson, where reference sites were used in all of the zones of the planet. The analysis involved areas with variety of tectonic properties, where the seismicity criteria are mixed. Naturally, the common criteria were often not the fault criteria (thickness of the Earth crust, the heat flux density, height, isostatic gravity anomalies, the depth of the consolidated Foundation, etc.) The method later became known as the "extraregional method".

2.6. Method of seismoactive nodes

Structural refinement of earthquakes has allowed to V.M.Reiman at the turn of the 50 's and 60's to make an idea using the Central Asian material of disjunctive nodes in which the strong earthquakes concentrate or sejsmogenetic nodes. Later became actively used the term the seismically active sites. The best method was developed by E.Y. Rantsman (Rantsman , 1979), which extended the scheme to many orogenetic regions of the world. E.Y. Rantsman links with sites the earthquakes epicenters, stressing that "the earthquakes focuses can reach hundreds of miles away and go far beyond the morfostructural nodes". To classify the structures of seismicity was proposed the complex system of formalized criteria (distance from the edges of the site, type of terrain, maximum height, and area of friable deposits) and mathematical apparatus. Study of seismogenerating structures made it possible to include cross rises in the number of structures that make up the nodes (Nesmeyanov, Barkhatov, 1978).

2.7. Paleoseismological method

Paleoseismological method (V.P. Solonenko, V.S. Khromovskikh, A. Nikonov, etc.) allows using paleoseismodislocations to trace possible seismic sources zones (PSS zones) and estimate their magnitude and seismic intensity. To evaluate these parameters the seismotectonic dislocation is used. Currently, there are many formulas (public and regional), describing the statistical associations between seismodislocations (length, amplitude displacement) and seismological parameters (magnitude, the depth of the epicenter, intensity of seismic vibrations) of earthquake. To determine the occurrence frequency of earthquakes it is necessary to have a reliable assessment of the age of paleo-seismic dislocations. All possible approaches are used: geological-geomorphological, archaeological, historical data and radiocarbon dating of sediments, broken by seismodislocation and later. Dendrohronological method is used, which takes into account the changes in the growth of trees associated with earthquakes, as well as lihenometrical method of dating seismogenical samples and dedicated to its some species of lichens.

2.8. Detailed seismic zoning

As an example, the assessment of seismic hazard, let's consider some estimations on the DSZ level in the territory of North Ossetia (Zaalishvili & Rogozhin, 2011).

On the basis of an analysis of methods for identification of PSS zones was elected out of regional seismotektonic method to objectively identify the sejsmogenic sources. Despite some shortcomings, the entire method is characterized by the quantitative indicators and has strong decision-making apparatus. The method has been used by prof. E.A. Rogozhin in North Ossetia when solving various scientific tasks. In addition, using this method some similar tasks were solved not only for Russian but also overseas territories (Israel, Italy etc.) (Rogozhin, 1997, 2007; Rogozhin et al., 2001; Rogozhin et al., 2008). At the same time, this does not preclude obtaining reliable results and other known methods.

The methodology used in most probabilistic seismic hazard analysis was first defined by Cornell and as usually accepted it consists of four steps (Reiter 1990, Kramer 1996): 1. Definition of earthquake source zones (SSZ), 2. Definition of recurrence characteristics for each source, 3. Estimation of earthquake effect and 4. Determination of hazard at the site. The probabilistic hazard maps for the territory of under study was compiled and we shell describe in brief this works according to the above noted steps.

2.8.1. Definition of earthquake sources

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 (Bazzuro & Cornell, 1999; Cornell, 1968; McGuire, 1995) 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 (McGuire, 1976). 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 (McClusky et al., 2000) and hazards, connected with them, of both natural and technogenic 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 (Gamkrelidze et al., 1998; Paleoseismology of Great Caucasus, 1979; Nechaev, 1998; Rogozhin et al., 2008; Trifonov, 1999; Ulomov et al., 1999).

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 (Gamkrelidze et al., 1998) and to the north of the ridge they were chosen on data of

E.A.Rogozhin and others (Rogozhin, 1997). According to the results of the executed expert evaluation of seismic potential (Mmax) the maps of seismic sources zoning of the territory of North Ossetia (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 (at works of detailed seismic zoning – DSZ) has been worked out in recent years (Rogozhin et al., 2008).

Let's consider the process of territory seismic hazard assessment for explanation of procedure usage by the example of the Central Caucasus (the territory of the Republic of North Ossetia-Alania).

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. Decoding of space satellite photos was executed in colored multispectral variant as well as in black-and-white variant. Different variants of the image synthesis were used for the analysis of polyzonal scanner pictures. Besides, identification of the lineaments was also executed separately on channels. Combined deductive – inductive approach was used for lineaments identification: integrated structures were decoded on the base of strongly generalized images with the following zooming in for detailing and vice versa local peculiarities of tectonic and exogenous structures with the following zooming out and generalization. The method of stepwise generalization was used with quantization on the scale levels 1:25000; 1:50000; 1:100000; 1:200000; 1:300000; 1:400000; 1:500000. In the scale range 1:25000 - 1:1 500000 space photomap on basis of snapshots Landsat-7 is used and in the range 1:500000-1:2 millions – space photomap, created on basis of Landsat–4/5 snapshots.

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 is described in the number of publications (Reisner & Ioganson, 1997; Rogozhin et al., 2001), 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 North Ossetia the most hazardous are Vladikavkaz, Mozdok, Sunzha and Tersk PSS zones (table 1), (Fig.2) (Arakelyan et al., 2008; Rogozhin et al., 2008).Parameterization of seismic sources was made after creation of these maps, i.e. maximum possible magnitude M_{max} for each seismic source was assessed. This is the most difficult problem in the process of parameterization of PSS zones. M_{max} was determined on the data of a number of authors (Chelidze, 2003; Rogozhin, 2007).

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).

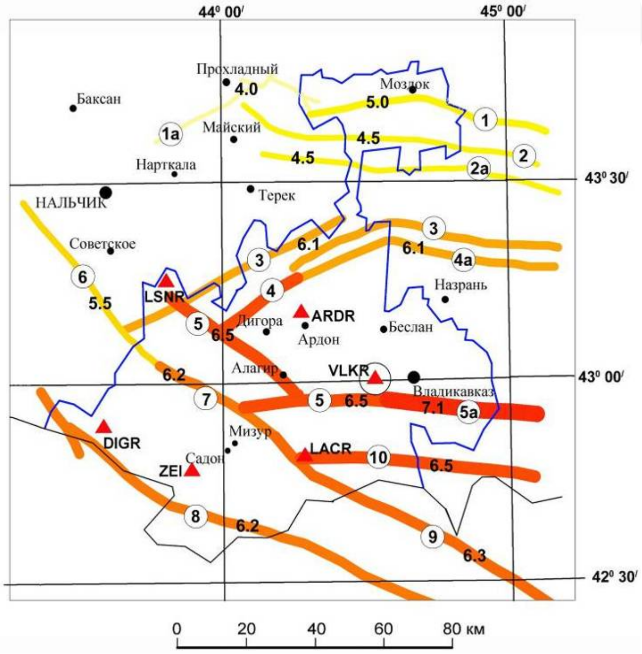


Figure 2. Map of PSS zones of the territory of the Republic North Ossetia-Alania (Rogozhin, 2007). Red triangles – basic seismic stations in the region. Blue and black lines are the state borders of North Ossetia.

№	PSS zone	Magnitude	H, km	Kinematics.
1	Mozdok eastern	5.0	10	reverse faulting
1a	Mozdok western	4.0	5	strike-slip
2	Tersk	4.5	5	reverse faulting
3	Sunzha northern	6.1	15	reverse faulting
4	Sunzha southern (western branch)	6.5	15	strike-slip
4a	Sunzha southern (eastern branch)	6.1	15	reverse faulting
5	Vladikavkaz (western branch)	6.5	15	reverse faulting
5a	Vladikavkaz (eastern branch)	7.1	20	reverse faulting
6	Nalchik	5.5	10	strike-slip
7	Mizur	6.2	15	strike-slip
8	Main ridge	6.2	15	reverse faulting
9	Side ridge	6.3	15	reverse faulting
10	Karmadon	6.5	15	reverse faulting

Table 1. PSS zones for North Ossetia characteristics (numbers in the rings on Fig.1).

2.8.2. Definition of reoccurrence characteristics

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), compiled in the frame of the Global Seismic Hazard Assessment Program (GSHAP), for the period 2000 BC - 1993, N.V. Kondorskaya (editor), (Ms>3.5) Earthquake catalogues of Northern Eurasia (for 1992-2000), Catalogue of NSSP Armenia, Special Catalogue for the Racha earthquake 1991 epicentral area (Inst. Geophysics, Georgia) and also the Catalogue of NORTH OSSETIA 2004–2006.

Corrected Catalogue of Caucasus contains data for more than 61000 of earthquakes, including 300 historical events (Byus, 1955a, 1955b, 1955c; New Catalogue of strong Earthquakes in the USSR..., 1982), 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 frequency-magnitude 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 frequency-magnitude law is determined by formula of Gutenberg-Richter:

$$\lg\left(\mathrm{N}/\mathrm{T}\right)=a-\mathrm{b}M \tag{1}$$

where a and b are parameters, the inclination and level of recurrence graph at M=0.

For each PSS zone (both linear and square) frequency of earthquake origination was studied on basis of observed seismicity. For study of Gutenberg-Richter ratio earthquakes were 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. Distances from each event to the all PSS zones were measured and only zones, which were on closer distances from the event than three standard deviations, were taken into account. Based on distances value, weighting coefficient was assigned to each zone, from the curve of density distribution of the standard deviation possibility.

