Seismic hazard assessment of Georgia (probabilistic approach)

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Abstract. The probabilistic seismic hazard maps has been constructed for the territory of Georgia. Cornell approach, namely computer program SEISRISK III after Bender and Perkins 1987, was used for calculations. Three main elements were used for seismic hazard analysis following the Cornell approach: definition of seismic source zones (SSZ), parameters of seismicity and attenuation relationship.
The map of active faults of Georgia after E. Gamkrelidze et al. was used as a basis for definition of SSZ. After locating SSZ-es their parameterization is carried out.
The catalogue of earthquakes of Georgia was checked and revised. Some hypocentral parameters of earthquakes has been recalculated. Special algorithm has been used for definition of foreshocks, aftershocks and swarms. As a result the catalogue of so called independent events was compiled. *a* and *b* values have been calculated for SSZ-es.
Peak ground acceleration (PGA) and macroseismic attenuation models for the Caucasus and adjacent area was used for calculation of acceleration and intensity levels having 1%, 2%, 5% probability of not been exceeded during exposure time of 50 years. The map of observed maximal intensities was compared with the maps of different exposure periods and the difference between observed and calculated maps has been estimated to choose the optimal map for seismic zonation.

Introduction

Georgia is situated in Caucasus. It is one of the most seismically active regions in Alpine-Himalayan collision belt. The analysis of the historical and instrumental seismological shows, that this is the region of moderate seismicity. The strong earthquakes with magnitude up to 7 and macrosiesmic intensity 9 (MSK scale) occurred here. The reoccurrence period of such event is of order 10^3-10^4 years.
Seismic hazard assessment of Georgia was connected with compilation of seismic zonation maps of former USSR. Therefore seismic zonation maps of Georgia has been compiled in 1937, 1957, 1968 and 1978. The first map was compiled on the basis of "seismic actuality" principle – "the next strong earthquake will occur in the area of previous strong event". In next maps some seismotectonic elements were used, they were improved step by step, but all of them have serious drawbacks. The Soviet zoning maps were considered in details in several articles (Ulomov 1999, Balassanyan et al. 1999, Ulomov et al 1998). The main mistake of these maps was underestimation of seismic hazard of several seismically active ares. As a result, these maps were changing after each strong earthquakes, which occurred in the area of lower seismic hazard (according to the zonation map). Sometimes the difference between predicted and experienced intensities reached 2-3 units on MSK scale.
For example, according to the official seismic zoning map of former USSR, adopted in 1978, the expected intensity of shaking in Racha (Georgia) region should be 7 by MSK-

64 scale; at the 1991 event the intensity reached 9 at some locations. It have to be noted, that after Spitak earthquake of 1988 the official map of 1978 has been replaced in 1990 by a temporary map, compiled according to seismotectonic principles. This map, by the way, correctly predicts intensity of Racha event, which occurred several months after a new map has been adopted. But this change was useless for prevention of devastation, caused by earthquake: the main part of building stoke were constructed well before the new map adoption, that is, according to 1978 code. So, they could withstand shaking of intensity 7 only.

Taking into account lessons of Spitak and Racha earthquake, government of new independent state - Georgia - decided to create new general seismic zoning map of country, using modern methods of seismic hazard assessment.

Tectonic Setting

The seismicity of the area reflects the general tectonics of the region. The Caucasus is one of the most active segments of the Alpine-Himalayan collision belt. The main seismotectonic feature is the junction between Arabian and Eurasian plates. The northern movement and counterclockwise rotation of Arabian plate causes westward movement of Turkish block, eastward movement of Iranian block along the strike-slip faults and the creation of thrust faulting systems in Caucasus. Fault structures in Georgia (Gamkrelidze et al, 1998) exist mainly at the boundaries of tectonic units. The majority of faults were active during the Late Alpine (Orogenic) stage and have been developing till now. The Caucasian northwest and longitudinal faults, oriented along latitudes should be noted from this viewpoint. Several intrazonal faults have the same direction. All these faults are characterized mainly by the prolonged development and were born into different stages of extension of the Caucasus (middle Paleozoic, Early Jurassic, Late Jurassic, Early Cretaceous, Late Cretaceous, Middle Eocene, Late Pliocene) at the margins of the paleostructures of the Caucasus and Transcaucasus: of the island arcs, of the marginal sea of the Greater Caucasus, Atchara-Trialetian intraarc rift. Almost each of longitudinal faults was transformed into the deep reverse fault, thrust fault or tectonic nappe during the Orogenic stage of the Caucasus development, in a process of intense compression of the earth crust. Transverse faults of the Caucasus (submeridional, northeast and northwest) developed lately. Some of them have been developed within the certain large tectonic units (e. g. in the west part of Georgian block) or are strictly through ones (Tskhinvali-Kazbegi fault).

The majority of faults are lateral. Almost each main fault is revealed in different geophysical fields. The most of them are seen in aerial photographs. It was shown by means of the multidisciplinary data, that the fault structures are actually the margins between blocks. The map of active faults of Georgia, compiled by Gamkrelidze, et al is shown on Fig. 1.

