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SEISMIC RISK CARTOGRAPHIC VISUALIZATION FOR CRISIS MANAGEMENT

ABSTRACT. Earthquake loss estimations before future events and following strong earthquakes in emergency mode and their corresponding visualization are extremely important for proper decision on preventive measures and effective response in order to save lives and properties. The paper addresses the methodological issues of seismic risk and vulnerability assessment, mapping with GIS technology application. Requirements for simulation models, databases used at different levels, as well as ways of visualizations oriented for Emergency Management Agencies, as well federal and local authorities are discussed. Examples of mapping at the different levels: global, country, region and urban one are given and the influence of input data uncertainties on the reliability of loss computations is analyzed.

KEY WORDS: earthquake loss estimation, maps of risk and vulnerability, support of decision making.

INTRODUCTION

Earthquakes are among the most damaging natural phenomena striking mankind; when occurring in a densely populated territory, they can prove devastating. They are sudden and not predictable in the present scientific context, in the sense that scientists are not yet in the position of warning efficiently the exposed populations that an event is being prepared in the short term.

Progress will obviously come from a better understanding of the physical processes at earthquake source, as well as a finer knowledge of wave propagation and of interaction of waves with artifacts. In order, for the authorities in-charge and emergency managers, to be really efficient when confronted to a strong event just occurred or expected, they should be provided with the necessary data and models to estimate the potential damage caused by an earthquake occurring in a specific environment. Models and corresponding codes must be worked out, tested and improved; naturally, data is required. Most often, data needed shows specific features: extremely bulky, accumulated and stored locally, eventually restricted in its use by the owners if not simply unavailable.

Nevertheless, the potential impact of large earthquakes can be reduced by implementing preventive measures' plans based on seismic risk maps and timely and correct action just after a disastrous earthquake.

The paper discusses methodological issues for earthquake loss assessment, requirements for simulation models and databases used at different levels, as well as ways of visualizations oriented for different end-users, first of all for emergency managers and authorities in-charge. Examples of seismic risk and vulnerability mapping with Extremum Family Systems' application [Sushchev et al., 2010] are given, and the influence of input data uncertainties on the reliability of loss computations is analyzed.

PROCEDURE OF SEISMIC RISK AND VULNERABILITY ASSESSMENT

In Russia as in many countries the methods of risk assessment and mapping with the help of GIS technology have been developed taking into account the general concept adopted by UN experts [Karnik & Algermissen, 1978; Fournier d'Albe, 1982; Karnik, 1984; Boissonnade & Shah, 1984; Mitigating ..., 1991; UNISDR...., 2009; Risk..., 2010; Ranguelov, 2011] that seismic risk R_s

$$R_s = HV_s(I) \quad (1)$$

where – $V_s(I)$ is the seismic vulnerability of elements at risk (population and built environment) for the considered settlement; – H is the probability of seismic event *per* one year.

According to ISO 31010, risks are the combination of the consequences of an event or hazard and the associated likelihood of its occurrence. EU Guidelines on Risk Assessment and Mapping for Disaster Management (http://register.consilium.europa.eu/pdf/en/10/st17/st17833.en10.pdf) built on experience about existing good practice of risk assessments for major natural disasters available in Member States and developed by the end 2010 also follow the same concept.

More often two seismic risk indexes, such as individual and collective risk created by earthquakes, are considered. For estimation risk indexes and risk mapping the probabilistic approach is used. Individual risk due to seismic hazards R_s may be determined as the probability of fatalities R_s1; probability of fatalities and injuries R_s2, probability of fatalities, injuries and homeless R_s3 due to earthquakes within one year at a given place.

Collective risk due to seismic hazards R_{sc} may be determined as the expected number of fatalities $R_{sc}1$; the expected number of fatalities and injuries $R_{sc}2$; the expected number of fatalities, injuries and homeless $R_{sc}3$ as a result of earthquakes' occurrence *per* year.

