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## Assessment of Seismic Hazard of a Territory

V.B. Zaalishvili

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## 1. Introduction

The aim of this work is to analyze the modern concepts of the seismic hazard of the territory, its evaluation and development of an algorithm for such assessments. One of the main problems is the adequacy of such assessments. In order to analyze the physical mechanisms of different approaches the evolution of methods and techniques on one side, and their comparison with the other side should be presented. It is also necessary to show the physical validity of choice of approach and its accessibility and simplicity, which increases the reliability of the final results. The next task is to analyze the integral estimates of seismic hazard of a territory. It is necessary to consider the calculation of the expected seismic effects on the final stage of the algorithm.

Seismic hazard assessment is the basis of modern seismic design and engineering. Seismic hazard maps of different contents and scales are result of such investigations. It makes possible to take into account all the features of the territory forming mentioned hazard. In particular, expected on the territory typical seismic impacts and calculated on the basis of world achievements not only of the West but also of the East are taking into account features of possible seismic sources (active seismic faults, their seismic potential, etc.).

The new integrated method for seismic hazard assessment is presented. Probabilistic maps of seismic hazard are created in the result of this assessment. The following databases were formed to analyze seismic hazard and seismicity of the territory: macroseismic, seismologic and database of possible seismic source zones (or potential seismic sources-PSS). With usage of modern methods (over-regional method of IPE RAS-Russia) and computer program (SEISRisk-3 – USA) in GIS probabilistic seismic hazard maps for the Republic North Ossetia-Alania in intensity units (MSK-64) at a scale of 1:200 000 with exceedance probability of 1%, 2%, 5%, 10% for a period of 50 years that corresponds to recurrence period of 5000, 2500, 1000, 500 years were created. Furthermore, for the first time the probabilistic seismic hazard maps



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were made in acceleration units for territory of Russia. For the large scale building is likely to be used 5% probability map, i.e. for the major type of constructions, whereas for high responsibility construction should be used 2% probability map. The approach based on the physical mechanisms of the source is supposed to use to produce the synthesized accelerograms generated using real seismic records interpretation.

For each of zoning objects the probabilistic map of the seismic microzonation with location of different calculated intensity zones (7,8,9,9\*) is developed (the zones, composed by clay soils of fluid consistency at quite strong loadings can be characterized by liquefaction are marked by the index 9\*). Similar results are observed for maps in acceleration units.

The integrated approach is based on the latest achievements in engineering seismology. It can reduce measure of inaccuracy in earthquake engineering and construction and also significantly increase the adequacy or foundation for assessments.

Carrying out of investigations on mapping of seismic hazards such as detailed seismic zoning (DSZ), which is based on the most advanced field research methods and analysis of every subject of the sufficiently large region (for example Caucasus) in a scale of 1: 100 000 or 1: 200 000 allows to create a physically reasonable general DSZ map of any wide territory. Such maps are generated organically through summation or the imposition of the calculated seismic fields that are a reflection of seismic potential of the corresponding seismic sources.

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

Expected seismic hazard assessment is reduced to seismic potential estimation of a particular seismic source or a combination of sources. Wherein the mentioned potential is formed by a number of factors, such as geodynamic (tectonic movements), geological and geophysical features of the territory, the catalog of strong earthquakes, local soil conditions (geotechnical, hydrogeological and geomorphological conditions), resonance properties, attenuation rates, and others. At the same time physical validity problem of hazard level is one of the important problems of engineering seismology. The involved assessment of seismic hazard, presented as seismic zoning maps, in fact is a long-ranged forecast of the earthquake strength and location unlike short-range and middle-range earthquake forecast.

There can be marked out three types of analysis, three consecutive stages of seismic zoning:

- 1. general seismic zoning GSZ or SZ, which is realized in 1:5 000 000 or 1:2 500 000 scale;
- 2. detailed seismic zoning DSZ, which was originally carried out in 1:50 000 500 000 scale;
- 3. seismic microzonation SMZ, in 1: 5 000 10 000 scale.

In the result of seismic zoning the appropriate maps of GSZ, DSZ and SMZ were created. The difference between DSZ and GSZ lies in investigation scale. During DSZ can be and has to be studied all potential sources of possible earthquakes that may be not taken in account because of their relatively small seismic potential during GSZ analyzing. It is necessary to note that in

actual conditions of consequences of seismic hazard generation with that types of sources can have, if not great, but evident negative effect. At once both types of zoning are quite similar, not to mention minuteness.

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

Seismic hazard assessment of any given territory on the initial stage was performed using mainly deterministic methods. In the deterministic methods, all parameters of a close particular source (magnitude), medium (particular site), the distance from the source to the site, the wave attenuation when propagating through a particular medium (the propagation paths of seismic energy in the form of waves) are mostly known or thoroughly investigated and finally form the medium (soils) reaction of a site in the form of maximum seismic effect. Medium is considered in a simplified form - combined horizontal layers. A number of such deterministic computer programs is known.

At present in developed countries the hazard assessment is increasingly performed using probabilistic methods. Probabilistic seismic hazard assessment techniques include various alternative models of earthquake sources (focuses), return periods of events, accounting of attenuation models of seismic energy and accordingly the seismic effect. Herein the probabilistic method takes into account uncertainty bounds of certain parameters that are mainly random and the most important - the probabilistic nature of the actual implementation of the seismic event that is formed by a number of random factors. The last circumstance significantly reduced the intensity of emotions that was in the 60-70 years of the last century about development of a reliable method for prognosis of strong earthquakes. Multifactorial nature of the earthquake, on the other hand made it even more complicated to obtain reliable prognoses. Although increasing depth of investigation made such a prognosis more reliable.

Almost all major seismic zoning maps in former USSR were deterministic. They include the first map of 1937 and map of 1978.

In 1947 S.V. Medvedev proposed to differentiate the seismic hazard zones depending on the return period of strong earthquakes and durability of various buildings and structures [9]. Thus, in 1947, an offer to take into account seismicity or seismic activity of the territory when creating maps was made. Later, the famous scientist of former USSR Yu.V.Riznichenko for the first time introduced the concept of seismic "shakeability" and developed the first algorithm and program for its calculation [16]. Unfortunately, these and other progressive ideas and developments have not been used in the process of creating new maps for a variety of reasons. With that, this approach was developed in the West [5]. Just then K.A. Cornell suggested differentiating between seismic hazard and risk. The risk began to be understood not as risk of seismic event occurrence, but only as economic and social losses. The probabilistic seismic zoning maps with the probability of seismic hazard exceeding (or not exceeding) in certain time periods were first created in the West.