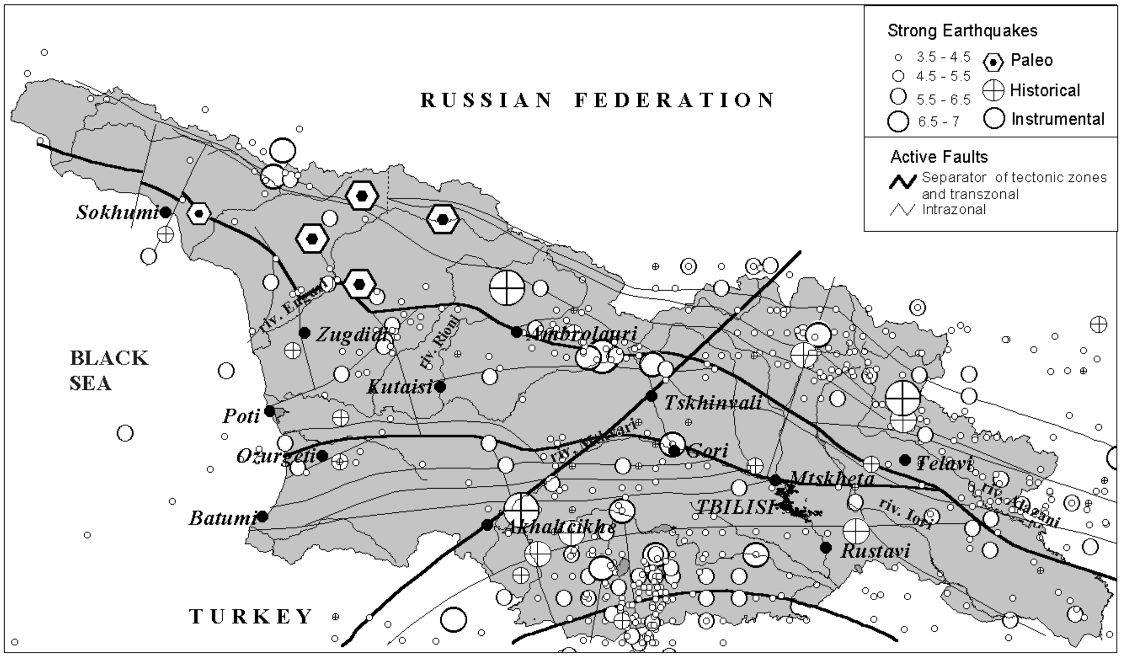

Fig. 1. Map of active faults (by Gamkrelidze et al. 1998) and epicenters of Georgia

Seismicity

Historical Seismicity. Catalogue of earthquakes of Georgia consists of two different parts historical and instrumental. Documentary historical catalogue stretches back to the beginning of the Christian era. The information about the earthquakes of this period has been extracted from ancient Georgian and Armenian annals, as well as from other sources (New Catalogue… 1982, Bius 1948, Tskhakaia&Papalashvili 1973). Fig. 1 shows the epicenters of earthquakes of historical and instrumental periods.

The parameters of historical earthquakes are determined on the basis of the macroseismic data analysis, from contemporary documentary description of damage caused by earthquakes. For the older events the errors, in both location and date, may be substantial. While bearing this in mind the correlation between locations of historical events and active faults is evident. The magnitude of largest events were estimated as ~ 6.5-7 and macrosiesmic effect as 8-9 on MSK scale New catalogue…1982). The largest historical events were mainly connected with active faults of the Greater Caucasus (Alaverdi earthquake of 1742, M_s=6.8, I_0=9, Lechkhumi-Svaneti large earthquake of 1350, M_s=7.0, I_0 =9 etc.) and Javakheti plateau in the Lesser Caucasus (Tmogvi earthquake of 1088, M_s=6.5, I_0=9, Akhalkalaki earthquake of 1899, M_s=6.3, I_0 =8-9). The strong Samtskhe earthquake of 1283, M_s=7.0, I_0=9, seems to be connected with the Borjomi-Kazbegi strike-slip fault.

Recent Seismicity. The instrumental period in Georgia begun in 1899 - the seismic station was installed in Tbilisi. At the beginning of XX century some additional seismic stations were opened in Georgia. They there equipped by the low sensitivity apparatus generally of mechanical type. In 1950 formation of the regional system of seismological data acquisition and treatment was finished. Since 1962 the modern instrumental period begun in Caucasus. The network was equipped by high sensitivity seismic equipment. In the beginning of eighties till 1992 the number of seismic stations have been increased and some local networks installed. The threshold magnitude has been reduced sharply to M=1.5. During the last years the number of seismic stations has been decreased (from 40 stations in Georgia in 1991 to 10 in 1997) due to political and economical problems.

The seismological database of the institute of Geophysics includes the information about 57 000 earthquakes.