2.8.3. Estimation of earthquake effect

Earthquake effect was estimated using two different parameters: macroseismic intensity and peak ground acceleration (PGA). Macroseismic intensity (MSK scale) was traditionally used for seismic zonation in former USSR. Macroseismic and instrumental data on 43 significant earthquakes occurred in Caucasus were revised to obtain the necessary information (Javakhishvili et al. 1998). Data on 37 earthquakes was selected and in some cases were compiled new isoseismal maps in the 1:500 000 scale. In a process of computations was observed a fact that the value of the attenuation coefficient in vicinity (within the limits of the first three isoseismals) of the source of the Ms>6 earthquake is very high (ν˜4.5-5.0), in comparison with small and moderate events (ν~3.4). This fact has been tested on the other Caucasian strong earthquakes (Ms>6) and in general has been confirmed. In spite of the lack of data in the first approximation the equation of correlation in this case obtains the following form for small earthquakes:

$$I = 1.5M_s - 3.4\lg(\Delta^2 + h^2)^{1/2} + 3.0 \tag{2}$$

and

$$I = 1.5M_s - 4.7\lg(\Delta^2 + h^2)^{1/2} + 4.0 \tag{3}$$

for large events.

The attenuation model according to the (2) formula is given on fig.3.

It should be noted, that for hazard estimation we have used the second relationship. Besides that we have restricted maximal value in epicentral area for M=7, (6.5) earthquakes with intensity 9, M=6 (5.5) earthquakes with intensity 8, etc. this was done to avoid very high intensities in epicentral area. The epicentral areas were estimated using relationships for earthquake source sizes given in (Ulomov 1999).

On the other hand strong motion instrumental data in Caucasus and adjacent regions allows us to use PGA and spectral acceleration attenuation law for seismic hazard analysis. Since the installation of the first digital strong-motion station in the Caucasus area 451 acceleration time histories from 269 earthquakes were recorded (Smit et al. 2000). Based on the acceleration time histories recorded between June 1990 and September 1998 with the permanent and temporary digital strong-motion network in the Caucasus and adjacent area, 84 corrected horizontal acceleration time histories and response spectra from 26 earthquakes with magnitudes between 4.0 and 7.1 were selected and compiled into a new dataset. All time histories were recorded at sites where the local geology is classified as “alluvium”. Therefore the attenuation relations derived in this study are only valid for the prediction of the ground motion at “alluvium” sites.

The calculation of the correlation coefficients and the residual root mean square was performed with the well known Joyner and Boore two step regression model. This method allows a de-coupling of the determination of the magnitude dependence from the determination of the distance dependence of the attenuation of ground motion. Using the larger horizontal component for spectra of the selected acceleration time histories, the values of coefficients were obtained for the coefficients at different frequencies. Because it is easy to obtain peak acceleration from corrected acceleration time histories, empirical attenuation models with peak ground acceleration as dependent parameter have always played an important role in different seismic hazard and earthquake engineering studies. The resulting equation for larger horizontal values of peak horizontal acceleration is:

$$\text{Log PHA} = 0.72 + 0.44\text{ M} - \log\text{R} - 0.00231 + 0.28\text{ p}, \tag{4}$$

$R = (D2 + 4.52)^{1/2}$,

where PHA is the peak horizontal acceleration in [cm/sec^2], M is the surface-wave magnitude and D is the hypocentral-distance in [km]. p is 0 for 50-percentile values and 1 for 84-percentile.

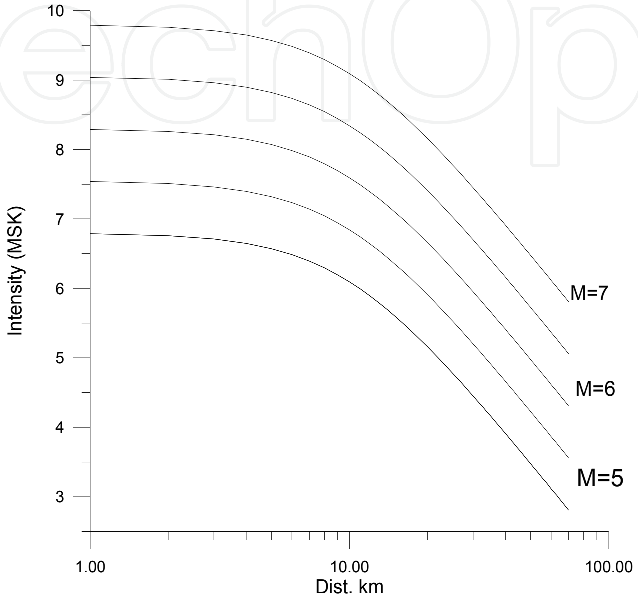


Figure 3. Attenuation model for intensity (MSK)

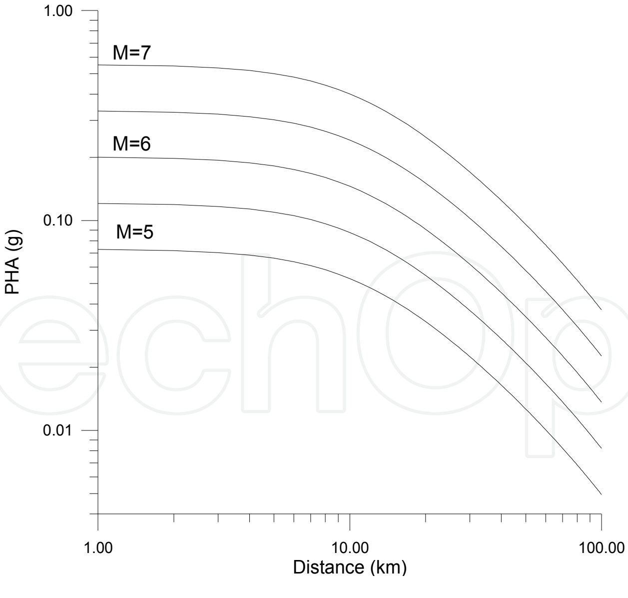


Figure 4. Attenuation model for acceleration

It is important to bear in mind that all equations given above represent a best fit of the selected dataset, and therefore represent mean values about which there is a considerable scatter. In the case of the attenuation model for the larger horizontal value of the peak horizontal acceleration the predicted mean plus one standard deviation is equal to 1.91

times the mean value. The scatter of the pha-models is the same as similar models for Europe and Western North-America (Smit et al., 2000). The attenuation is shown on fig. 4.

The comparison of the attenuation relationships for peak horizontal acceleration with similar relations for other areas shows a good agreement with the models from Western North-America. It is obvious, that the attenuation in Europe is lower compared to the Caucasus and adjacent area. The predicted peak values in the near-field are higher than the corresponding values obtained with other European models (Smit et al., 2000).

2.8.4. Determination of hazard

The probabilistic seismic hazard maps (the maps of detailed seismic zoning) have been constructed for the total area of North Ossetia in scale 1:200000 with exceedance probability for a period of 50 years (standard time of building or construction durability!) with 1%, 2%, 5%, 10% in GIS technologies, which corresponds to reoccurance of maximum probable earthquake for a period of 5000, 2500, 1000 and 500 years (Fig.5). The longer the period of time the higher the level of possible intensity. For a period of 500 years only a small part will be occupied by the zone of 7 intensity earthquake, for a period of 1000 years – 8 intensity and at 2500 years 9 intensity earthquake appearance, correspondingly.

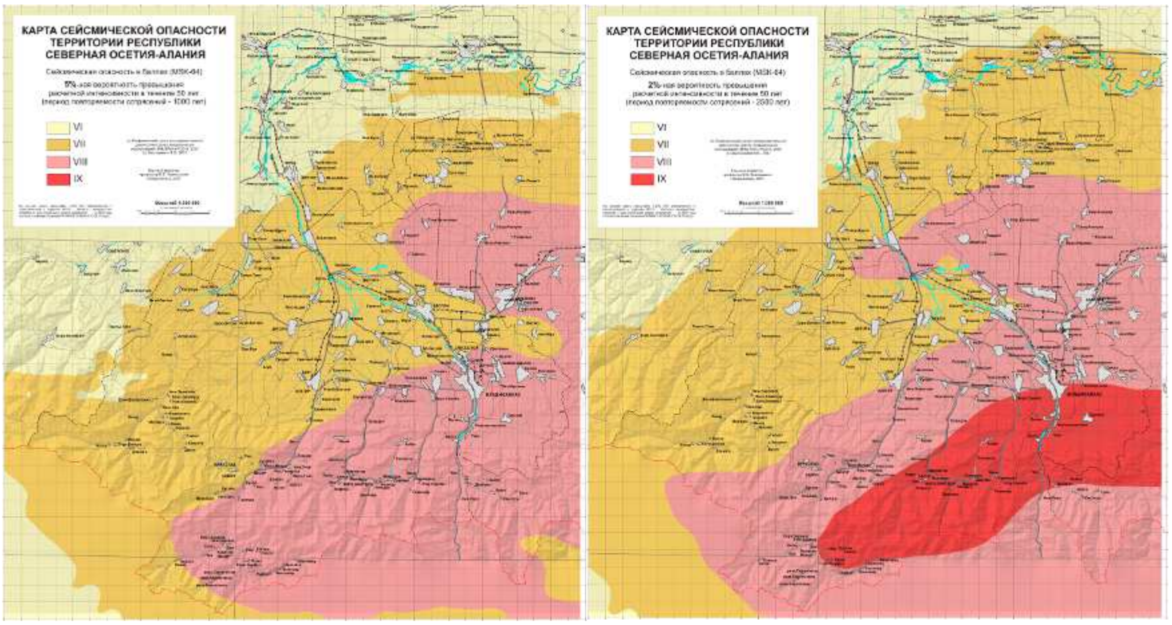
Cornell approach, namely computer program SEISRisk- 3, developed in 1987 by Bender and Perkins (Bender & Perkins, 1987) was used for the calculations. The map of observed maximum intensity was compared with the maps of different periods of exposition and the most real map was chosen on a basis of the 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 North Ossetia. Besides, for the first time probability maps of seismic hazard for Russian territory were made in acceleration units in scale 1:200 000 with exceedance probability for a period of 50 years - 1%, 2%, 5%, 10%.

According to the Musson (Musson, 1999) conception, it is necessary to use the data, which is maximum approximate to the real engineering-geological conditions, at assessments of territory seismic hazard. For the territory of North Ossetia the exposition equal to 1000 years is the most approximate to real conditions for mass building. It is necessary to consider greater exposition, for example, 2500 years etc. for unique buildings and constructions.