It is well known that nature is essentially non-linear. There are always uncertainties in nature laws that completely eliminate the use of deterministic seismic zoning maps. In other words, physically-based maps of seismic hazard differentiation or seismic zoning maps must be probabilistic. Herein the risk that always exists should be assessed and has to be the minimum.

This has led to a situation where the deterministic approach is expelled or banished from consideration. At the same time, it should be noted that the deterministic seismic hazard maps sometimes give estimates that are close to reality. In this context for calculation of seismic hazard in the beginning were used both map types.

The map that was developed later than the map of 1978 to some extent was taking into account the probabilistic nature of the formation of zones of seismic hazard, although essentially still not very different from deterministic.

The probabilistic approach was implemented for the first time in the new, more advanced seismic zoning maps of Russian Federation. These maps are called general seismic zoning maps or GSZ-97.

General map GSZ -97 is presented on Fig. 1. The map generalization is enough for state overall planning, but is not enough for reliable estimation of real objects seismic conditions.

The DSZ process is a complex of very complicated and expensive geology-tectonical, geophysical and seismical investigations for quantitative estimation of seismic effect in any site of perspective region [1]. This investigation type estimated quantitatively the source seismic effects only on concerned site GSZ (more precisely for mean soil conditions). [28]



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

The modern DSZ has clear and argumented content. There are some methods that may be used in GSZ and DSZ for seismic generic structures (SGS) identifications. It is identification of hazardous earthquake occurrence zones. [12]

#### 2.1. Seismogeological method

At the turn of XIX and XX centuries G.Abich, A.E.Lagorio and the other scientists found out as a result of earthquakes epicentral zones investigations that earthquakes are connected with tectonic structures. So, when describing the strongest Vern earthquake consequences (1887) Mushketov I.V. (1889) straightly connected earthquakes with fractures and faults. He believed that earthquakes have maximum effect on the lines of large and new faulting (Mushketov, 1891). He also discovered that some groups of earthquakes are connected with transverse structures. Later on the basis of the Kebi earthquake investigation results Bogdanovich K.I. introduced the concept of seismotectonic elements and showed migration of seismic shocks within seismically active zone.

Thus, seismogeological method determined the connection between strong earthquakes and tectonic structures. Such connections were named geologic criteria of seismicity. [12, 28].

#### 2.2. Seismotectonical methods

By the results of Garm region between Pamir and Tien Shan in the late 40-es of the XX century Gubin I.E. for the first time introduced the term seismotectonical method. Herewith he connected strong seismic events with ruptured occurrence with the width up to several tens of kilometers. He supposed that within such a zone "seismogenity" remains and "seismogenity level" corresponds to other similar zones which are characterized by development processes of equal intensity. Gubin's law of seismotectonic says that in active structures of similar type and size maximum earthquakes originated as the result of rock displacement along active faults are characterized by equal values of focuses and magnitudes. The method at that connects geologic criterion of seismicity with a velocity of new fault displacements.

#### 2.3. Seismostructural method

This method was offered in the middle of 50-es by Belousov V.V., Goryachev A.V., Kirillova I.V., Petrushevskiy B.A., Rezanov I.A., Sorskiy A.A. But the main development the method gained in the works of Petrushevskiy B.A. Such method connects seismic events with large structural complexes – blocks. Mentioned blocks were separated with the help of historical and structural analysis [12].

The analysis of blocks scale allowed connecting a considerable range of earthquake focuses depths with them and with deep faults. The deepest faults are located on the boundary of the Pacific Ocean and Eurasian and American continents. The concept about strong earthquake focuses connection with three-dimensional structures of Earth crust was later developed by Gorshkov G.P. (1984) [28]. Although the direction is considered as promising it needs to be fleshed out.

### 2.4. Tectonophysical method

The method was developed in the end of 50-es by Gzovsky M.V. [12]. The feature of the method is the connection of strong seismic event with the areas of maximum shearing stress. Such areas

are characterized by faults and maximum gradients of average velocities of tectonic movements. Although Gzovsky M.V. made earthquake energy dependent on a number of factors it is practically impossible to make exact calculations. It was defined exceptionally by qualitative but not quantitative terms of mechanical properties of Earth crust and its viscosity in the region of maximum shearing stresses.

#### 2.5. Method of quasi-homogeneous zones allocating

This method was first offered in the end of 50-es of the XX century as well as the previous method. The concept of the method consisted in detection of quasi-homogeneous areas where earthquake could be caused by the presence of geological and geophysical criteria. In this case it was supposed that some of them are connected with tectonic movements [12]. Since the number of characteristics is endless the number of situations with maximum magnitudes can also be endless. It stipulated an extension of characteristics and usage of all geological, seismological and geophysical data for allocation of zones with different seismic potential of tectonic nature. Data correlation allows giving prognosis of maximum magnitude  $M_{max}$ .

Today the techniques developed by Reisner and Ioganson are frequently used. At that the whole number of characteristics such as relief, crustal thickness, heat flow density, isostatic anomalies of gravity force, stratum depth of consolidated basement etc. is used for analysis. Realization of the techniques supposes usage of reference sites from all active regions of the world. In this connection such approach is named overregional [28].

#### 2.6. Method of seismically active nodes

This method was also offered in the end of 50-es of the XX century. Data analysis of central Asia earthquakes allowed Reiman V.M. connecting disjunctive nodes to which strong earthquakes or seismogenetic nodes are confined. The method was significantly developed by Rantsman E.Ya. (1979). She used the approach to the number of world regions and connected focuses of strong earthquakes with these nodes. Herewith the author noticed that "focuses can exceed nodes in size and amount up to thousands kilometers". Structure differentiation on their seismicity is realized with the help of formalized criteria (relief type, maximum height, distance from node edges, volume of soft sediments etc.). It was determined that transverse uplands form structures which generate nodes [12].