Speaking about seismic vulnerability, the authors use both concepts of fragility and vulnerability. Vulnerability may be estimated through physical and economical domains. Physical vulnerability $V_{ph}(I)$ is an index, which characterizes the loss of functional properties of the considered element at risk. In the case of buildings it may be estimated as a ratio between the expected number of damaged buildings of a certain type due to earthquakes with intensity *I* and total number of buildings belonging to this type.

When solving some problems the physical vulnerability of buildings can also be characterized by the average damage state of buildings $d_{average(I)}$ at seismic intensity *I*. For example, this indicator is used for visualization on maps the extent of damage to building stock in settlements [Larionov et al. 2003a, 2003b].

Economic vulnerability for buildings of different types $V_e(I)$ is characterized by ratio between the cost of repair and the initial cost of construction [Larionov et al. 2003a, 2003b, 2006; Frolova et al. 2003a; 2007].

The fragility laws are understood as the dependence-ships between the probability of buildings belonging to different types to be damaged (the probability P_{Ai} (I) of damage state not less than given value *I*; and probability P_{Bi} (I) of definite damage state), and the intensity of shaking in grades of seismic scales. In the special GIS-projects for earthquake risk and vulnerability assessment at different levels, fragility laws and vulnerability functions are used for different building types classified according to MMSK-86 scale [Shebalin et al. 1986]:

- buildings types A1, A2 (from local materials);
- buildings types B, B1, B2 (brick, hewn stone or concrete blocks);

Table 1. Comparison of building vulnerability classes according to MMSK-86 and EMS-92

Description of buildings' types according to EMS-98	Vulnerability class	
	EMS-98	MMSK-86
Rubble stone, field stone	A	A
Adobe (earth brick)	A	A
Simple stone	B	A
Massive stone	C	B
Unreinforced (bricks/concrete blocks)	B	B
Unreinforced (brick) with RC floors	C	B
Reinforced or confined	D	C
Reinforced without earthquake-resistant design (ERD)	C	C
Reinforced with minimum level of ERD	D	E7
Reinforced with average level of ERD	E	E8
Reinforced with high level of ERD	F	E9
Timber structures	D	C-E7

- buildings types C, C1, C2 (reinforced concrete, frame, large panel and wooden);
- buildings types E7, E8, E9 (designed and constructed to withstand the earthquakes with intensity 7, 8, 9).

The fragility laws and vulnerability functions are usually constructed on the basis of statistical analysis of strong earthquakes engineering consequences in the regions under study. In spite on the fact of great economic and social losses caused by the strong earthquakes worldwide, there is no comprehensive information on the behavior of different types of buildings, structures and other elements of risk for large values of the damage degrees *d* and for some countries there is no statistical data at all. In the case the data on engineering consequences of strong events are not available, seismic intensity scales may be used to compensate for the lack of information gained through direct surveys. Seismic intensity scales provide the descriptions, which summarize statistical data on different buildings behavior during recent strong earthquakes in various earthquake-prone areas worldwide. For instance, European Macroseismic Scale EMS-98 contains information on all of damage states to buildings of traditional construction and earthquake-resistant buildings with a description of their behavior during earthquakes of varying intensity *I*. To ensure comparability of vulnerability functions obtained using different scales, the expert estimation of different building types according to different scales should be undertaken. Table 1 gives an example for MMSK-86 and EMS-92 scales.

TOOLS FOR RISK AND VULNERABILITY MAPPING

The section describes details of mathematical models, as well as the risk and vulnerability visualization methods at different levels.

In order to produce the maps of risks and vulnerability for the territory under study the special GIS projects are usually developed. They include data bases with information describing the considered territory with corresponding level of details, software assigned for hazard and risk indexes' assessment, interface which allows thematic maps and text report according to established forms to be produced. The software usually allows:

- to obtain the distribution of earthquake intensities (Fig. 1) and peak ground motion accelerations;