The large events (M≥6) during instrumental period are - Teberda earthquake of 1905 (M_s=6.4, I_0=7), Kartli earthquake of 1920 (M_s=6.2, I_0=8-9), Tabatskuri earthquake of 1940 (M_s=6.0, I_0=8), Chkhalta earthquake of 1963 (M_s=6.4, I_0=9), Racha earthquake of 1991 (M_s=6.9, I_0=9), Barisakho earthquake of 1992 (M_s=6.5, I_0=8).

The Racha earthquake that occurred on April 29, 1991, at 09:12:48.1 GMT in the southern border of Greater Caucasus is the biggest event ever recorded in the region. The earthquake killed more then 200 people, left approximately 60 000 homeless and caused damage over thousands of square kilometers. A maximum intensity of 9 on the MSK scale was observed. The mainshock was followed by aftershocks that extended over several months. Among them there were three strong aftershocks with magnitude greater than M_s≥5.5: April 29, at 18:30, M_s=6.1, May 3 at 20:19 M_s=5.5and June 15 at 00:59, M_s=6.2. These events caused farther damage and casualties.

Hazard Analysis

On the basis of multidisciplinary data (seismological, geological, geophysical etc) a set of probabilistic seismic hazard maps for Georgia has been compiled. The seismic effect was calculated both for the ground acceleration and the macroseismic intensity. The methodology used in most probabilistic seismic hazard analysis was first defined by Cornell: it consists of four steps (Reiter 1990, Kramer 1997, Musson 1999):

1. ***Definition of earthquake source zones***, The area under investigation is divided into discrete seismic source zones, each of which deemed to be uniform in the character of its seismicity. There should be an equal probability that an earthquake of a given magnitude could occur at any place within a single source zone.
2. ***Seismicity (definition of recurrence characteristics) of source zones***. The seismicity within each source zone is studied, using the earthquake catalogue, in order to determine the magnitude-frequency relationships, seismic rate and other parameters.
3. ***Estimation of earthquake effect*** at the site. A locally appropriate attenuation relationship is chosen, to relate the expected ground motion at site during an earthquake to the magnitude of the earthquake and its distance from site. The uncertainty or scatter of the ground motion values is an important variable, which is essential for the analysis.
4. ***Determination hazard at site***. The hazard analysis is based on the fact that the probability that an earthquake of magnitude M occurs in a source zone within any given distance interval is proportional to the fraction of the area of the zone that occurs within this range of the site. Since each source zone is deemed to be homogenous, the fractional occurrences expected in any small sub-area of the zone can easily be calculated. An analytical integration is performed over all ground motion values, magnitudes, and source zones. From the results it is possible to determine the probability of any intensity or acceleration value being exceeded, assuming That

seismic process to follow a Poison distribution.

One important issue is how to treat uncertainties in the basic parameters of the seismicity distribution. Different approaches has been used for this purpose (Reiter 1990, Kramer 1997, Musson 1999).

The probabilistic hazard maps for the territory of under study was compiled and we shell describe in brief this works according to the above noted steps.

1. Definition of earthquake sources The map of active faults of Georgia after E. Gamkrelidze et al. 1998 was used as a basis for definition of seismic source zones (SSZ). After locating SSZ-es their parameterization was carried out, i.e. for each of them seismic potential M_{max} - the largest possible magnitude -was estimated This is the most difficult task in a process of SSZ parameterization. In this work M_{max} was determined using various relations.

The upper limit of M_{max} has been evaluated in the first place. Relationships given in *Varazanashvili 1998* were used for this purpose, since they match regions of moderate seismicity like the Caucasus and Georgia:

The second significant parameter, characterizing SSZ-es is a range of depths at which the most of sources originate. Four zones were distinguished throughout the territory of Georgia: 1) The Greater Caucasus, 2) Intermountain depression, 3) Lesser Caucasus, 4). The Transcaucasian area of transverse elevation passing across the Lesser Caucasus within the limits of Georgia, in the form of Javakheti Plateau.