#### 2.7. Paleoseismological method

The method (Solonenko V.P., Khromovskikh V.S., Nikonov et al.) allows allocating PSS zones and assessing their seismic potential (maximum magnitude and seismic intensity) on the basis of study of paleosiesmodislocations spatial orientation. As a rule, seismotectonic dislocations are used for the assessment of these parameters. The number of formulas which connect statistic correlations between seismodislocation characteristics (length, shift amplitude) and seismologic parameters (magnitude, focus depth, seismic impacts intensity) of earthquake is known. Return period of earthquake is determined by paleoseismodislocations age. Herewith all existing approaches are compared: geologic-geomorphological, archeological, historical data and the results of radiocarbon dating, dendrochronology, connections of tree growth and earthquakes and lichenometry (lichen dating).

## 3. Detailed seismic zoning

Analysis of the considered approaches shows that each method characterizes one or another aspect of the problem. Herewith some of them are developed straight on the assumption of practice demands. Other methods suppose a number of complimentary stages for achievement of final problem investigation. Overregional method is referred to the first group and we'll try to use it.

For avoidance of any doubt let us consider typical way of seismic hazard level determination and all other attributes necessary for goal achievement. So let's begin to realize the problem of assessment on the level of detailed seismic zoning (DSZ) by the example of the territory of the Republic North Ossetia-Alania (Zaalishvili, Rogozhin, 2011).

As was mentioned above we chose overregional seismotectonic method for allocation of PSS zones; such method permits to identify seismic or seismogenic source quite completely. Although there are some disadvantages on practice the method gives quantitative indices and it is characterized by the certain decision-making algorithm. The method was successfully used in works of prof. Rogozhin E.A. in many countries of the world (Russia, Israel, China, Kirghizia etc.). We were able to realize the method in North Ossetia exactly due to his active support. 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 [5, 15, 28]: 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 were created on the basis of investigation of corresponding territory main characteristic. 1-4 stages of such work realization are given further by the example of the territory of North Ossetia.

#### 3.1. Definition of earthquake sources

As it was mentioned previously probabilistic assessment gain the largest extension at seismic hazard assessment of territory in the world in recent years. Various investigations had shown that such assessment gives physically more proved results. Indeed, at such assessment it is possible to forecast more sequentially a location of expected seismic events, their intensity etc. [14, 17]. The main difference from other methods consists in the fact that special processing of the existing data allows accounting uncertainties caused by our half knowledge of cause-and-effect relations and random factors at formation of our understanding about spatiotemporal realization of one or another seismic event. It is necessary to mention the computer program EQRISK of McGuire [8]. This program noticeably simplified assessments of seismic hazard what caused its wide extension. It came to a point where seismic hazard assessment with the help of probabilistic approach sometimes is called Cornell - McGuire's method.

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 [6, 12, 17, 20, 21]. On the basis of investigation results of the active faults located southward of the Great Caucasian ridge, parameters of seismic source zones were chosen according to data of I.P.Gamkrelidze work [6]. We used the investigation results of Ulomov V.I., Rogozhin E.A., Trifonov V.G. for accounting the indices of Northern Caucasus in our work. On the first stage of seismic hazard map making there was carried out an approximate or expert calculation of seismic sources (PSS zones) for the territory of the Republic North Ossetia-Alania. Further the map of allocation (zoning) of such PSS-zones was made.



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

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..

No	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.2)

Usage of this method 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 (Fig.2), (table 1), [14, 17, 28]It is necessary to notice that on the next stage each possible seismic source was subjected to more exact assessment of its seismic potential. This stage is named a parameterization of seismic sources. The M<sub>max</sub> was determined by the data of the above mentioned authors.

On the next stage of investigations it was necessary to determine a range of strong earthquake focuses depths. There are no such deep hypocenters as in other regions. The range varies a little and the depth amounts 20-25 km. Herewith it is necessary to notice that hypocenters depths obviously increase monotonically to Grozny city and Caspian Sea. With a lack of data about earthquake distribution the average value of depth was assumed equal to 10 km (see Table 1).

#### 3.2. Seismicity of North Ossetia-Alania and its connection with PSS zones

The catalogue of strong earthquakes was defined further. It supposes to check the existing data by correlating it with catalogues of certain authors and results of international investigations. Seismicity data for each zone were defined by the following catalogues: 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 [26, 28]. The issue is seismic events which are referred to historical period meaning last 20 centuries or a new era. So the catalogue was defined. In certain cases when needed a depth of event focuses was recalculated.

Values *a* and *b* of law of frequency and the largest magnitude were determined only for large zones. This fact was caused by absence of such data. Well known formula of Gutenberg-Richter was applied in calculations:

$$\lg(N/T) = a - bM \tag{1}$$

where: N-number of events for a time period T, a and b are parameters of inclination and level of recurrence graph at M=0, respectively.

Analysis of recurrence graph dependence on distance allowed determining representativity and weighted contribution of each seismic zone. Herewith the opportunity of taking into account curve deviation of density distribution became available.

#### 3.3. Estimation of earthquake effect

Thus seismic effect was estimated in intensity units and peak ground acceleration (PGA). Observation data and instrumental data on 43 significant earthquakes that occurred in Caucasus were revised to obtain the necessary information [19].

Data on 37 earthquakes was selected and in some cases the maps in the 1:500 000 scale were created. It was determined at the formation of the maps that within three isoseists for events with magnitude Ms>6 coefficient values are quite high ( $\nu$ ~4.5-5.0). For small and moderate earthquakes such values are less ( $\nu$ ~3.4). Data analysis allowed obtaining two different formulas for strong and weak earthquakes:

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

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

where:  $M_s$  – the surface-wave magnitude,  $\Delta$  – epicentral distance, h – focal depth

We used the second formula at the assessment of seismic hazard. Maximum intensity in the focus at that was 9 points (for magnitudes 6.5-7.0) and for 8 points the magnitudes were 5.5-6.0.

Due to the fact that on Caucasus in the period between June 1990 and September 1998 about 500 accelerograms were obtained for 300 relatively strong earthquakes [19] they became the basis for the formulas of macroseismic fields. The data of temporary and constant instrumental systems on Southern Caucasus and nearby areas were used during the data analysis. They included 84 corrected accelerograms from 26 earthquakes with magnitudes between 4.0 and 7.1. Correlations were obtained with the help of two step regression model (Joyner and Boore). The resulting equation for larger horizontal values of peak horizontal acceleration is:

$$LogPHA = 0.72 + 0.44M - \log R - 0.00231 + 0.28p,$$
  

$$R = (D^{2} + 4.52)^{1/2},$$
(4)

where:

PHA - peak horizontal acceleration in cm/sec<sup>2</sup>,

M – surface-wave magnitude,

D – hypocentral-distance in km;

p is 0 for 50-percentile values and 1 for 84-percentile.

