SEISMIC MICROZONATION OF VLADIKAVKAZ CITY: HISTORICAL REVIEW AND MODERN TECHNIQUES

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SUMMARY:
Seismic microzonation (SMZ) is a method of zoning the city or a large construction site in zones of the same ground response for standard seismic effect of a certain level and assessment of the relative changes in the characteristics of vibrations on the surface relative to reference site to which the initial intensity is attributed.
In this paper the approach used abroad is integrated with the achievements of Russian scientists, especially in the field of the instrumental method, which is the main method of SMZ.
Seismic conditions of the territory of Vladikavkaz city were objects of the investigations, as the basis for seismic resistant design and construction. Development of the final map of seismic microzonation was based on the results of instrumental (weak earthquakes registration, seismic impedance and microseisms tools) and calculational (Multiple Reflected Waves and FEM tools) methods, as well as newly developed instrumental-calculational method. For the first time in Russia on the basis of probabilistic seismic hazard maps of the territory of North Ossetia probabilistic maps of seismic microzonation were designed.

Keywords: seismic hazard, seismic microzonation, site effect, GIS

1. INTRODUCTION

Seismic microzonation (SMZ) can be viewed as a method of zoning ofa city or a large construction site in sites with the same groundresponse for standard seismic effect of a certain level and assessment of the relative changes in the characteristics of vibrations on the surface relative to the characteristics of vibrations of so-called reference site to which the initial intensity is attributed. In Russia the referencesites are siteswith average seismic properties of ground conditions of certain territory. In Armenia and Georgia sites with the worst ground conditions are generally considered as reference, although in some cases they can be averages [Zaalishvili, 2000]. In the United States the reference sites are Rock sites. In former USSR sites with standard ground conditions traditionally were chosen after macroseismic investigation of historical strong earthquakes.
Sites with the same intensity are combined in different seismic zones. Engineering-geological, hydrogeological and geomorphological conditions are taken into account. On the other hand, the target of seismic microzonation is development of initial dataof various levels of seismic impacts for structural engineering and urban planning.
Modern principles of seismic microzonation used abroad require differentiation the territories indifferent types of ground conditions. The territory is divided into a grid with equal cells. Further the parameters of the forming characteristics of ground conditions in each of these cells are defined, which requires active use of GIS technology [Zaalishvili, Berezko, 1999]. In particular, such studies have been carried out in 2000, in the process of implementation of the international project for a large area of Tbilisi, with various types of soils, in different physical conditions [Zaalishvili et al., 2001].
In General, the process of seismic microzonation can be divided into three phases. In the first phase, initial regional seismic characteristics of the earthquake at rock level are determined for each cell. In the second stage, the site profiles are modeled on the basis of the results of the drilling and field testing. The third phase includes an analysis of the expected response of sites to evaluate characteristic of earthquake on the surface and interpreting the results of microzonation [Ansal et al., 2004, 2010]. When the available data of engineering geological zoning (usually the results of surveys of past years) do not correspond to modern requirements (for example, insufficient data on fill content in gravels), the instrumental studies based on some selected grid in the territory is essential for the reliability of the

final result.
In the paper approach used abroad iscombined with techniques of Russian school of seismic microzonation, especially of instrumental method which is the primary method of SMZ. Seismic process is a complex multifactor process, so final maps of seismic microzonation are based on the results of integrated use of instrumental, calculational and recently developed instrumental-calculation methods [Zaalishvili, 2006; Zaalishvili et al., 2007].
To define initial seismic impacts for average ground conditions a set of probabilistic seismic hazard maps (1%, 2%, 5%, 10%) of RNO-A in scale 1:200000 was created [Zaalishvili et al., 2007, 2011; Zaalishvili, Rogozhin, 2011 a, b]. During seismic microzonation the instrumental method of SMZ [Zaalishvili, 1997, 2000] was used in the form of earthquakes registration, seismic rigidity and microseisms, as well as calculational method in the form of reflected waves and finite element methods [Otinashvili, Zaalishvili, 2001; Zaalishvili et al., 2001; 2008]. For large-scale housing construction 5% probability of exceedance of estimated intensity in 50 years was assumed as the most “real” for analyzing territory [Musson, 1999]. This probabilistic seismic hazard map, corresponds to return period of 1000 years [Rogozhin et al., 2004].