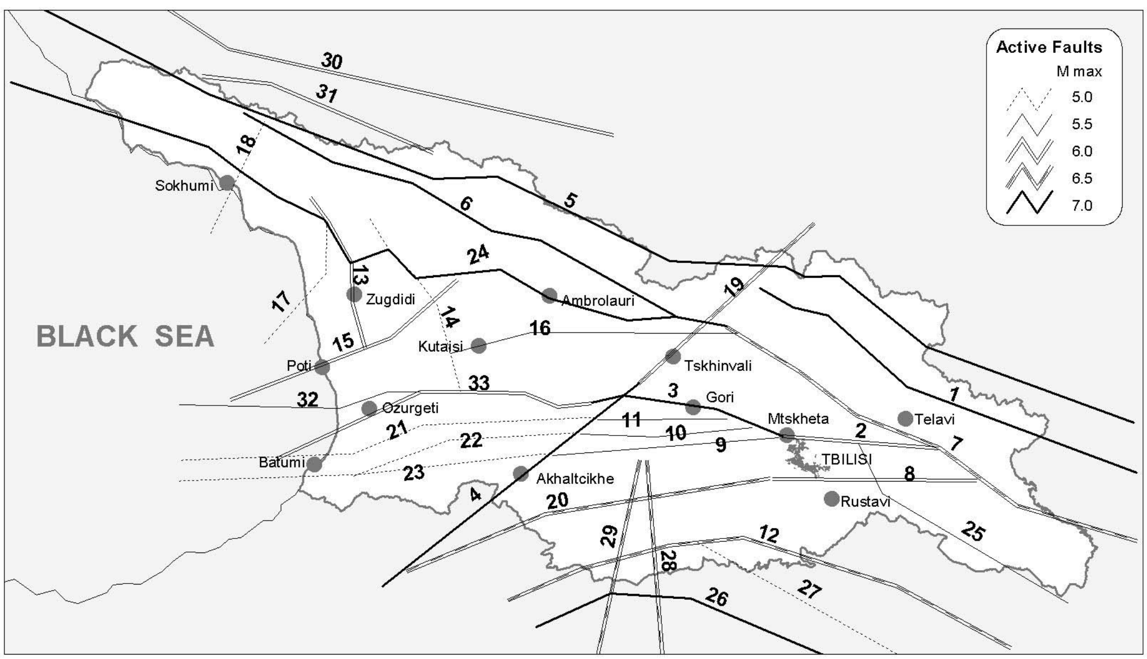

Fig. 2. Seismic source zones (see table 1.)

Two ranges of depths can be selected: $\Delta h = 3 - 7$ km ($h_1 = 5$ km) and $\Delta h_2 = 9 - 15$ km ($h_2 = 12$ km). The first range is associated with the relatively small earthquakes M<5, and the second range - with the large ones M≥5. Average value of depth 10 km was used for calculations.

33 seismic source zones has been distinguished. The parameters of these zones are given

in table 1.
Table. 1

NO	A	B	M max	NAME
1	2.68	-0.760	7.0	Gebi - Lagodekhi
2	1.88	-0.930	6.0	Northern marginal of Adjara - Trialeti zone
3	2.38	-0.930	7.0	Northern marginal of Adjara - Trialeti zone
4	2.59	-0.930	7.0	Tskhinvali - Kazbegi
5	2.69	-0.760	7.0	Main thrust of The Greate Caucasus
6	2.26	-0.760	7.0	Frontal overthrust of the Caucasus nappes
7	2.05	-0.760	6.5	Gagra - Java
8	2.18	-0.930	6.0	Southern marginal of Adjara - Trialeti zone
9	2.60	-0.930	5.5	Adjaris - Tskali - Tedzami
10	2.60	-0.930	5.5	Southern axial of Adjara - Trialeti zone
11	2.60	-0.930	5.5	Norfern axial of Adjara - Trialeti zone
12	3.22	-0.930	6.5	Loki - Agdam
13	1.97	-0.990	6.0	Tskhakaia - Tsaishi
14	1.78	-0.990	5.0	Vartsikhe - Gegechkori
15	2.78	-0.990	6.0	Poti - Abedathi
16	1.78	-0.990	5.5	Kutaisi - Sachkhere
17	2.53	-0.990	5.0	Achigvara
18	2.48	-0.990	5.0	Gumista
19	2.53	-0.990	6.5	Tskhinvali - Kazbegi
20	2.72	-0.930	6.5	Southern marginal of Adjara - Trialeti zone
21	2.46	-0.930	5.0	Norfern axial of Adjara - Trialeti zone
22	2.46	-0.930	5.0	Southern axial of Adjara - Trialeti zone
23	2.46	-0.930	5.0	Adjaris - Tskali - Tedzami
24	2.59	-0.760	7.0	Gagra - Java
25	2.66	-0.990	5.5	Frontal overthrust of molasse napple
26	2.88	-0.930	7.0	No Name
27	2.65	-0.990	5.0	No Name
28	3.47	-0.990	6.5	Kechuti
29	3.47	-0.990	6.5	Abul - Samsari
30	1.74	-0.760	6.0	No Name
31	1.45	-0.760	6.0	No Name
32	2.59	-0.930	5.5	No Name
33	2.38	-0.930	6.0	Northern marginal of Adjara - Trialeti zone