The maps of 5% probability are likely to be used for the large scale building, i.e. the major type of constructions, whereas the maps of 2% probability should be used for high responsibility construction only (Fig.5).

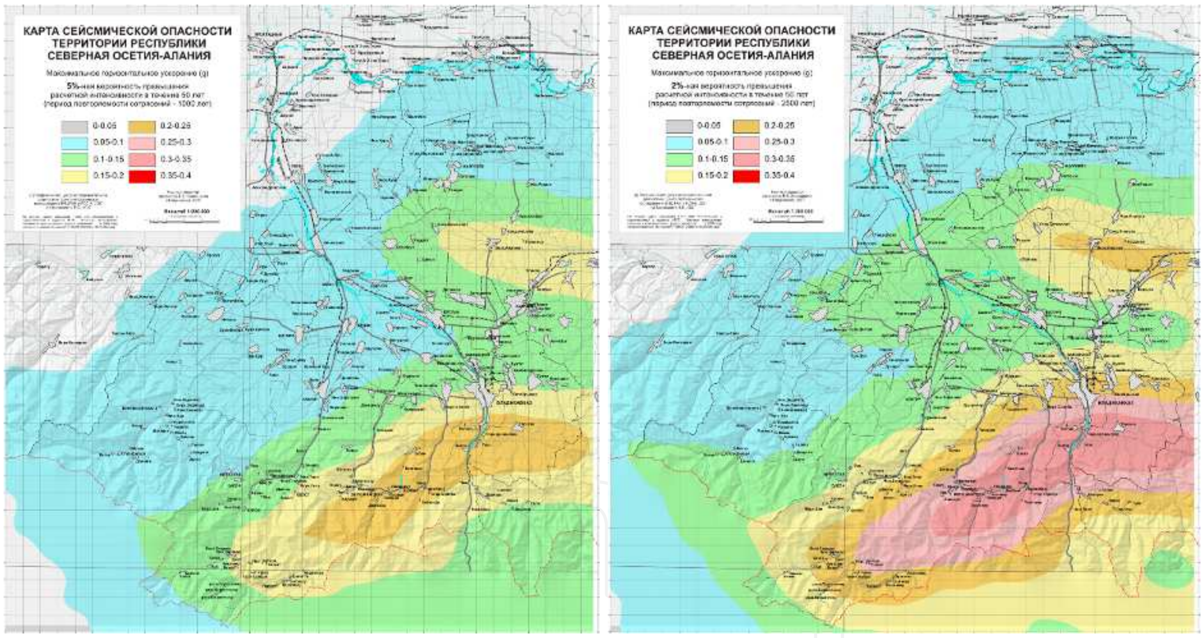
One can see great hazard in the south of North Ossetia on the map, where exists the increased level of seismic hazard (due to powerful Vladikavkaz fault, lying nearby).

As a matter of principle it is possible to make maps in scale 1:100 000 etc., but it actually makes no practical sense. Although accuracy of such maps must be higher, adequacy of the results can be considered as doubtful due to absence of reliable data on local peculiarities of past, i.e. historical earthquakes display. Laboriousness (irretrievable) at that increases multiply.



a) b)

Figure 5. Probabilistic maps of seismic hazard (DSZ) in the intensities (MSK-64) with the exceedance probability 5% (a) и 2% (b) for North Ossetia territory and adjacent areas (Zaalishvili, 2006).



a) b)

Figure 6. Probabilistic map of seismic hazard (DSZ) in accelerations (PGA)with exceedance probability 5% (a) and 2% (b) for North Ossetia territory (Zaalishvili, 2006).

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 1:200 000. 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

(Fig. 7). 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 North Ossetia 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.

It is possible to make detailed maps of seismic hazard for the whole Caucasus, including Azerbaijan, Armenia and Georgia, due to the features of spreading of hazardous seismic sources, which «neglect» states' boundaries. It is also possible to develop the maps jointly with Turkey and Iran and it's real to include such countries as Israel, Egypt, and Lebanon etc.

Maps of detailed seismic zoning can be called «long-term» prediction maps. It means that long-term prediction of hazardous phenomena is realized on their basis and, correspondingly the place of earthquake-proof building-stock is determined

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.

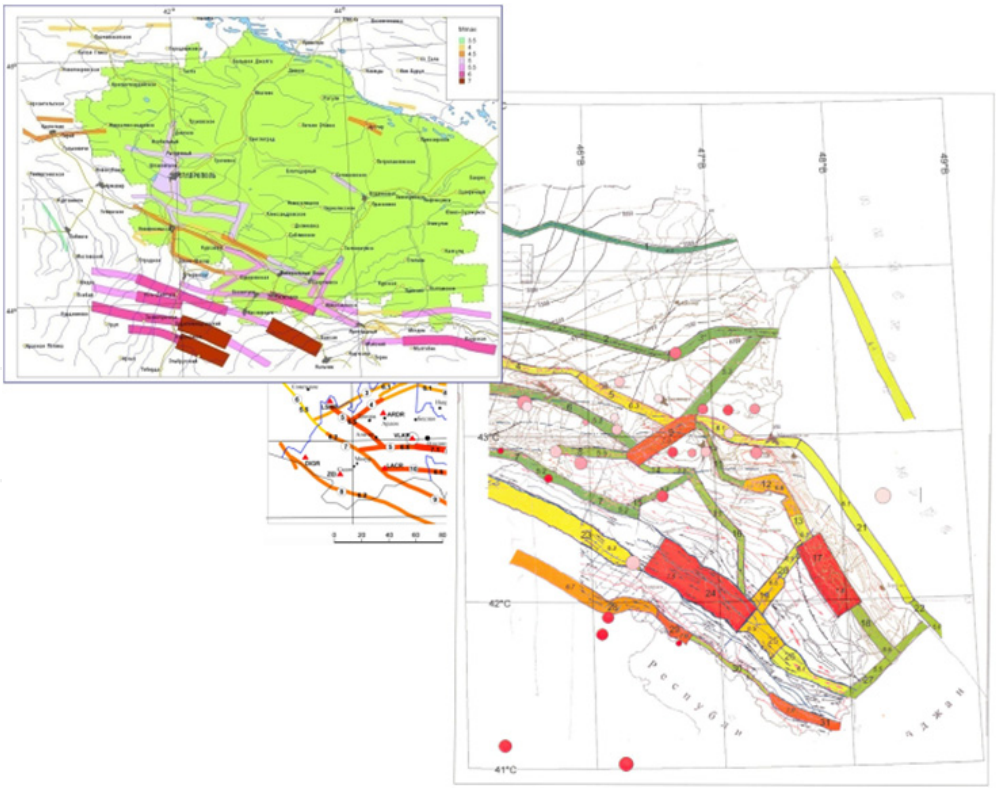


Figure 7. The mosaic of maps of hazardous potential seismic sources on the territories of the Northern Caucasus (model of the future joint map).

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 Russian 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.

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 view. 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 g corresponds to the intensity 7 earthquake, 0.2g – to the intensity 8, 0.4g – 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. Namely it makes possible to design maps of the seismic hazard independently in units of PGA. Such maps for the territory of North Ossetia for exposition of 50 years with exceedance probability 1%, 2%, 5%, 10% in scale 1:200 000 were created (Fig. 6). It is obvious that at changing of smoothering 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.

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.

3. Seismic microzonation of territory

Seismic microzonation (SMZ) actually is final stage of seismic hazard assessment. SMZ results are direct foundation for earthquake-proof construction. In the process of seismic microzonation sites with etalon ground conditions corresponding to specified seismic hazard level are specified. In Russia grounds with mean seismic properties for given territory are traditionally referred as etalon ground conditions. Usually these are soils with shear wave velocity of 250–700 m/s [SP 14.13330.2011]. In Georgia, for example, in dependence of specific engineering-geological situation etalon grounds in their seismic properties can be worst or mean for given territory. In USA firm rock grounds are referred as etalon. Seismic microzonation consists in intensity increments calculation caused by differences in ground conditions. Works on seismic microzonation are realized by instrumental and calculational methods.

3.1. Instrumental method of seismic microzonation

Instrumental method is the main SMZ method. Exactly it urges to solve a problem of forming earthquake intensity forecast. At the same time the calculation method, which allows to model any definite conditions of area and influence features, is often characterized by more reliability. It has great importance to soil thickness with high power. Combined usage of both methods significantly increases results validity.

3.1.1. Seismic microzonation on basis of strong earthquakes instrumental records

It is supposed at usage of strong earthquakes records for SMZ purposes, that at some strong seismic influence the observing soil behavior is adequate to the display of their potential seismic hazard at future strong earthquakes (Nikolaev, 1965). This fact was the reason of stimulation of a number of large international scientific-research projects on organization of long-term instrumental observations with the help of powerful measurement systems in the Earth’s different regions with high seismic activity for the purpose of obtaining the strong movements of soils, which are the base of buildings and constructions (the groups SMART-1 and SMART-2 on the Taiwan island etc.).

At the same time, presence of unit record of a real strong seismic influence at its inestimable value for SMZ often can’t give the adequate forecast of soil behavior at a next following strong earthquake. This problem can be solved by creation of a number of records of seismic influences, generated by hazardous for the zoned territory active fractures, i.e. by zones of possible earthquake source (PES).

3.1.2. Seismic microzanation with the help of weak earthquakes records

In the connection of the fact that strong earthquakes occur seldom, the intensity increments, as a rule, are assessed by records of weak earthquakes, when a linear dependence between the dynamic stress and the deformation takes place.

Soil conditions considerably change (fig. 8) the right shape of the original undistorted signal, incident from the crystal foundation. Complex shapes of isoseisms pointed out to the undoubtful link between the earthquake display intensity and soil conditions (Reiter, 1991).

Increase of the soil thickness depth (alluvium) considerably changes the character of earthquake records (Reiter, 1991) in the process of approaching the city (fig. 8).