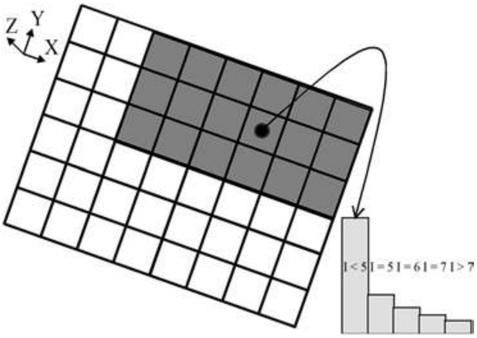

Fig. 1. Probabilistic presentation of seismic hazard information in Extremum System

- to determine the fragility laws and vulnerability functions for the buildings and structures of different type (Fig. 2) which are characteristic for the considered area, as well as for the other elements of infrastructure;

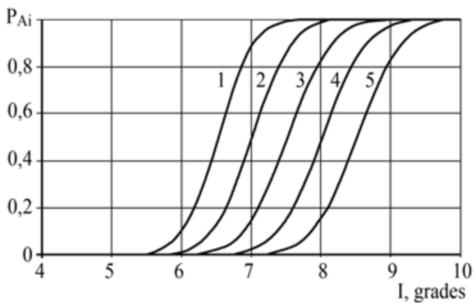

Fig. 2. Fragility laws for *B* type buildings (MMSK-86):

probability of damage state not less than given value; 1, 2, 3, 4, 5 – buildings damage states P_A

- to determine the vulnerability functions and laws of earthquake impact on population (Fig. 3);

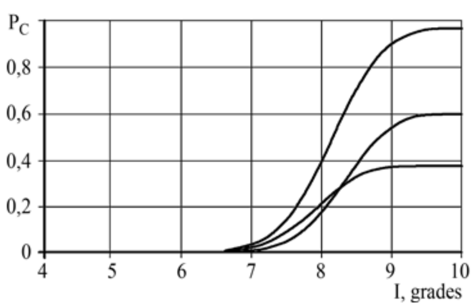

Fig. 3. Laws of earthquake impact on people in *B* type buildings:

1 – total social losses; 2 – injuries; 3 – fatalities

- to estimate damage due to scenario events according to the maps of seismic zoning or possible earthquake source zones maps;
- to estimate damage due to just occurred and scenario earthquakes, as well as and co-lateral hazards;
- to compute individual and collective seismic risk and risks due to other hazards;
- to compute individual and collective integrated risks.

For possible earthquake consequences assessment at different levels the proper databases and mathematical models should be chosen taking into account the end user requirements about the details of expected results. The table 2 shows the relationship between the details of mathematical models and the level at which the problem should be solved.

The reliability of loss and risk assessment in both modes: emergency and preventive one, strongly depends on [Bonnin et al., 2002a, b; 2004; Frolova et al., 2003a]:

- completeness and reliability of databases on elements at risk (population and built environment) and hazard sources;
- reliability of vulnerability functions and fragility laws of elements at risk;
- errors in strong earthquakes' parameters determination by Alert Seismological Surveys for computations in emergency mode;
- relevance and reliability of seismic hazard maps with different details.

All simulation models and data bases, used for risk and earthquake consequences estimation, bring in their own uncertainties and propagate the uncertainties of the previous steps of the estimation procedure. Therefore, the process of Tools' calibration is rather complicated used at all stages from, estimating shaking intensity to

Table 2. Details of mathematical models and the forms of results visualization at different levels

Level of earthquake loss estimation	Details of models	Ways of visualization on maps
Global	Usage of macro indexes based on countries economic development; Usage of averaged models of hazards and vulnerability functions	Hypsometric layers; Isolines corresponding to different values of loss and risk; Marks of different color and size
Country or Regional	Usage of regional models of hazards and vulnerability functions	Hypsometric layers; Isolines corresponding to different levels of loss and risk; Marks of different color and size
Urban	Usage of engineering methods of computations; Application of numerical methods for solving the problems	Zones (districts of settlements) of different color
Facility	Application of numerical methods for estimation of dynamic parameters of ground motion and structures strength capability; analysis of "fault and event trees"	Measurable index of damage, loss and risk; Qualitative and quantitative pattern

assessing the damage to different elements at risk. Visualization of the simulated results at each step facilitates the proper choice of calibration parameters.