2. Definition of recurrence characteristics. The seismicity within each source zone was analyzed using the catalogue of earthquakes of Caucasus. The catalogue was checked and revised. Some hypocentral parameters of earthquakes have been recalculated. Any complete earthquake catalogue is clearly non-Poissonian. The probabilistic analysis relies mainly on the assumption that seismicity follows a Poisson process, therefore it is essential to remove any non-Poissonian behavior from catalogues. If only mainshocks are considered, then it has been found that the earthquake behavior for reasonable large areas is described satisfactorily by the Poisson model. In this case the use of hazard estimation models that assume a Poisson distribution is valid. The effect on the hazard estimation caused by the elimination of aftershocks from consideration is generally regarded as unimportant, or acceptable on the grounds that aftershocks are an order of magnitude smaller than main shocks (Musson, 1999). Since it is not valid to derive recurrence statistics from the complete catalogue and apply this to to predicting mainshock occurrence, it is necessary to decluster the catalogue by removing all aftershocks, foreshocks and swarms, collectively referred to as dependent events (Musson has suggested another name - accessory shocks). Otherwise, one will obtain incorrect estimation of the probability of large main shocks, since the slope of the magnitude-frequency curve will be affected by the appearance of many small events which are not main shocks (in effect the removal of dependent events makes the magnitude-frequency curve less steep). The process of declustering is not an entirely straightforward procedure. As it is remarked by Reasenberg and Jones (1989), "aftershocks can only be identified in a statistical fashion: they bear no known characteristics differentiating themselves from other earthquakes". There are different methods for declustering of catalogues. We don't consider so called manual inspection, due to the fact that total number of event is large. Special algorithm wasused for definition of foreshocks, aftershocks and swarms. We considered separately relatively strong events (M>4.5) and smaller ones. For strong events we have studied in details the aftershock sequence (or swarms). For the beginning the aftershock area of each event was defined. The background seismicity (i. e. seismicity during the periods without strong events, when there is no clusters in catalogue) was studied in these areas as well as the seismicity rate for each of the epicentral areas. There is some ambiguity in this procedure, especially in the regions of high seismicity. In the areas where the elapsed time between two strong events is quite long, it is easy to define average background seismicity rate. On the other hand, in the areas of high seismicity (Javakheti region for example) the aftershock sequences sometimes partly overlap each other and it is necessary to carry out more detail investigation. The time, when the seismic rate decreases to average background level, we considered as the end of the for/aftershock sequence. After estimation of the aftershock area, duration (space-time window) and average seismic rate we begin to remove dependent events. At the first step we remove all events, except mainshock, in the chosen space-time window. In for/aftershock sequences the largest event (in case of events with equal magnitude the first one) is considered as the mainshock. On the second step, using random sampling, we choose events of each magnitude range (using range of 0.5 unit) in such a way, that their number should correspond to the average rate for this area. The similar procedure we carry out for small events (M<4.5), with only difference that we take some standard space-time windows for each magnitude range. In such a way we have compiled catalogue of "independent" events. Threshold magnitude for the whole catalogue, as well as *a* and *b* values of the recurrence law has been determined for the above four tectonic zones, because its computation for separate SSZ-es due to the lack of data was not possible. *b* value of the recurrence law, given by Gutenberg-Richter formula:

$$\log N = a - bM, \qquad (1)$$

has been determined for the four main tectonic zones: 1) The Greater Caucasus, 2) intermountain depression, 3) Lesser Caucasus, 4). Javakheti Plateau. The following b values has been received for above listed zones: b_1=0.76, b_2=0.99, b_3=0.93 and b_4=0.93. Afterwards, corresponding values of *b* have been attributed to SSZ-es enclosed in corresponding tectonic zones. Seismic rate for each zone was calculated. The parameters are listed in table 1.

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

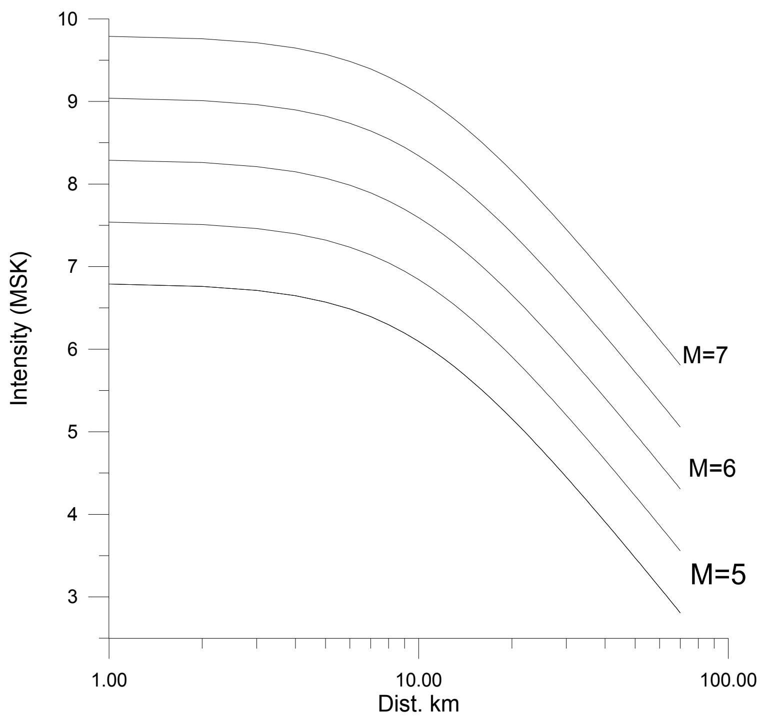

Fig. 4. Attenuation model for intensity (MSK)

$$I=1.5M_s-3.4\lg(\Delta^2+h^2)+3.0 \quad , \quad (1)$$

for small earthquakes and

$$I=1.5M_s-4.7\lg(\Delta^2+h^2)+4.0 \quad , \quad (2)$$

for large events.