Calculation of intensity increment with the help of weak earthquakes is realized by the formula (Medvedev, 1962; Recommendations on SMZ, 1974, 1985):

$$\Delta I = 3{,}3 \lg A_i / A_0, \tag{5}$$

where A_i, A_0 are the amplitudes of investigated and etalon soils vibrations.

The usage of tool in the form of registration of strong and weak earthquakes needs the organization of instrumental observations in a waiting mode.

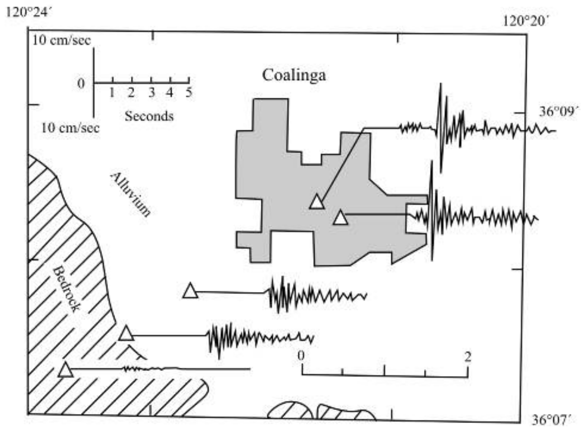


Figure 8. Scheme of California earthquake in Koaling sity

3.1.3. Seismic microzanation with the help of weak earthquakes records

In the connection of the fact that strong earthquakes occur seldom, the intensity increments, as a rule, are assessed by records of weak earthquakes, when a linear dependence between the dynamic stress and the deformation takes place.

Calculation of intensity increment with the help of weak earthquakes is realized by the formula (Medvedev, 1962, Recommendations on SMZ, 1974, 1985):

$$\Delta I = 3{,}3 \lg A_i / A_0, \tag{6}$$

where A_i, A_0 are the amplitudes of investigated and etalon soils vibrations.

The usage of tool in the form of registration of strong and weak earthquakes needs the organization of instrumental observations in a waiting mode.

3.1.4. Seismic microzonation using microseisms

The results of microseisms observations (Kanai, 1952) are used as subsidiary instrumental tool of SMZ. Predominant periods are determined at that in order to assess resonance properties of soils and amplitude level of microvibrations. Strictly speaking, the reference of microseism on their origin to the purely natural phenomena is not quite correct. Numerous artificial sources, influence degree of which can't be controlled, undoubtedly, take part in their forming along with the natural sources (fig. 8.6).

Intensity increment for strong earthquakes on microseism is calculated by the formula (Recommendations on SMZ, 1974, 1985):

$$\Delta I = 2\lg A_i / A_0, \tag{7}$$

where A_i, A_0 are the maximum amplitudes of microvibrations for investigated and etalon soils.

Impossibility of the compliance of necessary standard conditions of microseism registration and large spread in values of maximum amplitudes limit the usage of microseism for calculation of soil intensity increment. The above mentioned causes the application of microseism tool only in complex with other instrumental tools.

Spectral features for different sites are estimated by means of H/V-rations (Nakamura, 1989).

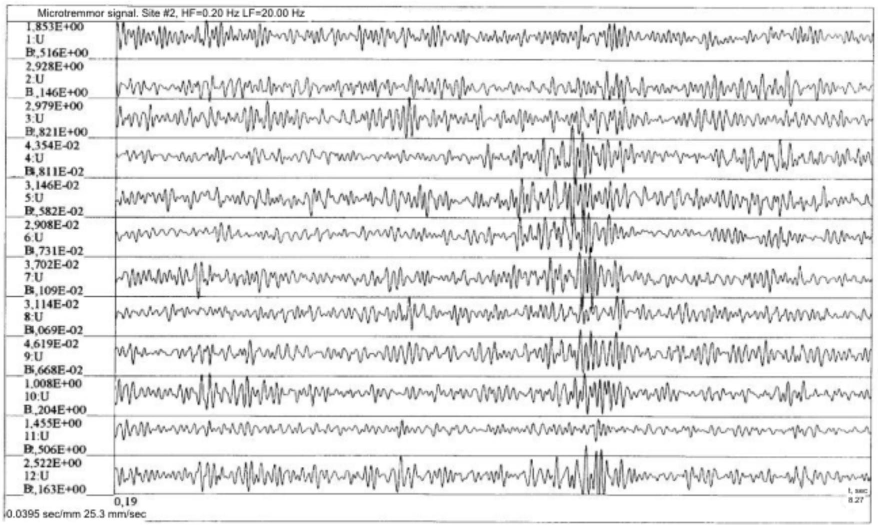


Figure 9. Microseisms records (10.07.1996, Voronezh Region, Russia)

3.1.5. Seismic microzonation using explosive impact

The intensity increment ΔI of the soils of the zoned territory is calculated by the formula (Medvedev, 1962; Recommendations on SMZ, 1974, 1985) at usage of weaker explosions:

$$\Delta I = 3{,}3\lg A_i / A_0, \tag{8}$$

where A_i, A_0 are vibrational amplitudes of the investigated and etalon soils.

Execution of powerful explosions on the territory of cities, settlements or near the responsible buildings is connected with large and often insurmountable obstacles (technical and ecological problems, safety problems, labouriousness and economical expediency) and practically isn't used nowadays. This leads to the wide spreading of nonexplosive vibration sources.

3.1.6. Seismic microzonation using nonexplosive impulse impact

The features of SMZ methods development led to the situation when the tool of elastic wave excitation with the help of low-powered sources (for example, hammer impact with m = 8–10 kilograms) has become the most wide spread in the CIS countries, in order to determine S- and P-wave propagation velocities in soils of the typical areas of territory. Velocity values are used in order to calculate the intensity increment using the tool of seismic rigidities by S.V.Medvedev (Medvedev, 1962; Recommendations on SMZ, 1974, 1985):

$$\Delta I = 1{,}67 \lg \left(\rho_0 V_0 / \rho_i V_i\right), \tag{9}$$

where $\varrho_0 V_0$ and $\varrho_i V_i$ is the product of the soil consistency and P-wave (S-wave) velocity – seismic rigidities of the etalon and the investigated soil accordingly.

The intensity increment, caused by soil watering, is calculated by the formula

$$\Delta I = K \mathrm{e}^{-0{,}04 h_{\mathrm{GL}}^2} \tag{10}$$

where K = 1 for clay and sandy soils; K = 0,5 for large-fragmental soils (with sandy-argillaceous filler not less than 30%) and strongly weathered rocks; K = 0 for large-fragmental firm soils consisting of magmatic rocks (with sandy-argillaceous filler up to 30%) and weakly weathered rocks; h_{GL} is the groundwater level.

The simplicity and immediacy of practical application of S.V.Medvedevs' tool, which is called the tool of the "intensities", led to its widespread in CIS countries and countries of Eastern Europe, Italy, USA, India, and Chile in 1970-es. The tool of the "intensities" was advantageously different from other tools by the immediacy, simplicity in initial data obtaining and its processing and independence from seismic regime of the territory. It to a certain extent hampered the development and making up of new tools. Unfortunately, the calculation results of predicted values of intensity increment are often quite incorrect as data of macroseismic observations of destructive earthquake consequences shows (Shteinberg, 1964, 1965, 1967; Poceski, 1969; Stoykovic and Mihailov, 1973).

By means of the special investigations it was determined that the reliability of calculated intensity increments considerably increases at usage of modern powerful impulsive energy sources (fig. 9).

The lowering of final results quality is to a certain extent caused by the fact that in the tool of "intensities" the seismic effect dependence in soils on frequency or "frequency discrimination" of soils (Shteinberg, 1965) and also the origin of typical "nonlinear effects" at strong movements isn't taken into account. A.B.Maksimov tried to remedy this deficiency by developing the tool, where frequency peculiarities of soils were taken into account (Maksimov, 1969):

$$\Delta I = 0.8 \lg \rho_0 V_0 f_0^2 / \rho_i V_i f_i^2 \tag{11}$$

where f_0, f_i are predominant frequencies of etalon and investigated soils.

A.B.Maksimovs' tool didn't find wide distribution, as frequency differences of soil vibrations with sharply different strength properties (at usage of traditional for the seismic exploration of small depths low-powered sources) were insignificant and the calculation results on the formulas (9) and (11) were practically similar (Zaalishvili, 1986).

Intensity increment was determined by the following formula (Zaalishvili, 1986):

$$\Delta I = 0.8\,\lg \rho_0 V_0 f_{\mathrm{wa}0}^2 \,/\, \rho_i V_i f_{\mathrm{wa}i}^2 \tag{12}$$

where f_{wa0}, f_{wai} are weight-average vibration frequencies of etalon and investigated soils.

Weight-average vibration frequency of soils was calculated at that on the formula [Zaalishvili, 1986]:

$$f_{\text{св}} = \sum A_i f_i \Big/ \sum A_i \tag{13}$$

where A_i and f_i are the amplitude and the corresponding frequency of vibration spectrum.

Figure 10. Surficial gasodinamical pulse source (SI-32)

3.1.7. Seismic microzonation using vibration impact

At usage of a vibration source (fig. 10) the calculation of intensity increment is realized with the help of the formula (Zaalishvili, 1986):

$$\Delta I = 2\lg S_i \,/\, S_0, \tag{14}$$

where S_i and S_0 are the squares of vibration spectra of investigated and etalon soils.

The developed tool was used at SMZ of the territories of cities Tbilisi, Kutaisi, Tkibuli, single areas of the Bolshoy Sochi city. The tools' feature consists in the fact that it allows to assess soil seismic hazard without any preliminary investigations: at realization of direct measurements of soil thickness response on standard (vibration or impulse) influence. Later the formula was successfully used at SMZ of the sites of Novovoronezh Nuclear power-plant (NPP) with the help of an impulsive source (Zaalishvili, 2009).

Figure 11. Vibration source (SV-10/100)

3.1.8. Seismic microzonation on basis of taking into account soil nonlinear properties

The comparison of the absorption and nonlinearity indices with the corresponding spectra of soil vibrations shows that at higher absorption the spectrum square prevails in LF field and at high nonlinearity it prevails in HF field of the spectrum. In other words, the presence of absorption is displayed in additional spreading of LF spectrum region, and the presence of nonlinearity – in spreading of HF range.