2. HISTORY OF SEISMIC MICROZONATION OF VLADIKAVKAZ CITY

In our research the results of previous geophysical studies on the territory of Vladikavkaz city held in the 1969-2006 were analyzed [Napetvaridze et al., 1970; Sharapov et al., 1991]. The first work on seismic microzonation of the territory held back in 1969-1970. Just note that the map of seismic microzonation proved to be the first and last official approved map – direct basis for earthquake engineering. Almost all construction in the city since then officially and semi-officially based on this map (fig. 1).
Twenty years have passed and in the 1990-1991 such work on seismic microzonation once again took place (fig. 2). It was caused by a number of circumstances. First, during passed period recommendations for seismic microzonation (1971) which were actualized in 1985, and finally in 1988 manual on seismic microzonation was issued. Secondly, for 20 years the City had developed rapidly, and has continued to expand. It should be noted that in the past period, new scientific approaches had appeared. In the same time building codes have changed in every 20 years. So soon after the Tashkent earthquake of 1966, new Building code (SNiP-69) was developed. Over the next 10 years, the time had come to develop new Building code (SNiP-81). These Building codesincluded the most modern views of scientists and engineers. It is these Building codes those United States scientists have named one of the best of the world. It took another 20 years and after another destructive Spitak earthquake in 1988, the process of the following Building code forming had started. Unexpected destructive Racha earthquake 1991, made the process irreversible. In 1992 the resolution increased seismicity in the Caucasus on one point was issued by the construction ministry.
In 1996 a new Building code of Russian Federation was created, while incorporating the main provisions of the previous Building codes, but also greatly developed in the seismological part.
At this background, the work on seismic microzonation in 1990-1991 looks anachronistic, and the results of the work on seismic microzonation were not approved for various reasons.
The present work on seismic microzonation of the territory of Vladikavkaz city held in the 2009-2010 is almost exactly in the 20-years interval interval between such works.
From 1969, have appeared new methods and technologies of construction, and also in general view on the level of seismicity in the Caucasus has changed significantly that was more or less a reflection of recently used Building code. Usually, each strong and destructive earthquake occasionally opens up new factors forming site effect. Thus, the use of calculational method would assess resonant frequencies of ground conditions of Spitak which could be used in the construction and to prevent the destruction of buildings caused by resonant phenomena in the system“soil-construction” (destruction of practically all buildings of 111 series). As the consequences of the earthquake in Mexico showed that the seismic effect significantlydepend on powerful ground thickness. Effects of Niigata earthquake gave us ideas about a possible liquefaction of soils, the phenomenon, which has so far not rigorously defined, etc. And past works reflect the evolution of the factors influencing seismic effect of earthquakes. Thus, in 1970, along with traditional at that time evaluation methods and techniques

for the first time in the USSR the calculational method was used as a reflected wave method in the seismic microzonation [Napetvaridze et al., 1970]. At the same time usedapproaches could not take account of the above mentioned approaches (1971, 1985, 1988, etc.). However, used techniques were most real for period prior to 1985. But with the force into application usage of fill content for some soil type the work has become clearly outdated. Absolutely strange looks in these circumstances to perform such work without fill content account in 1990-1991.

To clarify various characteristics of soils modern measuring tools and equipment were used: ground-penetrating radar "OKO-2”, electrical survey station ERP-1 and seismic prospecting station “Laccolite X-2M”. Equipment is based on the latest achievements of domestic science and has modern computer programs forfield materials processing.