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

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

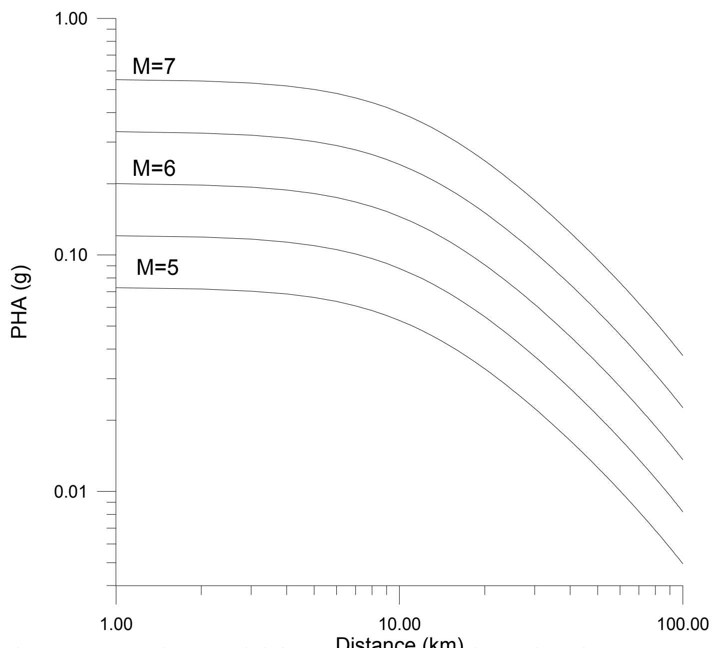

Fig. 5 Attenuation model for peak horizontal acceleration (PHA)

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

$$\text{Log PHA} = 0.72 + 0.44\,M - \log R - 0.00231R + 0.28\,p \quad , \qquad (3)$$

and $R = (D^2 + 4.5^2)^{1/2}$

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

percentile values.
It is important to bear in mind that all equations given above represent a best fit of the selected dataset, and therefore represent mean values having a considerable scatter. In the case of the attenuation model for the larger horizontal value of the peak horizontal acceleration the predicted mean plus one standard deviation is equal to 1.91 times the mean value. The scatter of the *PHA*-models is the same as for similar models for Europe and Western North-America (Smit et al. 2000). The attenuation model is shown on Fig. 4.
The comparison of the attenuation relationships for peak horizontal acceleration with similar relations for other areas shows a good agreement with the models from Western North-America. It is obvious, that the attenuation in Europe is lower compared to the Caucasus and adjacent area. The predicted peak values in the near-field are higher than the corresponding values obtained with other European models (Smit et al. 2000).
4. Determination of hazard. The probabilistic seismic hazard maps has been constructed for the territory of Georgia. Cornell approach, namely computer program SEISRISK III after Bender and Perkins 1987, was used for calculations The set of maps for macroseismic intensity and peak ground acceleration (PGA for 50 years exposure time and 1%, 2%, and 5% probability of exceeding has been constructed.
Intensity and PGA values were calculated for 0.05° by 0.05° grid (about 5.5 km for longitude and 4.3 for latitude). Calculations was carried out for the wider region in order to take into account border zones, whose seismicity can affect seismic hazard in the territory under study. According to the computer program three different models can be use for seismic source zones: point, linear and areal source models. We have used only linear models, as we assume, this model is more reasonable from the point of view of earthquake source mechanics. For each zone seismic rate of earthquakes above the threshold magnitude was estimated, the above noted *b* values and M_{max} was was used for calculating of seismic rate of each magnitude range (from $M_{threshold}$ to M_{max} by step 0.5 unit).
These maps are shown on Fig.4 (for macrosiesmic intensity) and Fig. 5 (PHA).