All the mentioned allowed to obtain the formula for calculation of intensity increment on basis of taking into account nonlinear – elastic soil behavior or elastic nonlinearity (at usage of vibration source) [Zaalishvili, 1996]:

$$\Delta I = 3 \lg A_i f_{wai} / A_0 f_{wa0}, \tag{15}$$

where $A_i f_{wai}$, $A_0 f_{wa0}$ is the product of spectrum amplitude on weight-average vibration frequency of investigated and etalon soils.

The formula (14) characterizes soil nonlinear–elastic behavior at the absence of absorption.

If the impulsive source is used at SMZ than the formula will have the form (Zaalishvili, 2009):

$$\Delta I = 2 \lg A_i f_{wai} / A_0 f_{wa0}. \tag{16}$$

3.1.9. Seismic microzonation on basis of taking into account soil inelastic properties

As soil liquefaction and uneven settlement of the constructions are observed at strong earthquakes (Niigata, 1966; Kobe, 1995), the most actual problem of SMZ is to assess possible soil nonelasticity adequately and physically proved at intensive seismic influences.

In order to assess directly nonelasticity of soil, the special scheme of the realization of experimental investigations (fig. 11, a) with gas-dynamic impulsive source GSK-6M (with two oscillators) was used. Selected location of the longitudinal profile allowed to influence alternately by two emitters from adjoining and somewhat far radiation zones. In the spectrum of soil vibrations, caused by near emitter, the HF component, which quickly attenuates with distance (fig. 11, b), predominates. In case of influence by distant emitter to the soil surface, the LF component predominates in the spectrum of vibrations (fig. 11, c). In other words, at nonlinear-elastic deformations the main energy is concentrated in the HF range of spectrum and at nonelastic – in the LF range. The signal spectrum has the symmetrical form in the far and practically linear-elastic zone.

Elastic linear and nonlinear vibrations are characterized for the given source by the constancy of the real spectrum square, which is the index of definite source energy value, absorbed by soil (which is deformed by the source). The analysis of strong and destructive earthquake records and also the analysis of specially carried out experimental influences showed that at nonelastic phenomena spectra square of corresponding soil vibrations is not the constant value. It can decrease and the more it decreases, the less the soil solidity and the greater the influence value (Zaalishvili, 2009).

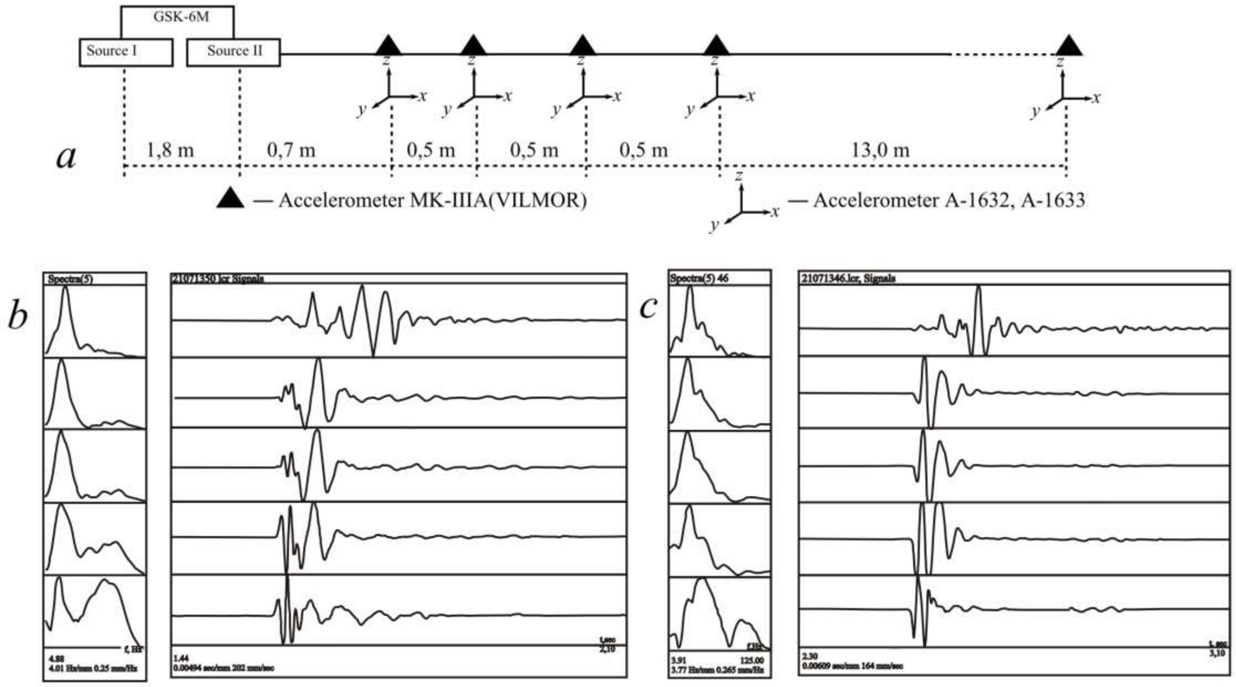


Figure 12. Investugation of site spectral features by means of GSK-6M seismic source: a) experiment scheme; b) record of second source impact; c) record of first source impact

At usage of vibratory energy source, the whole number of new formulas (Zaalishvili, 2009) in order to assess soil seismic hazard with taking into account the values of their nonelasticity were obtained:

$$\Delta I = 2{,}4 \lg [(S_{ri})_n(S_{r0})_d / (S_{ri})_d(S_{r0})_n], \qquad (17)$$

where $(S_{ri})_{n,d}$ and $(S_{r0})_{n,d}$ are the squares of real spectra of investigated and etalon soils in near and distant zones of the source.

$$\Delta I = 3{,}3 \lg (A_i f_{awi})_n (A_0 f_{aw0})_d / (A_i f_{awi})_d (A_0 f_{aw0})_n, \qquad (18)$$

where $(A_i\ f_{awi})_{n,d}$ and $(A_0\ f_{aw0})_{n,d}$ are the amplitudes and weight-average frequencies of investigated and etalon soils in near and distant zones of the source.

In case of powerful impulsive source usage the offered formulas will have a form:

$$\Delta I = 1{,}2\ [\lg\ (S_{ri})_n\ (S_{r0})_d\ /\ (S_{ri})_d\ (S_{r0})_n], \tag{19}$$

where $(S_{Pi})_{\text{бд}}$ and $(S_{P0})_{\text{бд}}$ are the squares of real spectra of investigated and etalon soils in near and distant zones of the source;

$$\Delta I = 2\ \lg\ [(A_i f_{awi})_n\ (A_0 f_{aw0})_d\ /\ (A_i f_{awi})_d\ (A_0 f_{aw0})_n], \tag{20}$$

where $(A_i\ f_{awi})_{n,d}$ and $(A_0\ f_{aw0})_{n,d}$ are the amplitudes and weight-average frequencies of investigated and etalon soils in near and distant zones of the source.

The formulas (17) and (18) are true only for loose dispersal soils. The formulas (17) and (18) were used at SMZ of the territory of Kutaisi city. Besides, with the help of the formulas (19) and (20) nonelastic deformation properties of soils in full-scale conditions on the site of Novovoronezh NPP-2 were defined more exactly (Zaalishvili, 2009). The formulas were obtained on basis of physical principle, which underlies the scheme, applied at the assessment of soil looseness measure (Zaalishvili, 1996, Nikolaev, 1987).

3.2. Calculational method of seismic microzonation

Calculational method of SMZ is used in order to analyse features of soil behavior with introduction of definite engineering–geological structure characteristics of investigated site as initial data: values of transverse wave velocities, index of extinction, modulus of elasticity, power of soil layers, their consistency etc. Calculational method includes thin-layer medium, multiple-reflected waves, finite-difference method, finite-elements analysis (FEA) and other techniques.

One can take nonlinear soil properties into account in the problems of earthquake engineering by means of instrumental and calculation methods. The instrumental method of SMZ is the main method. Nevertheless it is quite often necessary to solve such problems using calculational method, which allows to model practically any conditions, which are observed in the nature. At the same time the practice reqirements lead to the necessity of calculation of soil vibrations for the conditions of their nonlinear-elastic and nonelastic deformations. At the solution of such problem it is assumed that elastic half-space behaves as linear-elastic medium and the covering soil displays strong nonlinear properties at intensive seismic or dynamic influences (Bonnet & Heitz, 1994).

Instrumental stress-sstrain dependences can be used, for example one obtained for plastic clay soil shown in fig. 12. The conception of the so-called soil bimodularity, offered by A.V.Nikolaev (Nikolaev, 1987, Zaalishvili, 1996; 2000) is taken into account in the given dependence. Considerable differences in behavior of “weak” soils at compression and dilatation lie in the base of the phenomenon. Such soil is characterized at dilatation by quite small shear modulus.

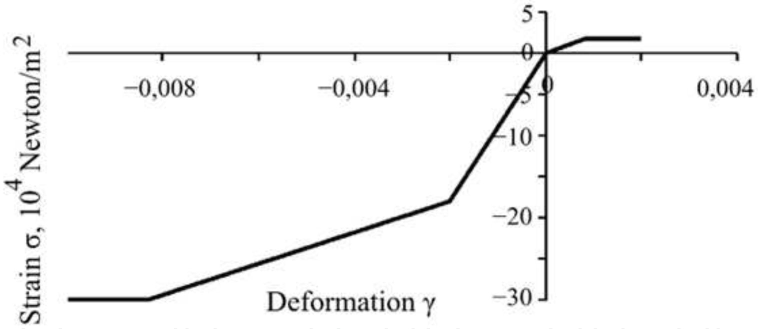


Figure 13. Instrumental stress-sstrain curve, showing property of soil bimodularity

The solution of the given nonlinear problem for soils in the analytic form is based, as a rule, on considerable assumptions due to the complication of adequate taking into account behavior features of such complex system as the soil (Bonnet & Heitz, 1994). Therefore the numerical solution of nonlinear problems on the modern stage of knowledge is the most proved if the data of field or laboratory investigations is taken into account in these or those connections. Thus, the correlations, which are determined by the experimental investigations, are the basis of the solution of calculation nonlinear problems. In other words calculation programs for the solution of calculation nonlinear problems essentially are analytical-empirical. The most adequate programs are exactly like these (SHAKE, NERA etc.).