It is necessary to mention that coefficients of attenuation for horizontal accelerations are similar to the coefficients for Western part of North-America. Herewith analogous indices in Europe are less than on Caucasus and adjacent areas.

#### 3.4. Determination of hazard

The probabilistic seismic hazard maps in intensity units (MSK-64) and in acceleration units for the territory of North Ossetia were worked out in a scale 1:200000 with exceedance probability for a period of 50 years (standard time of building or construction durability!) with 1%, 2%, 5%, 10%. All works were carried out in GIS technologies. At that return periods are equal to 5000, 2500, 1000 and 500 years correspond to the given probabilities (Fig. 3, 4).

The essence of the approach consists in the fact that the longer a considered time period the higher an intensity of design earthquake is. The recurrence is changing depending on the level of design intensity. So, expected intensity equal to 10 points corresponds to a period of 5000 years, 9 points – 2500 years, 8 – 1000 years, and finally, intensity level equal to 7 points corresponds to return period of 500 years [18, 26-28].

For calculation of design seismic effect we used computer program SEISRisk- 3 [5, 8]. When choosing an intensity map it is necessary to correlate obtained maps with real intensity effect of expected earthquake on considered territory. At that we must choose the map which will correspond most of all to a real situation particularly to territory features [10].



**Figure 3.** Probabilistic maps of seismic hazard (DSZ) in the intensity units (MSK-64) with the exceedance probability 5% (a) and 2% (b) for North Ossetia territory and adjacent areas [27].



**Figure 4.** Probabilistic map of seismic hazard (DSZ) in acceleration units (PGA) with exceedance probability 5% (a) and 2% (b) for North Ossetia territory [27, 28].

Thus, for the first time in Russia we realized seismic hazard assessment quite detailed. In this connection it is necessary to remind that seismic hazard map that is included in building code

of Russia has the scale M 1:2 000 000 and our map has the scale M 1:200 000! Besides it must be noted that some part of the map of General seismic zoning of Russia has the scale M 1:8 000 000! It, undoubtedly, can characterize the maps in a scale M 1:200 000 as the maps of detailed seismic zoning. It should be noted that we simultaneously worked out seismic hazard maps both in traditional for Russia intensity units and in acceleration units.

Further analysis of the data which characterize the territory allowed concluding quite reasonably that 5 % map with exceedance probability of 50 years is the most appropriate for the Republic territory. It corresponds to earthquake recurrence of 1000 years. Exactly such recurrence was revealed for seismic events with 8 points intensity with the help of special field investigations of the previous earthquakes on the territory of North Ossetia. Thus, we recommended this map for mass construction. At calculation of responsible buildings and constructions to seismic impacts where risk of expected economic and social losses reaches higher values we recommend 2 % map for seismic hazard level with exceedance probability of 50 years (Fig.3). The zone of increased 9 intensity is clearly seen on intensity map. Such intensity is caused by presence of powerful Vladikavkaz fault (Fig.2). Correlation of seismic hazard maps in intensity and acceleration units shows that for acceleration map we have smoother change of hazard level (Fig.3, 4). Indeed, offset distance with any level of hazard can't show such abrupt intensity changes only in cases of appearance of additional hazards or changing of some other conditions, for example, soil conditions, which we don't take into account. That is why seismic hazard maps in acceleration units are more preferable for engineers. The history of forming of seismic processes observation networks stipulated quite full absence of acceleration records on the territory of Russia. On the other hand acceleration maps usage allows reaching any monotonous transition between different zones boundaries with change of consideration stage. It is very important under the conditions of increased seismic hazard. New approach where nonintegral values instead of whole-number values (for example, 8.1 or 7.5) are considered as intensity level of seismic hazard was worked out in recent years in Russia. It is hard characterizing and even understanding an assessment of seismic effect equal to 0.1 or 0.7 intensity. In spite of its conditional and uncertain characteristic this approach was used on practice widely at Olympic objects constructing in Sochi. It is obvious that authors used the so-called "expert" assessments here.

The way out is independent creation of seismic hazard maps in units of peak ground accelerations (PGA). We have worked out such maps for exposition of 50 years with exceedance probability. They have the scale M 1:200 000 and probability 1%, 2%, 5%, 10% (Fig. 4). Rapid change of acceleration levels on those maps can be excluded within reasonable rates. Exactly these maps (which were the first on the territory of Russia and CIS) while being probabilistic maps of detailed seismic zoning will be the basis for creation of probabilistic maps of seismic microzonation. Maps of seismic microzonation as a rule are made in scales 1:2000, 1: 5000 or 1: 10 000 [28]. It is possible to made maps in larger scale but it doesn't have practical sense. Indeed, soil conditions do not generally change faster and at construction of certain building or structure we always know soils on more detailed level. In this connection it is necessary to remember that we create maps of microzonation in the form of schemes for typical soils of investigated territory.

At the same time hydroelectric stations or atomic power stations may need higher level of protection. That's why considerably larger return periods can be considered for such objects. According to the accepted approaches for investigated territory the period will be 5000 years with the intensity 10 points. At the same time this period easily can be 2500 years with intensity 9 points for majority of other responsible objects (high-rise building etc.). Herewith very interesting consequence appears. It consists in the fact that level of territory security under otherwise equal conditions depends on a level of economic potential of this or that country. Developed country within common sense can presume any economically accessible level of design intensity. And we can see that earthquake consequences of the same level are always more drastic and catastrophic for poor hindward country. On the other hand in authoritarian state it all depends on a good will of bodies of government, which know that fact. Exactly due to that at strong consequences of natural and anthropogenic processes they can be concealed truckle to bodies of government. For example, the fact that death toll after strong Ashkhabad earthquake in 1948 amounted to 80 000 people was brought to light only many years on. In all fairness it must be noted that such and more egregious facts also took place later in other countries.

## 4. Seismic microzonation of territory

The sites with reference soil conditions corresponding to specified seismic hazard level are specified in the process of seismic microzonation. In Russia as reference soil conditions for a given territory are traditionally considered the soils with mean seismic properties (usually soils with shear wave velocity of 250–700 m/s). For example in Georgia depending on specific engineering-geological situation for a given territory the reference soils in their seismic properties can be worst or mean. In USA firm rocks are referred to reference soils. Seismic microzonation concludes the computation of intensity increments caused by soil condition differences. Seismic microzonation is carried out with the help of instrumental and calculational methods [28].