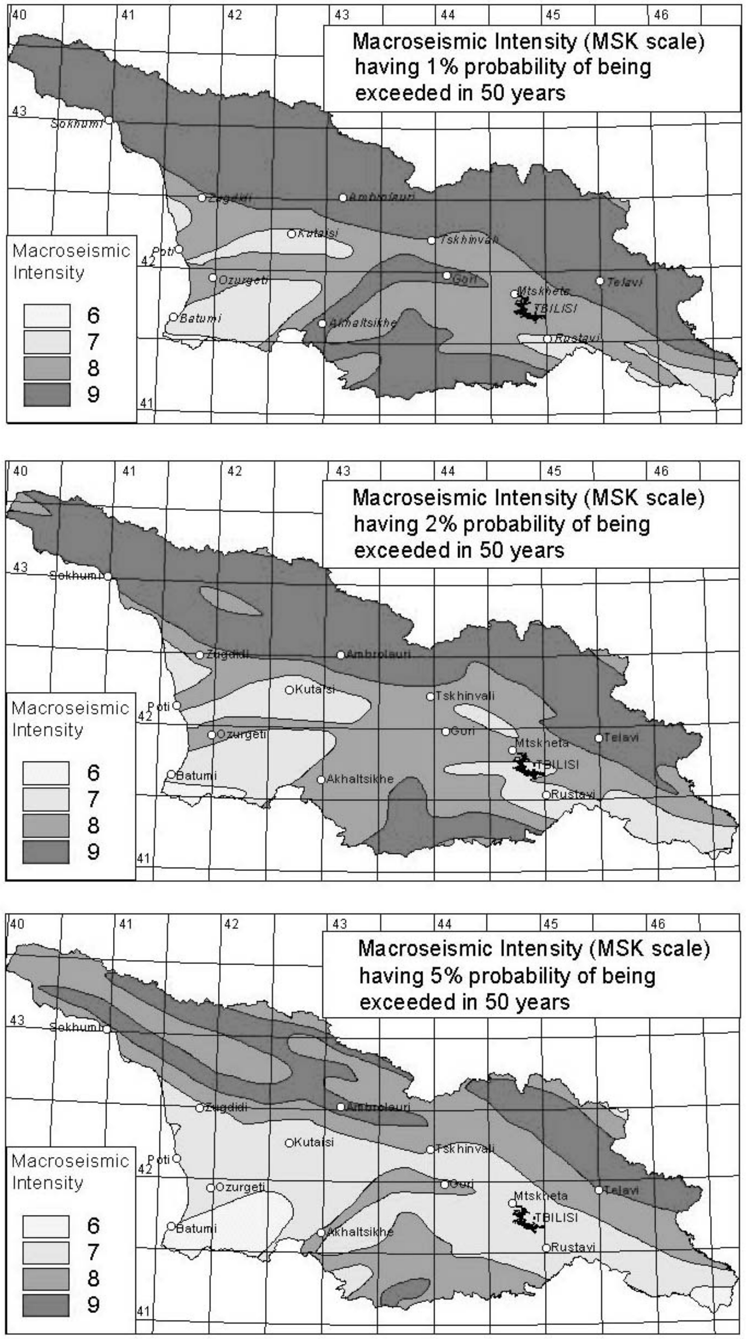

Fig 4. Macroseismic intensity having 5% (a), 2% (b) and 1%(c) probability of being exceeded in 50 years

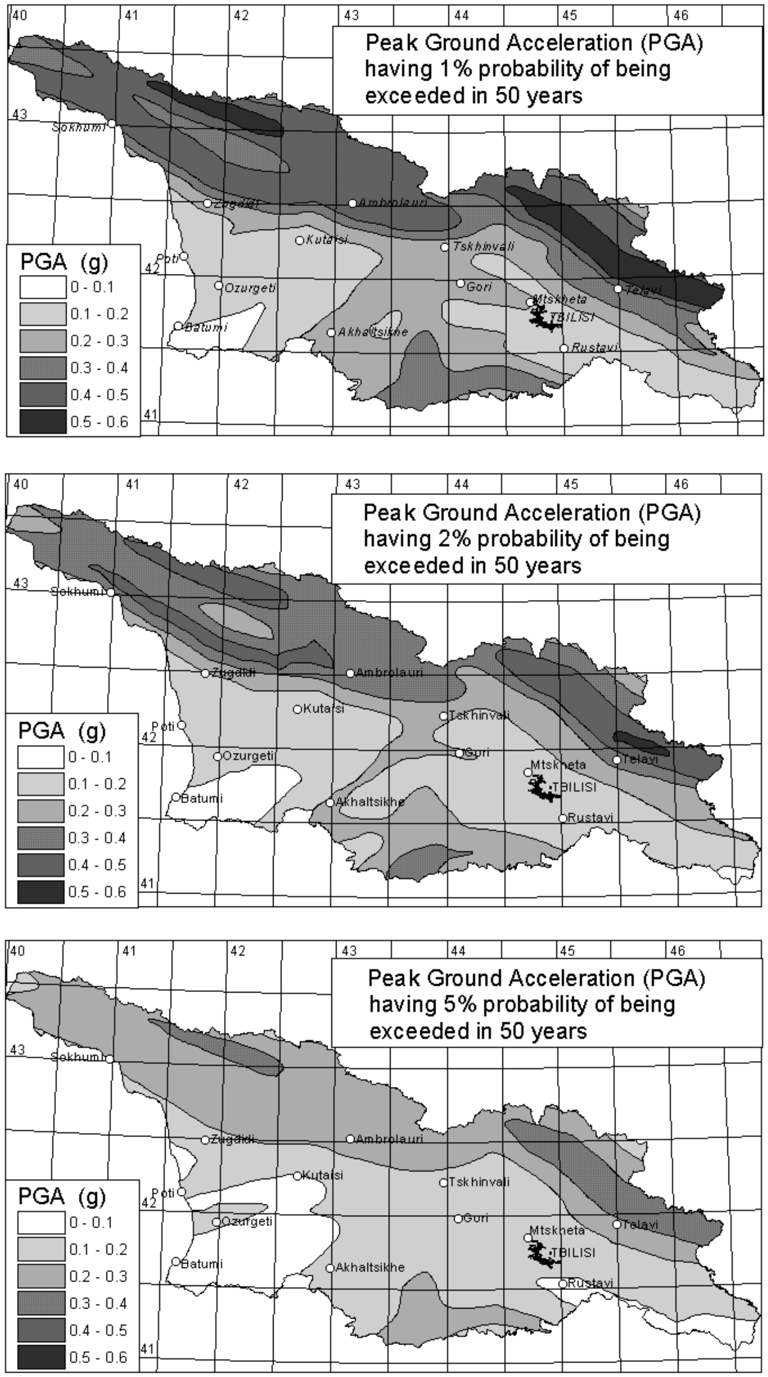

Fig 5. PGA (in G units) having 5% (a), 2% (b) and 1%(c) probability of being exceeded in 50 years