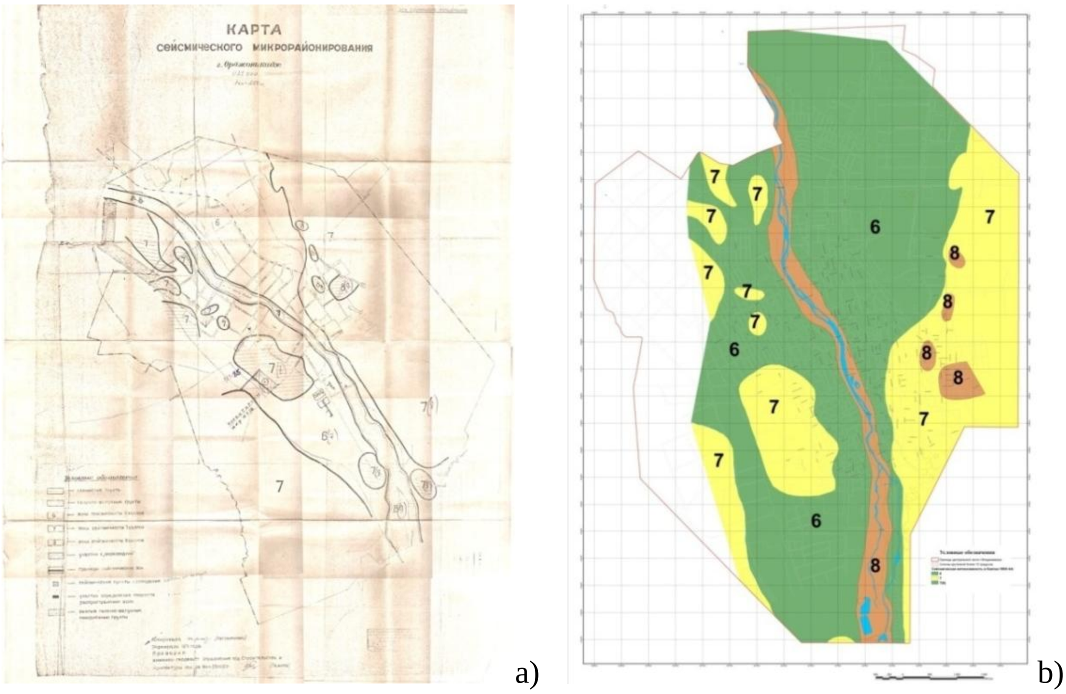


Figure 1. The map of seismic microzonation of 1970: original (a), GIS-project (b)

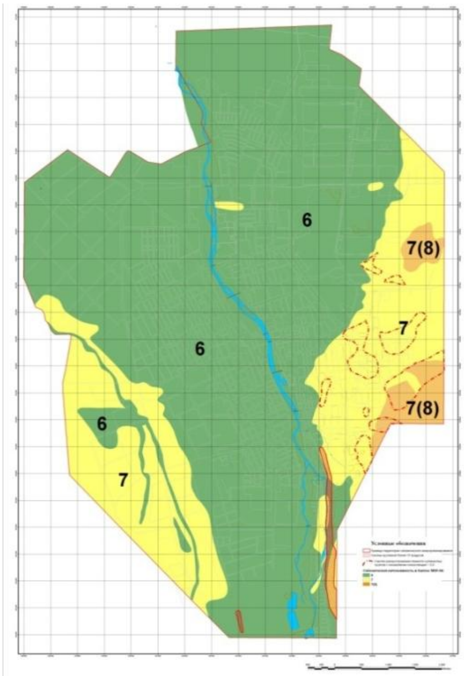


Figure 2. The map of seismic microzonation, 1991 (GIS)

3. INSTRUMENTAL METHOD

In accordance with regional building codes **rigidity seismic tool** is required for use as a primary seismic microzonation on objects of any class [RSN 60-86]. The increment of intensity was determined using the known formula of S.V. Medvedev [Medvedev,1965]:

$$\Delta I_M = 1.67 \lg \frac{\rho_0 v_0}{\rho_i v_i}, \tag{1}$$

where $\rho_0 v_0$ and $\rho_i v_i$ – seismic rigidities of etalon and investigating sites respectively.

By synthesizing the results of research carried out throughout the city, for average ground conditions we have the following characteristics: v_s = 350 m/s and ρ = 1.85 t/m^3. Calculations were carried out on the modified formula Maksimov-Zaalishvili, which takes into account resonant properties of soils at low levels of exposure, thus improving the validity of the results [Zaalishvili, 2000]:

$$\Delta I_{MZ} = \lg\left(\frac{\rho_0 v_0}{\rho_i v_i} e^{2.5(\lg v_0 - \lg v_i)}\right), \tag{2}$$

The results, which include analysis of the category of soil according to the map of engineering geological zoning mapped to compare with the results of other techniques (fig. 3).