3.2.1. Equivalent linear model. SHAKE and EERA programs

Equivalent linear model is one of the first models, which take nonlinear soil behavior into account. Equivalent linear approximation consists in modification of the model of Kelvin–Voight (for taking some types of nonlinearity into account) and, for example, is realized in the programs SHAKE (Schnabel et al., 1972) and EERA (Bardet et al., 2000).

Equivalent linear model is based on the hypothesis that shear modulus G and attenuation coefficient ξ are the functions of shearing strain γ (fig. 18.1). In the programs SHAKE and EERA (Equivalent-linear Earthquake site Response Analyses) the values of shear modulus G and attenuation coefficient ξ are determined (in the process of iteration) so that they correspond to the deformation levels in each layer.

3.2.2. IM model. NERA program

In 2001 realization principle, which was used in the program EERA, was applied in the programming of NERA (Nonlinear Site Response Analysis) (Bardet, Tobita, 2001), which allows to compute soil thickness nonlinear reaction on seismic influences. The program is based on the medium model, offered by Iwan (1967) and Mroz (1967), which is often called the IM model for short. As it is shown in the fig. 18.2, the model supposes the simulating of nonlinear curves strain-deformation, using a number of n mechanical elements, which have different stiffness kj and sliding resistance R_j, where $R_1 < R_2 < \ldots < R_n$. Initially the residual stresses in all elements are equal to zero. At monotonically increasing load the element j deforms until the transverse strain τ reaches R_j. After that the element j keeps positive residual stress, which is equal to R_j.

The equation, describes dynamics of soil medium, is solved by the method of central differences.

3.2.3. Calculation of nonlinear absorptive ground medium vibrations using multiple reflected waves' tool of seismic microzonation

Let's suppose that we have the seismic wave, which falls on the soil thickness surface. Let's assume that soil thickness is nonlinear absorptive unbounded medium with the density ρ and S-wave propagation velocity v_S. At small deformations the value of shear modulus G will be maximum for the given soils:

$$G = G_{\max} = \rho {v_S}^2 \tag{21}$$

At the deformation increase the value G remains constant at first but at reaching some value (which is definite for each material or soil) the value G considerably changes, i.e. the soil begins to display its nonlinear properties. At the continued deformation increase the growth of stresses decelerates and then can remain unchanged until material destruction or hardening, i.e. until structural condition change.

As the main soil index, which characterizes its type and behavior at intensive loads, the value of plasticity PI was chosen. The parameters, which are necessary for calculations, are determined on basis of empirical ratios (Ishibashi, Zhang, 1993):

$$k(\gamma, PI) = 0.5\left\{1 + \tanh\left[\ln\frac{0.000102 + n(PI)}{\gamma}\right]^{0.492}\right\} \tag{22}$$

where

$$n(P_I) = \begin{cases} 0.0 & for \quad \mathrm{PI} = 0, \\ 3.37 \cdot 10^{-6} PI^{1.404} & for \;\; 0 < PI \le 15, \\ 7.0 \cdot 10^{-7} PI^{1.976} & for \quad 15 < PI \le 70, \\ 2.7 \cdot 10^{-5} PI^{1.115} & for \;\; PI > 70 \;\; ; \end{cases}$$

$$d = 0.272\left\{1 - \tanh\left[\ln\left(\frac{0.000556}{\gamma}\right)^{0.4}\right]\right\} \mathrm{e}^{-0.0145 PI^{1.3}} .$$

Then the change of shear modulus is determined on basis of the ratio

$$\frac{G}{G_{\max}} = k(\gamma, PI)(\sigma)^d, \tag{23}$$

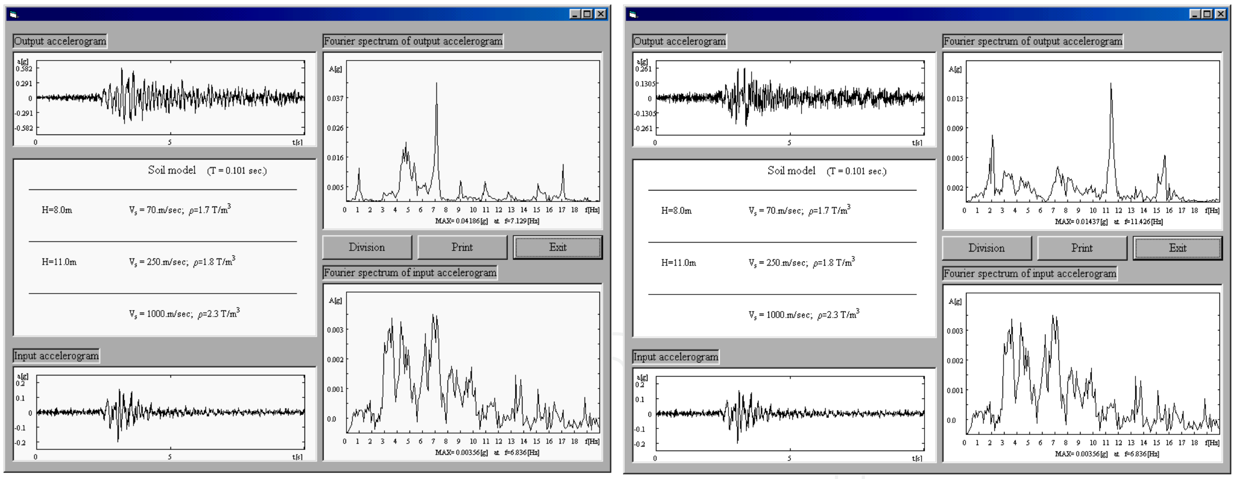
where G is the current shear modulus, σ is normal stress.

Seismic energy absorption is calculated by the formula

$$\xi = 0.333 \frac{1 + \exp\left(-0.0145 PI^{1,3}\right)}{2} \left[0.586 \left(\frac{G}{G_{\max}} \right)^2 - 1.547 \frac{G}{G_{\max}} + 1 \right] \tag{24}$$

On basis of the given ratios and introduced by us ratios for determination of necessary indices (normal stress, deformation etc), nonlinear version of the program ZOND was worked out. From the database of strong motions AGESAS, which was formed by us (Zaalishvili et al., 2000), the accelerogram, which was recorded on rocks in Japan, with the characteristics (magnitude, epicentral distance, spectral features etc.) similar to the territory of Tbilisi city, was chosen as the accelerogram, given into the bedrock.

The analysis of the results of linear and nonlinear calculations models of definite areas of Tbilisi city territory confirms the adequacy of calculations to the physical phenomena, which were obtained in soils at intensive loads (fig. 13) (Zaalishvili, 2009). With the increase of seismic influence intensity the nonlinearity display increases. Absorption grows simultaneously. Hence the resulting motion at quite high influence levels can be lower than the initial level. It corresponds to the fact, which is known on the results of analysis of strong earthquake consequences, which happened in recent yares (for example, Northridge earthquake, 1994).



Soil model (T = 0.101 sec.)

H=8.0m V_s = 70.m/sec; ρ=1.7 T/m^3

H=11.0m V_s = 250.m/sec; ρ=1.8 T/m^3

V_s = 1000.m/sec; ρ=2.3 T/m^3

MAX= 0.04186[g] at f=7.129[Hz]

MAX= 0.00356[g] at f=6.836[Hz]

Soil model (T = 0.101 sec.)

H=8.0m V_s = 70.m/sec; ρ=1.7 T/m^3

H=11.0m V_s = 250.m/sec; ρ=1.8 T/m^3

V_s = 1000.m/sec; ρ=2.3 T/m^3

MAX= 0.01437[g] at f=11.426[Hz]

MAX= 0.00356[g] at f=6.836[Hz]

a) b)

Figure 14. Results of calculations using multiple reflected waves' tool in linear (a) and nonlinear (b) cases.

3.2.4. Calculation of nonlinear soil response using FEM tool of seismic microzonation

The problem of the determination of soil massif response on dynamic influence with taking soil nonlinear properties into account can be solved by usage of finite element method (FEM) in the following way (Zaalishvili, 2009).

Soil medium is represented in the form of two-dimensional massif, which is approximate by triangular finite elements. The net, which consists of triangular elements, allows to describe quite accurately any relief form and form of the layer structure of soil massif with its physics-mechanical parameters. Within finite elemet the soil is homogeneous with inherent to it characteristics, which vary in time depending on influence intensity. Earthquake accelerogram of horizontal or vertical direction, which is applied, as a rule, to the foundation of soil massif, is used as the influence. Soil is in the conditions of plane deformation and is considered as an orthotropic medium. Axes of the orthotropy coincide with the directions of main strains.

The problem of nonlinear dynamics of soil massif is solved by means of the consecutive determination of mode of deflection of the system on the previous step. The system is linear-elastic on each step.

3.3. Instrumental-calculational method of seismic microzonation

In recent years a new «instrumental-calculational» method of SMZ (per se simultaneously having the features of both instrumental and calculational method) which includes tool of «instrumental-calculation analogies» has been developed in Russia in recent years (Zaalishvili, 2006). Its usage is based on direct usage of modern databases of strong motions.

As a basis at realization of tool instrumental database of strong movements, registered in definite soil conditions, is used. As a result of given database with the help of numerical calculations it is possible more or less safety to forecast behavior of these or those soils (or their combination) for strong (weak) earthquakes with typical characteristics for the investigated territory (magnitude, epicentral distance, focus depth etc.).

3.4. Relief influence on the earthquake intensity in SMZ problems

Morphological and morphometric features of relief meso- and macroforms influences on seismic intensity increment.