EARTHQUAKE RISK AND VULNERABILITY VISUALIZATION AT DIFFERENT LEVELS

The section gives examples of the maps of seismic risk and vulnerability with different details oriented for end-users. Widely used by EMERCOM of Russian Federation ways of maps' design and production presented. Difference in maps' visualization in emergency mode and preventive one is illustrated.

Earthquake loss estimation at global level in emergency mode

The results of seismic risk assessment at global scale in emergency mode are shown on Fig. 4. The example is given for the Gansu event in China, near Minxian, on July 21, 2013. The map (Fig. 4) shows the source of hazard, epicenter of the event by special sign; isolines of different color present the macroseismic field (possible distribution of shaking intensities in grades of MMSK-86 scale); signs of different size and color stand for number of inhabitants in the settlement and average damage state. Such maps are usually accompanied by text report with estimates of expected number of fatalities, injuries and homeless for the whole stricken area and detailed description of possible consequences for each settlement in the stricken area. In the case of the Gansu earthquake, the expected number of fatalities was estimated by Global Extremum System as 46–150 people, reported 95 fatalities according to EMDAT (http://www.emdat.be/disaster_list/index.html).

Taking into account the discrepancies in earthquake parameters determination by different Seismological Surveys, regional peculiarities in shaking intensity attenuation and buildings' behavior, the loss computations are usually made for few variants and many-variants maps are produced. During the loss computations due to the earthquake on July 21, 2013 in emergency mode, information about the event parameters (coordinates of epicenter, origin time, magnitude, source depth) was taken from the following alert seismological centers: GS RAS, CEPC and NEIC. Different shaking intensity attenuation relationships and different ratio k of macroseismic ellipse major and minor semi-axis (Table 3) were used, as well as different orientation of probable anisotropic shake field when source mechanism solution became available. The macroseismic field orientation at the angle of 302° was accepted in accordance with source mechanism solution obtained by NEIC. Table 3 shows the examples of different variants for loss computation due to the earthquake on July 21, 2013.

The Global Extremum System impact database for China (Fig. 5), which includes the descriptions