#### 4.1. Instrumental method of seismic microzonation

The main method of seismic microzonation is an instrumental method. Exactly this method urges to solve a forecast problem of forming earthquake intensity. However the calculational method which allows modeling any definite conditions of area and impact features is often characterized as more reliable. It is very important for high power soil stratum. Usage of both methods together significantly increases the results validity.

#### 4.1.1. Seismic microzonation on the basis of strong earthquakes instrumental records

A number of corresponding international projects were worked out for receiving a data about different soils behavior at strong earthquakes. It is necessary to mention that the data of permanent systems of instrumental observations on the island Taiwan (the groups SMART-1 and SMART-2.) [25, 26, 28] in our opinion were characterized by the most reliable background.

It is also necessary to notice that obtaining of even strong earthquake record cannot guarantee its adequate proper usage. Therefore working out of approaches which can increase physical validity of the data is very topical problem. In particular one can create design impacts with taking into account seismic sources features (for example, accelerograms) for the level of DSZ [25, 26, 28]. Further accounting a distortion of wave field caused by soil condition change we can receive new implementation of each site. Herewith usage of even single record of strong earthquake will give very important results for testing of strong earthquake design records.

#### 4.1.2. Seismic microzonation with the help of weak earthquakes records

It is obvious that the number of earthquakes is limited except the fact that you live in Japan. That's why registration of soil vibrations caused by weak earthquakes in absence of strong earthquakes became quite important factor. Formation of weak earthquake database became a reliable basis for data testing. Herewith that single virtual record of strong earthquake which at first glance was neglected will take an important place again. It is clearly seen that linear deformations during weak earthquakes must be transformed into nonlinear-elastic and even into nonelastic links "deformations – tensions". Amplitude-frequency characteristics of areas and recording form significantly vary when changing soils (Fig. 5) [25, 28].

Increase of the soil stratum depth (alluvium) considerably changes the character of earthquake records in the process of approaching the city.



Figure 5. Scheme of California earthquake in Koaling city

Calculation of intensity increment with the help of weak earthquakes is realized by the formula [25]:

$$\Delta I = 3.3 \lg A_i / A_0, \tag{5}$$

where:  $A_i$ ,  $A_0$  are the vibration amplitudes of investigated and reference soils, respectively.

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

#### 4.1.3. Seismic microzonation with the help of weak earthquakes records

Strong earthquake extremely seldom occur on territories with small and moderate seismic activity. At that hazard level not only decreases but it can even increase due to impossibility of timely unloading of high tensions. In this connection when calculating intensity increment of weak earthquake records the dependence "deformation – tension" is linear. It causes inaccuracies in soil behavior assessments at expected strong earthquakes when dependence is nonlinear.

Calculation of intensity increment with the help of weak earthquakes is realized by the formula [25]:

$$\Delta I = 3.3 \lg A_i / A_0, \tag{6}$$

where:  $A_i$ ,  $A_0$  are the vibration amplitudes of investigated and reference soils, respectively.

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

#### 4.1.4. Seismic microzonation using microseisms

The results of microseisms observations [25] are used as subsidiary instrumental tool of SMZ. 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. 6)

Intensity increment for strong earthquakes on microseism is calculated by the formula [25]:



where:  $A_i$ ,  $A_0$  are the maximum amplitudes of microvibrations for investigated and reference soils, respectively.

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 [11, 25].

Microtremmor	signal. Site #2, HF=0.20 Hz LF=20.00 Hz		
1,853E+00 1:U B,516E+00	Manany Manan Manan was and was a second s		
2,928E+00 2:U B,146E+00	have and the second second and the second		
2,979E+00 3.U B: 821E+00	prosperation and the second of		
4.354E-02 4:U B.811E-02	monorman and monorman and a part of the pa		
3,146E-02 5:U B: 582E-02	warmon man man man man and when man when a man when a man and the second and the		
2,908E-02 6.U B: 731E-02	www.www.www.www.www.www.www.www.www.ww		
3,702E-02 7:U B: 109E-02	man have man and have a second		
3.114E-02 8 U BL069E-02	and a second and the		
4,619E-02 9:U B:668E-02	when with my man was a second with the second of the second		
1,008E+00 10:U B 204E+00	Munan MMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM		
1,455E+00 11:U B 505E+00	Man marked and a second marked and a second and a second s		
2.522E+00 12:U B 163E+00	www.www.Wernander.wall. When were a second when we wanter were a second with the second secon		
0.0305 seriem 25.3	0,19 827		

Figure 6. Microseisms records (10.07.1996, Voronezh Region, Russia)

#### 4.1.5. Seismic microzonation using explosive impact

The intensity increment  $\Delta I$  of the soils of the zoned territory is calculated by the formula [25] 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 reference soils, respectively.

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 [28].

#### 4.1.6. 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 [25]:

$$\Delta I = 1.67 \, \lg \, \rho_i V_i / \rho_0 V_0 \tag{9}$$

where:  $\rho_0 V_0$  and  $\rho_i V_i$  is the product of the soil consistency and P-wave (S-wave) velocity – seismic rigidities of the reference and the investigated soil, respectively.

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

$$\Delta I = K \,\mathrm{e}^{-0.04h_{\mathrm{GL}}^2} \tag{10}$$

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 given approach of S.V.Medvedev gained unexpectedly wide extension in 70-es of the XX century due to its simplicity and efficiency (CIS countries and countries of Eastern Europe, USA, Chile, Italy, India). This approach could be realized on practice in a very short time etc. thanks to its territory seismic regime independence. To a certain extent this blocked the development of other alternative approaches. At the same time negative sides of such approach soon were revealed. In the case of watered soils absence formation of intensity increment exceptionally due to type of correlated soils didn't hold up against criticism and gave inconformity with displayed differences of correlated soils at strong earthquakes. Thereafter it brought to the approach disregarding almost in all countries besides CIS countries [25, 28]. On the other hand it is necessary to notice that in case of such work performance all opportunities must be used.

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. 7).



Figure 7. Surficial gas-dynamical pulse source (SI-32)

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 [22] 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 [25]:

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

where:  $f_{0}$ ,  $f_i$  are predominant frequencies of reference and investigated soils, respectively.

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 [22].