On basis of the analysis of numerous macroseismic observations the consequences of strong earthquakes, which took place on the territory of the former USSR, S.V.Puchkov and D.V.Garagozov offered the empirical formula for the intensity increment calculation (ΔI) depending on relief feature (Puchkov, Garagozov, 1973):

$$\Delta I = 3{,}3\lg\left(W_{\mathrm{gr}} / W_{\mathrm{et}}\right) + 3{,}3\lg\left(W_{\mathrm{top}} / W_{fnd}\right) \tag{25}$$

where W_{gr}, W_{et} are the accelerations of vibratory motion on soil and etalon; W_{top}, W_{fnd} are the accelerations on the top of mountain construction and its foundation.

It was determined as a result of the instrumental and theoretical investigations that for the microrelief the increment of seismic intensity increases from the foundation of mountain-shaped feature to its top and can reach approximately 1.8 degree. For the locality mesorelilef the tendency of the increase of seismic vibration intensity from foundation to the top remains. The increment of seismic intensity for the relief mesoforms is about 0.3 degree. It was shown that weak hilly relief, with the inclinations less than 10°, does not influence on the seismic vibrations intensity.

The investigations of S.V.Puchkov and D.V.Garagozov (Puchkov, Garagozov, 1973) showed that at vibrations of mountain range, composed by volcanic tuf, the amplitude of seismic vibrations in S-waves increases on the height 15 m in 1.46 times in comparison with the foundation. For the massif, composed by loamy sand and loams on the same height marks the vibrational amplitude increased in 1.8 times for p-waves and in 3.2 times for S-waves.

Slope steepness considerably influences on the increment of seismic intensity. The increase of slope steepness, composed by incoherent gravel-pebble and sabulous-loamy grounds is conductive to the sharp worsening of engineering-geological and seismic conditions of the territory. So, for example, it is determined that slope steepness more than 19°–15° (for dry sandy-argillaceous and gravel-pebble differences) produces the intensity increment up to 1 degree and at variation of slope steepness from 10° to 40° the amplitudes of seismic vibrations increase approximately in 2.5 times.

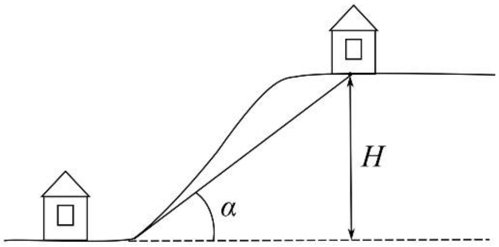
It is known that the increase of slope steepness from 40° to 80° produces the increment of seismic intensity equal to 1.5 degree (Zaalishvili, Gogmachadze, 1989).

The correlation analysis of the dependence of seismic intensity increment on true altitude, slope steepness and relief roughness showed that the main factors, which change the value of seismic intensity, are the first two indices [Puchkov, Garagozov, 1973]. It conforms well to the investigation results of V.B.Zaalishvili, who introduced the new parameter of the relief coefficient (Zaalishvili, Gogmachadze, 1989) (fig. 14).

Later the data analysis allowed to offer us (I.Gabeeva & V.Zaalishvili) the empirical formula for the possible amplification calculation K and intensity increment ΔI, which are caused by the relief (Zaalishvili, 2006):

$$K = -0.1 + 0.68 \lg R \tag{26}$$

where $R = \alpha \times H$ is the relief coefficient; α is the relief slope angle, degree; H is height, m.



$R = \alpha \times H$

Figure 15. Relief coefficient R

The analysis of the experimental data shows that intensity increment can vary at that independently of the type of rocks, from 0 to 1.5 degree.

Finally, let's try to assess the amplification of vibrational amplitude, which is caused by relief, with the help of the calculation method of FEM (Zaalishvili, 2006).

The algorithm for the calculation of seismic reaction of soil thickness for the two-dimensional model was developed for this purpose (fig. 15) (Zaalishvili, 2009). The results of the executed earliear investigations were used for the program testing (Puchkov, Garagozov, 1973). Mountain structure had the form of frustum of a cone with the height 30 m and slope angle of the generatrix 30º. The element maximum size was equal to 5 m, S-wave propagation velocity was 300 m/s, the density 1800 kg/m^3. The seismic influence was applied to the foundation of soil thickness in the form of instrumental accelerogram, modeling the vertically propagating SH wave.

It was determined that the vibrational amplitude considerably chances with the relief. The given dependence at that is various for the displacements, velocities and accelerations. The largest value of the amplification is observed for displacements and the maximum ratio of vibrational amplitudes, for example, in the point C to the point A, is 2.1 and for the point D – 3.2. It well satisfies the results of experimental observations where the ratio in the point C for the S-wave is equal to 2.3 and in the spectral region the maximum values are 1.8 (at T = 0.4 s) and 3.2 (at T = 0.7 s) for P- and S-waves accordingly. Spectral analysis also shows the resonance increase of vibrational amplitudes in the top part of the slope on the frequency 1.6 Hz (i.e. T=0.6 s).

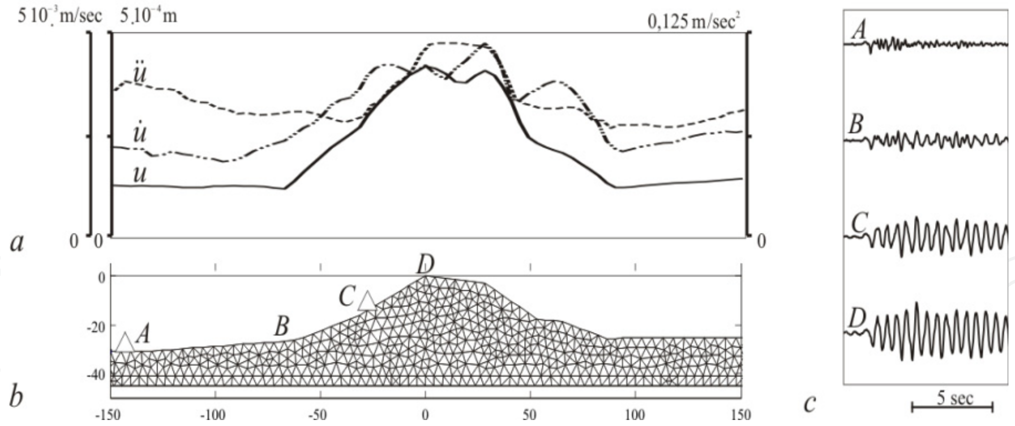


Figure 16. Final elements analysis (FEA) application example: a) Variation of amplitudes of displacement, velocity and acceleration along surface; b) calculational model; c) seismograms, calculated in points A, B, C, D.

Considerably fewer investigations are dedicated to the influence of the underground relief on the intensity. On the data of B.A.Trifonov (1979) the underground and buried topography of the rocks influences on seismic vibrations intensity, if the surface slope exceeds 0.3. At the vee couch of the rocks, which are covered by sedimentary thickness, the ratio between wave length and the sizes of vee stripping influences on seismic intensity change. Seismic intensity increment in the given case is formed by the wave interference and can be 1.5–2.0 degree (Bugaev & Kharlov, 1977; Bondarik et.al., 2007).

Thus, at the execution of SMZ works in the mountain regions or under the conditions of billowy relief, it is necessary to pay special attention to the influence of surface or underground relief on the intensity forming. It is necessary to continue the investigations in order to obtain statistically proved ratio for the calculation of intensity increment, caused by relief.

3.5. Seismic microzonation of Vladikavkaz city

If we consider 5% DSZ map as basis for seismic microzonation so seismic intensity of 8 corresponds to etalon grounds for whole territory.

Then, maps of seismic microzonation of cities must be created. According to the above mentioned maps of detailed zoning the maps of seismic microzonation with probability 1%, 2%, 5% or 10 %, correspondingly, were made up.

Though, that definitions of the word «zoning» are similar, actually they are quite different in essence. Unlike the maps of detailed seismic zoning, which give seismic potential (Mmax) and source features, the maps of seismic microzonation give assessments of soil condition influence (sands, rocks, pebbles, clays etc., their combination; watering; relief (as underground as surface); spectral distribution of incoming wave; predominant vibration frequencies on city square etc.) on forming of future earthquake intensity. As a rule, the scale of such maps is 1:10 000, in order to have the opportunity of taking them into account at building. Maps can be more detailed (1:5000 etc.) but this makes no sense as the type and physical condition of soils in space on the territory site can change fast. The most important thing is to assess intensity of possible earthquakes on areas with typical soil conditions for city territory.

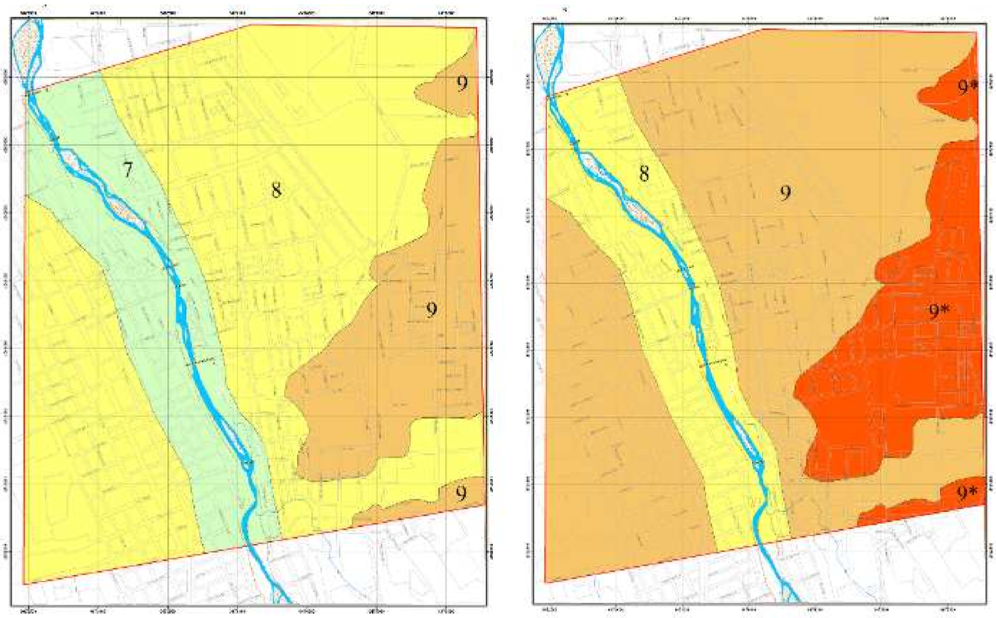
Maps of seismic microzonation can be made up for the certain territories (cities and settlements, as a rule). It is impossible to make them up in entire format because of the necessity of geological conditions knowledge on larger territories, which are mostly not built up. We often don't have such data even for the modern cities! It's practically impossible because the resources will be lost for nothing! And absurdity! In the other words there is no the microzonation map even for the territory of North Ossetia let alone the whole Northern Caucasus.