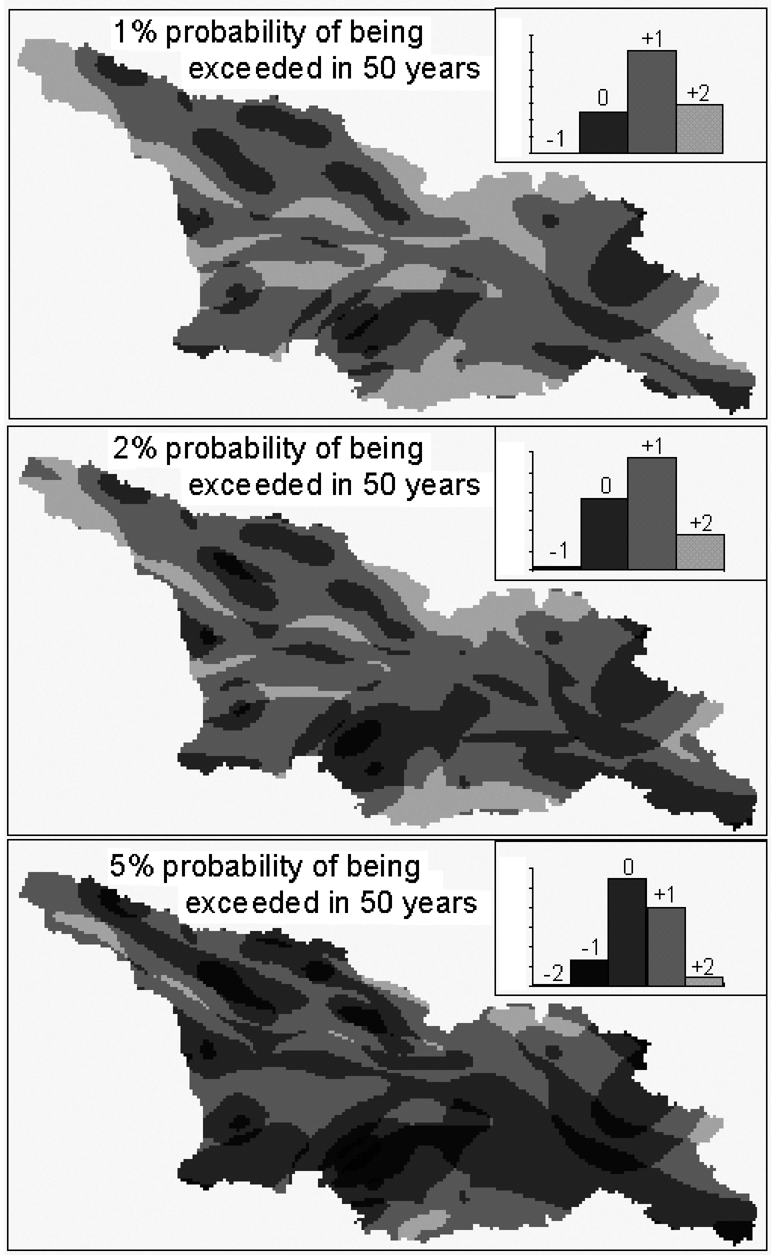

Fig. 6. *Comparison of predicted and observed intensities:* +2 overestimation of observed values by 2. +1 overestimation of observed values by 1. 0 coinciding with observed values. -1 underestimation of observed values by 1. -2 underestimation of observed values by 2.

Discussion and Conclusions. In order to choose the optimal version (probability), special tests have been carried out: namely these Prognostic maps have been compared with the map of observed intensities, using GIS technology. The optimal map should be balanced, that is it should not miss any strong (occurred) shaking and at the same time it should not strongly overestimate the hazard (that is, the area with maximal intensities be minimal).

The comparison of theoretical and experimental maps (Fig. 6) in GIS shows that maps for

5% probability miss several strong earthquakes, including those which happen in the instrumental period. Fig. Map to 2% probability covers almost all observed intensities; only in restricted areas of paleo - and historical earthquake predicted intensity is underestimated. Map for 1% probability do not miss any of high intensity.

The histograms, illustrating distribution of over - and underestimated areas (corresponding S_{io} and S_{iu}) for each probability are shown in Fig. it is evident that the minimal values, of parameter differences in theoretical and experimental data is achieved for 2%.

It have to be noted that the overestimated areas cannot be considered as a result of failure, that is as false alarms. The matter is that the recurrence period of strong earthquake of Caucasus as an area of continental collision is large, of order of thousands of years. Thus the areas with large theoretical seismic potential, which has not been realized in last millenniums, can be considered as seismic gaps, where strong earthquake can happen in future.

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