Intensity increment was determined by the following formula [25]:

$$\Delta I = 0.8 \, \lg \rho_0 V_0 f_{wa0}^2 \, / \, \rho_i V_i f_{wai}^2 \tag{12}$$

where:  $f_{wa0}$ ,  $f_{wai}$  are weighted-average vibration frequencies of reference and investigated soils, respectively.

Weighted-average vibration frequency of soils was calculated at that on the formula [22, 28]:

$$f_{\rm wa} = \sum A_i f_i / \sum A_i \tag{13}$$

where: A<sub>i</sub> and f<sub>i</sub> are the amplitude and the corresponding frequency of vibration spectrum, respectively.

4.1.7. Seismic microzonation using vibration impact

At usage of a vibration source (Fig. 8) the calculation of intensity increment is realized with the help of the formula [25]:

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

where:  $S_i$  and  $S_0$  are the squares of vibration spectra of investigated and reference soils, respectively.

The developed tool was used at SMZ of the territories of cities Tbilisi, Kutaisi, Tkibuli, single areas of the Large 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



Figure 8. Vibration source (SV-10/100)

of soil thickness response on standard (vibration or impulse) impact. Later the formula was successfully used at SMZ of the sites of Novovoronezh atomic power-plant (APP) with the help of an impulsive source.

#### 4.1.8. Seismic microzonation on the 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 the basis of taking into account nonlinear – elastic soil behavior or elastic nonlinearity (at usage of vibration source) [25, 28]:

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

where:  $A_i f_{wai}$ ,  $A_0 f_{wa0}$  are the products of spectrum amplitude on weighted-average vibration frequency of investigated and reference soils, respectively.

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

If the impulsive source is used at SMZ then the formula will have the form [25]:

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

#### 4.1.9. Seismic microzonation based on accounting of soil inelastic properties

The estimation of potential soil nonelasticity adequately and physically proved at intensive seismic loadings is the most important problem of SMZ as soil liquefaction and differential settlement of the constructions are observed at strong earthquakes (Niigata, 1966; Kobe, 1995).

For direct assessment of soil nonelasticity the specific scheme of the realization of experimental investigations (fig. 9, a) with gas-dynamic impulsive source GSK-6M (with two radiators) was used. Chosen longitudinal profile location allowed making impact sequentially by two emitters from near and somewhat far radiation zones. The HF component that quickly attenuates with distance (Fig. 9, b) prevails in the spectrum of soil vibrations, caused by near emitter. In a case of distant emitter impact the LF component predominates in the spectrum of vibrations (Fig. 9, 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 impacts 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 impact value is [28].

At usage of vibratory energy source, the whole number of new formulas [25] was obtained in order to assess soil seismic hazard with taking into account the amount of their nonelasticity:

$$\Delta I = 2.4 \left[ \lg \left( S_{ri} \right)_n \left( S_{r0} \right)_d / \left( S_{ri} \right)_d \left( S_{r0} \right)_n \right], \tag{17}$$

where:  $(S_{ri})_{n,d}$   $(S_{r0})_{n,d}$  are the squares of real spectra of soils under investigation and reference soils in near and distant zones of the source, respectively.

$$\Delta I = 3.31 g[(A_i f_{awi})_n (A_0 f_{aw0})_d / (A_i f_{awi})_d (A_0 f_{aw0})_n],$$
(18)

where:  $(A_i f_{awi})_{n,d}$  and  $(A_0 f_{aw0})_{n,d}$  are the amplitudes and weighted-average frequencies of soils under investigation and reference soils in near and distant zones of the source, respectively.

If a powerful impulsive source is used the offered formulas will be as following:

$$\Delta I = 1.2[\lg(S_{ri})_n (S_{r0})_d / (S_{ri})_d (S_{r0})_n],$$
<sup>(19)</sup>

where:  $(S_{awi})_{nd}$  and  $(S_{aw0})_{nd}$  are the squares of real spectra of soils under investigation and reference soils in near and distant zones of the source, respectively;

$$\Delta I = 2 \lg[(A_i f_{avi})_n (A_0 f_{av0})_d / (A_i f_{avi})_d (A_0 f_{av0})_n],$$
(20)

where:  $(A_i f_{awi})_{n,d}$  and  $(A_0 f_{aw0})_{n,d}$  are the amplitudes and weighted-average frequencies of soils under investigation and reference soils in near and distant zones of the source, respectively.



**Figure 9.** Investigation of site spectral features by means of GSK-6M seismic source: a) experiment scheme; b) records of first source impact; c) records of second source impact

The formulas (17) and (18) are adequate only for loose dispersal soils. The formulas (17) and (18) were used at SMZ of Kutaisi city territory. Besides, using the formulas (19) and (20) nonelastic deformation properties of soils in full-scale conditions on Novovoronezh APP-2 site were defined more accurately [25, 28]. The formulas were obtained based on physical principle that underlies the scheme used at the soil looseness assessment.

#### 4.2. Calculational method of seismic microzonation

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

Nonlinear soil properties can be taken into account in the problems of earthquake engineering with the usage of instrumental and calculation methods. The main method of seismic microzonation is the instrumental method. However, it is often necessary to use calculational method for solving such problems. Calculational method allows modeling virtually any conditions that are observed in the nature. The requirements of practice however reduced to the necessity of calculation of soil vibrations for nonlinear-elastic and nonelastic deformation conditions. Solving such a problem it is assumed that elastic half-space behaves as linear-elastic medium and at intensive seismic or dynamic impacts the covering soil stratum displays strong nonlinear properties.

Received instrumental stress-strain dependences can be applied, for example, for plastic clay soil shown in Fig. 10. Offered by A.V.Nikolaev [13] conception of the so-called soil bimodularity is taken into account in that dependence [25]. Considerable differences in "weak" soils behavior at compression and extension underlie in the phenomenon. Such soil is characterized at extension by very small modulus of shearing.

Solving of the given nonlinear problem for soils in the analytic form is usually based on considerable assumptions due to the complication of adequate accounting of behavior features of such complicated system as the soil. Thus, the numerical solving of nonlinear problems on the present-day stage of knowledge is the most proved under the condition that the data of field or laboratory investigations are considered in these or those connections [23, 24, 28].



Figure 10. Instrumental stress-strain curve, showing property of soil bimodularity

So, the basis for solution of calculation nonlinear problems is the correlation determined using experimental investigations. Otherwise stated, programs for solving of calculation nonlinear problems are in essence analytical-empirical. Such programs like SHAKE, NERA etc. are the most adequate.