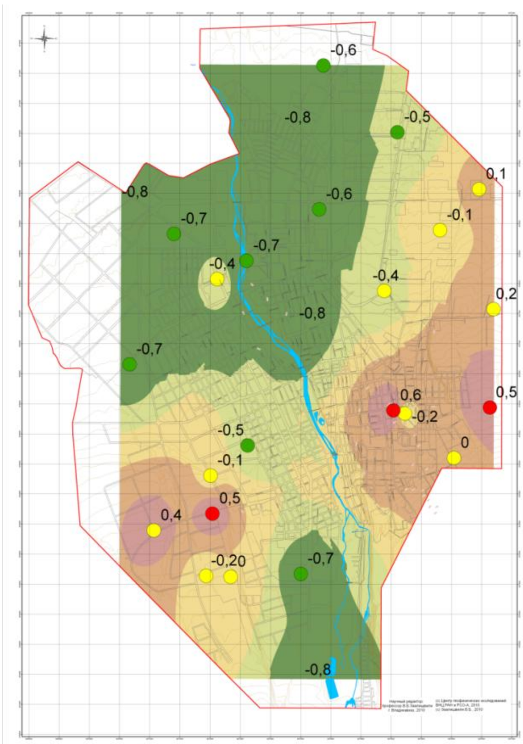


Figure 3. Intensity increments calculated by S. Medvedev's formulae

The next necessary instrumental method of seismic microzonation is the **tool of registration of earthquakes** [RSN 60-86, RSN 65-87]:

$$\Delta I = 3.3 \lg \frac{A_i}{A_0}, \tag{3}$$

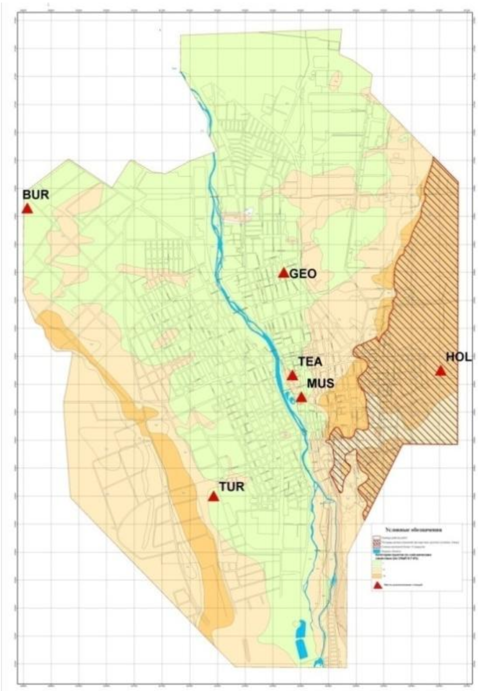
where A_i and A_0 – amplitudes on investigating and etalon sites (of the same registered earthquake).
Permanent network of seismic observations in sites with different ground conditions operating on the

territory of Vladikavkaz from 2004 helped get representative set of seismic records which characterize properties of building soil-foundation system. Observation points are equipped with modern seismic recorders “Delta-Geon”, seismic receiver SK-1P type replaced on S-5-S in August 2006. Compared with seismodetectorsSK-1P, S-5-S have longer period, so they can record events with greater intensity that it is within the scope of engineering seismology. Use the seismic receiver S-5-S also clarified the increment of seismic intensity for TEA station. In 2010, the network was expanded to include two stations along the Gadiyeva and Vladikavkzskaya streets (BUR and TUR, respectively, fig. 4-5). The results of intensity increments calculation on both instruments are summarized in table 1.

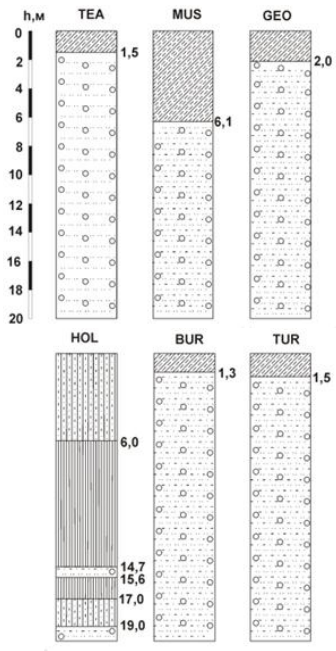
Table 1. Intensity increments based on earthquakes records

Code of Station	intensity increments, $\Delta I_{SK\text{-}1P}$	intensity increments, $\Delta I_{S\text{-}5\text{-}S}$	intensity increments, ΔI
MUS	-0,1	-0,1	0
GEO	0	0	0
HOL	0,4	0,6	1
TEA	-0,2	-0,6	-1
BUR	-	-0,2	0
TUR	-	0,3	0