Maps of seismic microzonation do not only show the place of earthquake-proof building up, but they also show on what intensity this or that building must be calculated and designed: on 6, 7, 8 or 9 points. And sometimes even on 10 points (for very soft grounds!). And this suggests investments of different financing for the realization of antiseismic measures (thicker armature, more connections etc.). Seismic risk can considerably be reduced at building-up zones with 7, 8 and 9 point of the calculated intensity by adequate site development on the territory of city, for example, as social losses will be minimal, though buildings will be damaged in this or that extent.

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 (Zaalishvili, 2000). 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 1%, 2%, 5% and 10% one can obtain corresponding maps of SMZ with probability of exceedance 1%, 2%, 5% and 10%, i.e. probabilistic maps of SMZ (Fig. 16).

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.



a) b)

Figure 17. 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 (Zaalishvili, 2009).

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.7).

4. Specified seismic fault and design seismic motion

Analysis and consequent account of initial accelerograms transformation will become the basis for site effect analysis at strong seismic loadings (fig. 17) (Zaalishvili et al., 2010).

Methods of such modeling are based on accordance of spectral properties of modeled and real earthquake. In a whole modeling accuracy depending on the purposes of total motion usage and what characteristics defining structural system behavior must be reproduced.

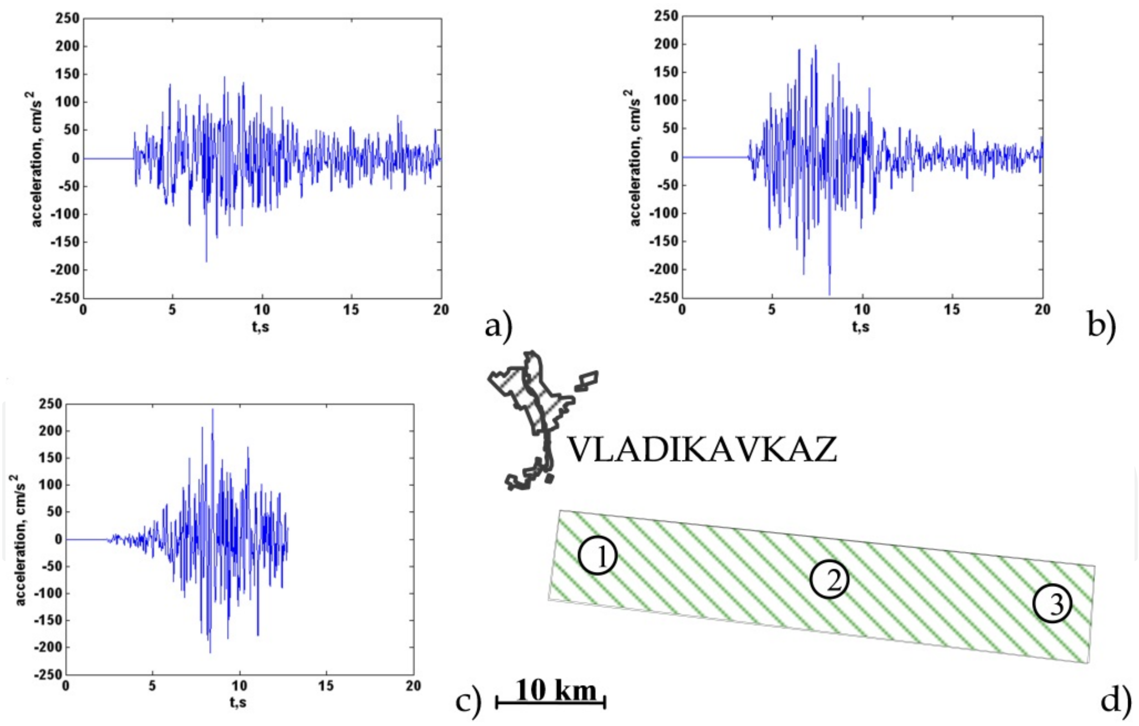


Figure 18. Synthetical accelerograms for different source locations: a – western part of fault; Sb – middle part of fault; c – eastern part of fault; d – scheme of sources of scenarios earthquakes

Earthquake source that is a region of rupture can be considered as point source only for much larger distances than fault size. At close distances effects of finite fault size become more significant. Those phenomena are mainly connected with finite rupture velocity, which causes energy radiation of different fault parts in different times and seismic waves are interference and causes directivity effects (Beresnev & Atkinson, 1997, 1998).

Let's compare amplitude spectra of obtained design accelerograms with spectrum of real earthquake from considered fault. Data analysis (fig. 18 and fig. 19) shows that spectra of calculated and real earthquakes in a whole are similar in their main parameters.

It must be noted that spectrum of vertical component of real earthquake is closer to design spectra. The last fact is quite obvious and is explained by proximity to earthquake source. Indeed, close earthquakes in general are characterized by predomination of vertical component. Record of TEA station (located in theater) was selected due to its location on dense gravel and has a minimal distortions caused by soil conditions.

Analysis of spectrum of weak earthquake shows that peaks are observed on 1.3 and 5.6 Hz (Fig. 18). In spectra of synthesize accelerograms mentioned amplitudes are also observed. At the same time medium response on strong earthquake, undoubtedly, differ from weak earthquake response (Fig. 19) (Zaalishvili, 2000).

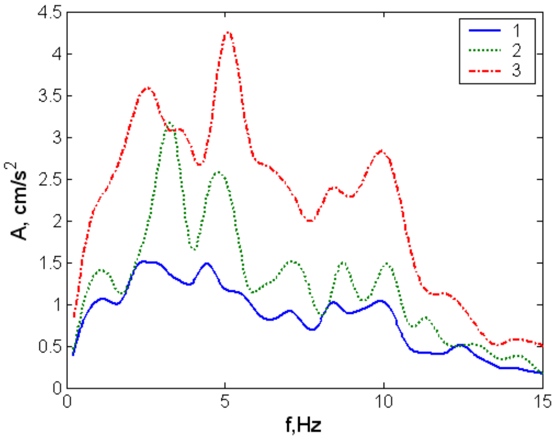


Figure 19. Spectra of design accelerograms at different source locations of earthquake M=7,1: 1 – western part of fault; 2 – middle part of fault; 3 – eastern part of fault

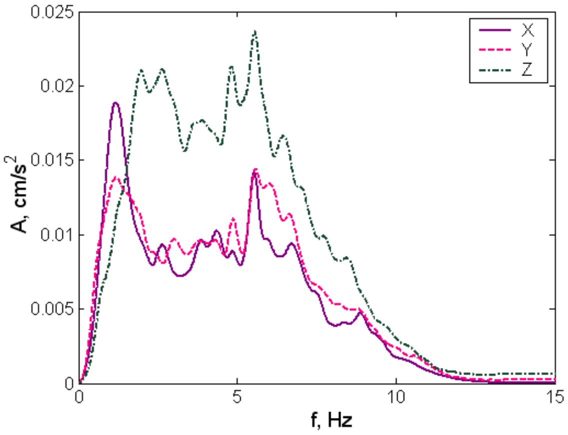


Figure 20. Spectra of accelerograms of weak earthquake with epicenter in the zone of Vladikavkaz fault. (25.08.2005 10:25 GMT, H = 8 km M= 2.5).

Usage of maps of detailed seismic zoning in units of accelerations at seismic microzonation level is possible only for calculation method giving results in units of accelerations. Today traditional instrumental method of seismic microzonation does not allow obtaining intensity increments in accelerations due to traditional orientation on macroseismic intensity indexes. The exclusion is the case of investigation of strong earthquakes accelerations when instrumental records are obtained (in presence of accelerometer) (Zaalishvili, 2000). At the same time investigations are conducted and the problem supposed to be solved.

On the other hand in recent years a new instrumental-calculation method was developed (Zaalishvili, 2006). New method is based on selection from database (including about 5000 earthquake records) soil conditions which are the most appropriate to real soil conditions of the investigated site. Then the selection of seismic records with certain parameters or their intervals follows (magnitude, epicentral distance, and source depth). Then maximal amplitudes are recalculated for given epicentral distances. Absorption coefficient can be calculated by attenuation model for given region.

Thus, a new complex method of seismic hazard assessment providing probability maps of seismic microzonation, which are the basis of earthquake-proof construction, is introduced. Undoubtedly such approach significantly increases physical validity of final results.

Considered procedures on the level of possible seismic sources zones exploration, maps of detailed seismic zoning and seismic microzonation may differ from described above. So paleoseismological investigations like «trenching» (Rogozhin, 2007), which allow determining more reasonable the recurrence and other features of seismic events realization are also possible when it is necessary.

Today, we have conditions for detailed seismic zoning maps development like the above mentioned but for all the territory of the Northern Caucasus on basis of the modern achievements of engineering seismology. It will give us a possibility to develop probabilistic maps of seismic microzonation with the help of powerful nonexplosive sources, methods taking into account physical soils nonlinearity (Zaalishvili, 2009).

Thus algorithm of seismic hazard assessment of the territory taking into account multiple factors forming seismic intensity was considered. Forms of typical seismic loadings for firm soils are given, which will be changed from site to site in dependence of differences in ground conditions (engineering-geological, geomorphological and gidrogeological conditions)

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