#### 4.2.1. Equivalent linear model – SHAKE and EERA programs

One of the first models which take into account nonlinear soil behavior is equivalent linear model. Equivalent linear approximation involves Kelvin–Voight model's modification (for taking some types of nonlinearity into account) and, for example, is realized in the programs SHAKE [2] and EERA [27]. Equivalent linear model is based on the hypothesis that shear modulus G and attenuation coefficient  $\xi$  are the functions of shearing strain  $\gamma$ . At calculations in both programs the parameters of soil multilayered structure were accounted in "natural occurrence" through the introduction of values of shear modulus G and attenuation coefficient

 $\xi$  for each layer in thickness structure. With the help of layer combination it allowed receiving a necessary deformation level which fully corresponds to real thickness deformation at hard loads.

#### 4.2.2. NERA program

It is necessary to notice that approach used in the EERA work out became later the basis of new computer program of NERA (Nonlinear Site Response Analysis) [2]. This program allows calculating nonlinear reaction of soil thickness on seismic impact. It is based on the medium model that was offered by Iwan (1967) and Mroz (1967). For short this model is often called the IM model. It is demonstrated that this model supposes strain-deformation simulating of nonlinear curves, using a number of n mechanical elements, which have different sliding resistance  $R_j$  and stiffness kj, where  $R_1 < R_2 < ... < R_n$ . Initially the residual stresses in all elements are equal to zero. At monotonically increasing load the element j deforms until the transverse strain  $\tau$  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.

# 4.2.3. 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  $\varrho$  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 [7, 25]:

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

where

$$n(P_{I}) = \begin{cases} 0.0 & \text{for } PI = 0, \\ 3.37 \cdot 10^{-6} PI^{1.404} & \text{for } 0 < PI \le 15, \\ 7.0 \cdot 10^{-7} PI^{1.976} & \text{for } 15 < PI \le 70, \\ 2.7 \cdot 10^{-5} PI^{1.115} & \text{for } PI > 70; \end{cases}$$
$$d = 0.272 \left\{ 1 - \tanh\left[ \ln\left(\frac{0.000556}{\gamma}\right)^{0.4} \right] \right\} e^{-0.0145 PI^{1.3}}.$$

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

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

where G is the current shear modulus,  $\sigma$  is normal stress.

Seismic energy absorption is calculated by the formula

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

On the 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 [25]. From the database of strong motions AGESAS, which was formed by us [26, 28], 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. 11). With the increase of seismic impact intensity the nonlinearity display increases. Absorption grows simultaneously. Hence the resulting motion at quite high impacts 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).



Figure 11. Results of calculations using multiple reflected waves' tool in linear (a) and nonlinear (b) cases.

#### 4.2.4. Calculation of nonlinear soil response using FEM tool of seismic microzonation

The problem of the determination of soil massif response on dynamic impact with taking soil nonlinear properties into account can be solved by usage of finite element method (FEM) in the following way [25].

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 element the soil is homogeneous with inherent to its characteristics, which vary in time depending on impact intensity. Earthquake accelerogram of horizontal or vertical direction, which is applied, as a rule, to the foundation of soil massif, is used as the impact. Soil is in the conditions of plane deformation and it is considered as an orthotropic medium. Axes of the orthotropy coincide with the directions of main strains [28]. 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.

#### 4.3. 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 [25]. Its usage is based on direct usage of modern databases of strong movements.

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 safely 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.).

#### 4.4. Relief influence on the earthquake intensity in SMZ problems

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 [25]. It conforms well to the investigation results of V.B.Zaalishvili, who introduced the new parameter of the relief coefficient (Fig. 12):



Figure 12. Relief coefficient R

Later the data analysis allowed to offer the empirical formula for the possible amplification calculation K and intensity increment  $\Delta I$ , which are caused by the relief [25]:

$$K = -0.1 + 0.68 \lg R \tag{25}$$

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

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 calculational method of FEM (Fig.13).



**Figure 13.** 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.

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 satisfies well 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).

Considerably fewer investigations are dedicated to the influence of the underground relief on the intensity. At the vee couch of the rocks, which are covered by sedimentary thickness, the ratio between wave length and the sizes of vee stripping have influence 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.

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.

#### 4.5. Seismic microzonation of Vladikavkaz city

If we consider 5% DSZ map as basis for seismic microzonation so seismic intensity of 8 points corresponds to reference 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 (Fig. 14).



**Figure 14.** The maps of seismic intensity microzonation for probabilities of 5% (a) and 2% (b) for the central part of Vladikavkaz city territory [26, 28].

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. 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 impacts, 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 [25]. The maps in accelerations units show the similar results. 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.

Engineering-geological zoning of territory is the basis of seismic microzonation. It assumes detailed investigations of features of the territory. Such works are quite expensive and laborconsuming. In the same time they are characterized by locality. During design of seismic microzonation maps it is important to adjust and refine data of engineering-geological conditions of investigated territory which are always exists in one or another form and can be used as approximate basis. And finally general view of these conditions must be given. Proven typification of main factors (thickness of quarternary deposits, velocity profile, groundwater level, surface and underlying soils slope angle, etc.). Actual examples of such investigations will be given– (Fig. 15):



**Figure 15.** Verification of engineering-geological conditions by means of H/V technique (a) and final map of seismic microzonaton of Vladikavkaz city (b).

Seismic microzonation maps, as the direct basis of earthquake design and practical construction, are maps of seismic hazard. Maps of seismic microzonation not just show where earthquake-resistant buildings are necessary. They show for what intensity buildings and constructions must be designed: 6, 7 or 8 or 9 points. This supposes the attachment of various financing for the implementation of the anti-seismic measures. It should be noted that the seismic zonation maps and microzonation can and should be constructed as well in units of acceleration. This will help to implement a more smooth transition from the borders of one seismic zone to another, thereby increasing the reliability of their allocation.

All types of maps and in particular maps of general and detailed seismic zonation as well as microzonation are nowadays formed in GIS technologies. The use of GIS technologies allows to lay a variety of information on a particular area or the whole territory, for example the city in the form of layers and to investigate their integral effect on the characteristics of seismic hazard occurrence.

## 5. 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. 16) [25, 28].

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

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 [3, 4].



**Figure 16.** Synthetical accelerograms for different source locations: a – western part of fault; b – middle part of fault; c – eastern part of fault; d – scheme of sources of scenarios earthquakes

Let's compare amplitude spectra of obtained design accelerograms with spectrum of real earthquake from considered fault. Data analysis (Fig. 17 and Fig. 18) 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 theatre) 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. 17). 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. 18).