Ground conditions of station “GEO” in the form of pebbles were assumed as average ground conditions. This designation is due to the number of fill> 30%.Influence of site conditions on frequency content was investigated and resonant frequencies allocated.



a)



b)

Figure 4. Location of seismic stations on the territory of Vladikavkaz city on engineering-geological map (a) Ground conditions of seismic stations (b)

Microseisms tool is a supplementary method that is used in combination with other techniques [RSN 65-87, Recommendations on seismic microzonation, 1985]:

$$\Delta I = 2\lg \frac{Amax_i}{Amax_e}, \qquad (4)$$

where $Amax_i$ и $Amax_e$ – maximal amplitudes of microseisms on investigating and etalon sites respectively.

Increments of seismic intensity based on a microseisms records of network of seismological observations are shown in table 2.

Table 2. Intensity increments based on microseisms records

Station code	Intensity increments, $\Delta I_{SK\text{-}1P}$	Intensity increments, $\Delta I_{S\text{-}5\text{-}S}$	Intensity increments, ΔI
MUS	-0.95	-0.20	0
GEO	0.00	0.00	0
HOL	0.03	0.68	1
TEA	-1,05	-0.60	-1
BUR	-	-0.20	0
TUR	-	0.25	0

The use of permanent points for microseisms registration allowed identifying daily variation of amplitudes of microseisms in various parts of Vladikavkaz. Use of microseisms records to estimate an intensity increment is generally characterized by high uncertainty [Zaalishvili, 2000, 2009]. It is obvious that the proximity of industrial sites to the location of the station “GEO”causes high amplitudes of microseisms at this station, the station “TEA” is located in proximity to the River Terek, also a powerful source of microseisms.

4. CALCULATIONAL METHOD

Calculational method in the form of multiple reflected waves tool was used (fig. 5) [Zaalishvili, Melkov, 2010]. Input accelerograms were obtained by stochastic method for Sunja possible seismic source zone (Western Branch). For Vladikavkaz fault, close to the city, accelerograms were obtained by means of FINSIM program [Beresnev, Atkinson, 1998]. Instrumental records of real strong earthquakes registered in various regions of the world were also used. Behavior of soils at strong motions was estimated with NERA program [Bardet, Tobita, 2001], taking into account nonlinear properties of soils.

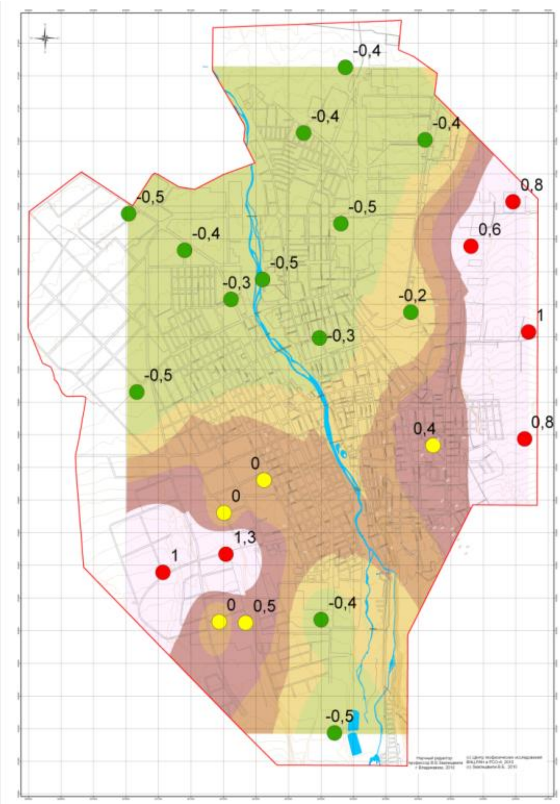


Figure 5. Intensity increments calculated using refracted waves calculational technique

5. MAP OF PREDOMINANT FREQUENCIES

Calculated frequencies were compared with the results of microseisms H/V analysis [Nakamura, 1989] and have a good accordance. Possibilities of microseisms usage for natural frequencies allocation are justified by the SESAME project [Guidelines…, 2004], shown the equivalence of the predominant frequencies allocated by spectral H/V relations for microseisms and by earthquakes records.

Equivalence of spectralcharacteristics obtained by different methods, allowed to use microseism records to detalize and refine edges of engineering geological zoning maps.On the territory of Vladikavkaz city microseisms were also recorded by mobile seismic stations (seismic recorders “Delta-Geon-02M” and seismodetectors SK-1P), and all the territory was covered. As a result detailed map of predominant frequencies on the territory of Vladikavkaz city was obtained (fig.6).

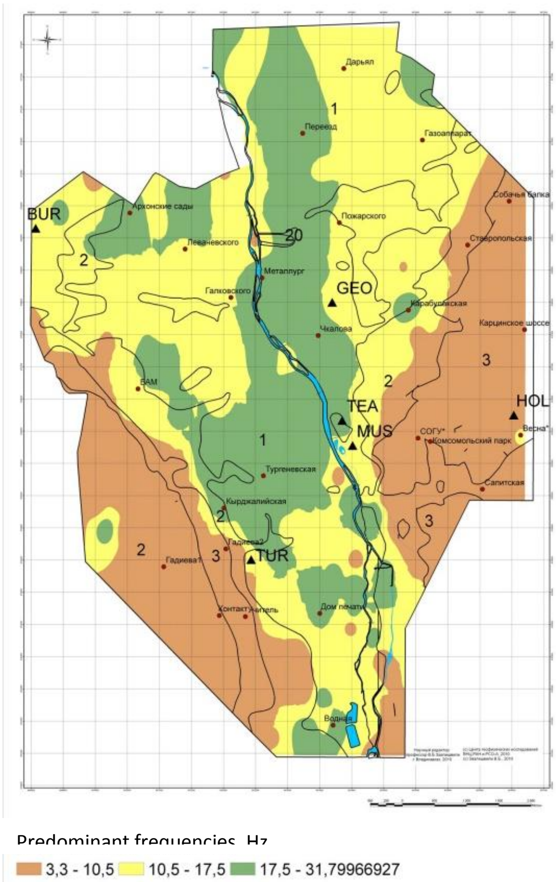


Figure 6. The predominant frequency and boundaries of the map of engineering-geological zoning

4. INSTRUMENTAL-CALCULATIONAL METHOD

Also for the first time **instrumental-calculational method** was used. It is based on the direct use of strong motion databases like K-NET (Japan) containing real records of strong earthquakes registered in different parts of the world. Instrumental-calculational analogies technique is based on comparison of records obtained in sites close to the investigated ground conditions and characteristics of possible earthquakes (magnitude, distance, epicentral distance, etc.) [Zaalishvili, 2006; Zaalishvili et al., 2007].

Calculations were made for Vladikavkaz fault closest to Vladikavkaz city, appropriate seismic event was selected from database (26.03.97 17:31). The results of the calculations are presented in table 3. Amplitude A_1 obtained at epicentral distance (Δ_1) was converted to the specified epicentral distance (Δ_2 = 10 km) according to the formula:

$$A_2 = A_1 e^{\alpha(\Delta_2 - \Delta_1)} \quad (5)$$

In the first approximation the absorption coefficient α can be considered constant, value of α for Japan according to [Okamoto, 1980] was used.
Soil conditions of station KGS001 are characterized by dense clayey soils with about 8 meters, underlying by gravels, the same soil conditions has "Museum" (MUS) station. Station KGS004 was selected equivalent to "Vesna" (HOL) station, where sandy and clayey soils of about 20 meters. Thus, the increment of intensity for station "Vesna" is finally equal to 1 point (Table 3).

Table 3. Intensity increments based on instrumental-calculational method

Station Code	Equivalent	M	h, km	Δ, km	Amax, cm/s^2	Amax (Δ=10км), cm/s^2	ΔI
KGS001	MUS («Museum»)	6.3	8	30	129	191	-
KGS004	HOL («Vesna»)	6.3	8	19	293	350	0.87

5. FINAL MAP OF SEISMIC MICROZONATION

Analysis of all of the results of the intensity increment calculation shows next values relative to intensity 8 of average ground conditions: for clay soils (softplastic, flowing consistency, etc.):+1 point; for gravel with sandy-clayey fill > 30%:0 point; for gravel with sandy-clayey fill< 30%: –1 point.
Map of seismic microzonation of Vladikavkaz city in scale 1:10 000 (fig. 7) was created. Zones with intensity 7, 8 and 9 points are allocated.