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. At the same time investigations are conducted and the problem is supposed to be solved.



**Figure 17.** 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

On the other hand in recent years a new instrumental-calculation method was developed [25]. 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



**Figure 18.** Spectra of accelerograms of weak earthquake with epicentre in the zone of Vladikavkaz fault. (25.08.2005 10:25 GMT, H = 8 km M= 2.5).

(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 engineering, is introduced. Undoubtedly such approach significantly increases physical validity of final results.

Today, we have conditions for detailed seismic zoning maps development like the above mentioned but for all the territory of the Northern Caucasus on the basis of the modern achievements of engineering seismology. Thus algorithm of seismic hazard assessment of the territory that is 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 hydrogeological conditions).

### 6. Conclusions

1. The goal of the work was to analyze the modern concepts of the seismic hazard of the territory, its evaluation and development of an algorithm for such assessments. One of the main problems is to account a level of possible result errors, or adequacy of such assessments. The evolution of methods and techniques for seismic hazard assessments is presented. The algorithm of direct account of certain characteristics of the territory is given. The integrity of seismic hazard assessments is specified. Calculation of the expected seismic effects is considered.

- 2. The physical basis for creation of probability maps of general seismic zoning on the example of Russia (occupying a huge area) which needs small-scale mapping of seismic hazard of type 1:2 000 000-8000 000 for the management purposes are considered. On the other hand, seismic hazard assessment of a particular territory involves a need for a more detailed account of geological and geophysical features of the investigated territory.
- **3.** Further the physical principles and methods for creating of probability (1%, 2%, 5%, 10%) detailed seismic zoning maps of a particular region in GIS technologies, characterized by greater large-scale: 1:25 000 200 0000, which corresponds to return period of maximum probable earthquake of 5000, 2500, 1000 and 500 years are considered. At the same time, geological and geophysical features are accounted here undoubtedly more accurately. The future creation of detailed seismic zoning maps of vast territories is substantiated.
- 4. The physical basis, methods and techniques for creation of seismic microzonation maps, including the use of modern high-power non-explosive sources (vibration and impulsive action) are considered. The physical formation mechanisms of algorithms of direct account of a number of soils indicators under heavy loads, which are the basis of relevant computer programs, are considered. It identifies changes or distortion of the amplitude-frequency characteristics of the original or the incoming wave field of seismic impact caused by the interaction of absorption and nonlinearity (or inelasticity) phenomena in different typical soils of the territory.
- 5. Despite the similarity of names, the physical mechanisms of seismic microzonation are fundamentally different from the general and detailed seismic zoning. Seismic microzonation takes into account soil conditions and the territory is a direct basis of earthquake engineering and construction. At the same time to detailed zoning map of certain probability (for example, 10%) will correspond seismic microzonation map of the same probability obtained on its basis, i.e. likelihood of recurrence of 10% or 500 years.
- 6. The possibility of successful differentiation of soil conditions on the basis of the analysis of the relationship of the horizontal vibration spectrum of the initiated signal to the vertical spectrum and the predominant frequency of the ground motion is shown. The process of formation of seismic microzonation map of modern urban territory is considered.
- 7. At the end, based on the direct account of the features of the seismic source (for example, characteristics of the seismogenic fault) the formation of the expected seismic effect is shown. Comparison of calculated and real impacts showed their good similarity.
- 8. Complex of probabilistic maps of detailed seismic zoning, seismic microzonation maps and type of expected seismic impact is full and physically justified integral assessment of seismic hazard of territory.

## Nomenclature

ACCELEROGRAM - record of ground acceleration changes in time, obtained by accelerographs. BEDROCK - a relatively hard, solid rock that commonly underlies soil or other softer unconsolidated sedimentary materials.

DEFORMATION - a change in the original shape and/or volume of a material due to stress and strain.

DENSITY - either (1) the quantity of something per unit measure such as unit length, area, volume, or frequency (see, for example, power spectral density), or (2) the mass per unit volume of a substance under specified conditions of pressure and temperature.

DETAILED SEISMIC ZONING (DSZ) – type of seismic hazard assessment. The main tasks of DSZ – define seismic generating zones, assess focal parameters and their effects.

EARTHQUAKE - a shaking of the Earth that is either tectonic or volcanic in origin or caused by collapse of cavities in the Earth. A tectonic earthquake is caused by fault slip.

EARTHQUAKE ENGINEERING - the field of earthquake engineering is defined as encompassing man's efforts to cope with the harmful effects of earthquakes.

ENGINEERING SEISMOLOGY - that part of seismology which aims primarily at providing seismological data for earthquake engineering, earthquake hazard and earthquake risk applications.

EPICENTER - it is the point on the surface of the Earth, vertically above the place of origin (Hypocenter or Focus) of an earthquake. This point is expressed by its geographical coordinates in terms of latitude and longitude

EPICENTRAL DISTANCE - distance from a site (usually a recording seismograph station) to the epicenter of an earthquake. It is commonly given in kilometers for local earthquakes, and in degrees (1 degree is about 111 km) for teleseismic events.

FOCAL DEPTH - the conceptual "depth" of an earthquake focus.

GENERAL SEISMIC ZONING (GSZ) - type of seismic hazard assessment of a vast territories through the allocation of large seismic generating zones that determine area seismicity. In the result of GSZ are constructed maps in a scale  $1:250\,000 - 1:8\,000\,000$ , allowing rational planning of the development of different areas, to assess the total cost required for the anti-seismic measures on a national scale.

PEAK HORIZONTAL ACCELERATION - the maximum acceleration amplitude measured (or expected) in a strong-motion accelerogram of an earthquake, abbreviated PHA.

SEISMIC MICROZONATION (SMZ) – type of seismic hazard assessment. Initial seismicity or region intensity is set by maps of general and detailed seismic zoning (GSZ and DSZ). SMZ takes into account soil conditions that increase or decrease initial intensity of seismic vibrations.

VELOCIGRAM - record of ground velocity vibrations in time, obtained by velocigraphs.

## Author details

#### V.B. Zaalishvili

Address all correspondence to: vzaal@mail.ru

Geophysics and Engineering Seismology Department of Geophysical Institute of Vladikavkaz Scientific Centre of RAS, Russian Federation

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