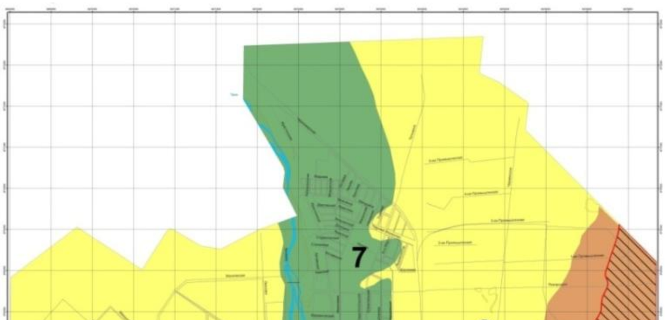


Figure 7. Map of seismic microzonation of the territory of Vladikavkaz city

The sites with unfavorable for the construction soil conditions are marked with dash. These sites

include the proliferation of subsidence of clay soils and sites with tilt the terrain of more than 15°.
It should be noted that if overlap clay thickness is small and structures are founded directly on the underlying gravels with sandy-clayey placeholder < 30% seismicity maybe justifiably, classified as a 7 point regardless of map seismicity.
On the basis of different probability maps it is possible to create 1%, 2% and 10% maps of seismic microzonation of Vladikavkaz city, allowing the construction of various buildings.
Thus, using modern scientific approaches the probabilistic seismic microzonation map of Vladikavkaz was constructed.
For a variety of reasons SMZ methods, based on the use of powerful sources and developed by one of the authors of the paper had not been used. At the same time, all the methods required in the process of seismic microzonation (weak earthquakes registration method and seismic rigidity method) were used.

CONCLUSIONS

1. Probabilistic seismic hazard maps (1%, 2%, 5%, 10%) of territory at M 1: 200 000 allows the same degree of risk within the territories covered by each of the maps, and are the basis of a probabilistic seismic microzonation maps.
2. Using 5% of probabilistic seismic hazard maps of the territory of North Ossetia, with 1000 years return period, seismic microzonation map of the Vladikavkaz territory, intended for mass construction was created.
3. The increment of seismic intensity by seismic rigidity tool was calculated. The Maximov-Zaalishvili formula was also used, which allowed uniquely identify seismicity of individual sites.
4. Processed records of seismological observation local net and defined increment of seismic intensity of Vladikavkaz by weak earthquakes tool. A significant impact on the terrains of amplitude-frequency characteristic of associated sites was found.
5. The increment of seismic intensity using microseisms tool was calculated. Spectral method for H/V relations makes it possible to determine the predominant periods of vibrations in soil thickness. Microseims tool allows to reliably differentiate between different types of soil conditions on the basis of predominant frequencies/periods. This allows using the tool in conjunction with the basic tools of instrumental method for specification of engineering geological zoning maps.
6. With the help of microseisms some sites within the same categories of engineering geological zoning map were selected. In the pebbles field it is primarily associated with sandy-loamy placeholder which directly defines seismic properties of soils, which are directly recorded as microseism.
7. Calculations based on calculation method as the tool of multiple reflected waves, the finite element tool and NERA program. Accelerograms of real earthquakes, synthetic records obtained by stochastic method for Sunja zone of zones of danger earthquake appearance (Western Branch) and for Vladikavkaz fault, which is close to the city, obtained by the program FINSIM were used as input accelerograms.
8. A new instrumental-calculation method as a tool of calculation instrumental analogies was used. The tool is based on a strong motion database, consisting of nearly 50 000 records strong and destructive earthquakes. For calculations records of earthquakes in sites close to the ground conditions and characteristics of earthquakes (magnitude, distance, epicentral distance, etc.) were selected.
9. For the first time in Russia 5% probabilistic map of seismic microzonation was designed on the basis of 5% probabilistic seismic hazard map of the territory of North Ossetia. For design of responsible structures 2% probabilistic map of seismic microzonation will be constructed on the base of 2% probabilistic seismic hazard map of the territory of North Ossetia. Such an approach allows to turn to probabilistic maps from outdated deterministic seismic hazard maps.
10. For the first time new instrumental-calculation method was applied for final results justification and accuracy of allocation of seismicity zones.

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