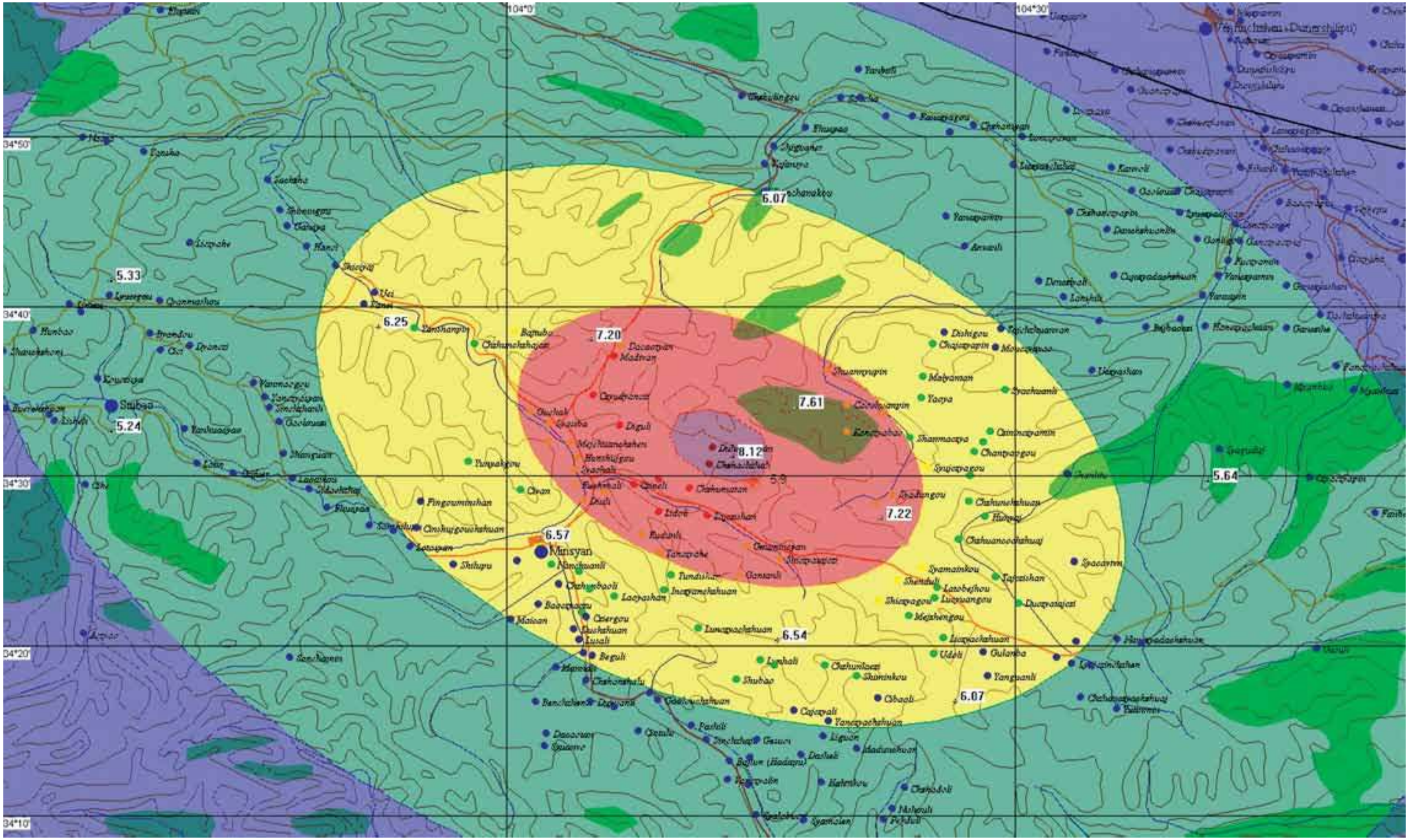

Fig. 4. Results of possible loss simulation by Extremum for the July 21, 2013 earthquake in China (variant 5, Table 3):

dots are settlements in the stricken area; colour of dots shows the average damage state of building stock (black: total collapse; brown: partial collapse; red: heavy; yellow: moderate; green: slight damage; blue: no damage); figures show the values of expected shaking intensities

Table 3. Input data for simulation of the consequences of the July 21, 2013 event in China

no.	Survey	Lat., Log.	M	h, km	equation	Ratio *k*	Ellipse orientation
1	USGS	34,499; 104,243	5.9 (M_W)	9,8	[Shebalin, 1977]	1.5	along faults
2	USGS	34,499; 104,243	5.9 (M_W)	9,8	[Shebalin, 1977]	1.5	Angle 302°
3	USGS	34,499; 104,243	5.9 (M_W)	9,8	IASPEI, 1993 Eastern part	1.5	Angle 302°
4	USGS	34,499; 104,243	5.9 (M_W)	9,8	IASPEI, 1993 Western part	1.5	Angle 302°
5	CEIC	34,5; 104,2	6.6	20	IASPEI, 1993 Eastern part	1.5	Angle 302°
6	CEPC	34,5; 104,2	6.6	20	IASPEI, 1993 Western part	1.5	Angle 302°
7	GS RAS	34,53; 104,21	6.1 (M_S)	10	IASPEI, 1993 Eastern part	1.5	Angle 302°
8	GS RAS	34,53; 104,21	6.1 (M_S)	10	IASPEI, 1993 Western part	1.5	Angle 302°
9	GS RAS	34,53; 104,21	6.1 (M_S)	10	[Shebalin, 1977]	1.5	Angle 302°
10	CEIC	34,5; 104,2	6.6	20	(Shebalin, 1977]	1.5	Angle 302°
11	CEIC	34,5; 104,2	6.6	18	[Shebalin, 1977]	1.5	Angle 302°
12	CEIC	34,5; 104,2	6.6	18	[Shebalin, 1977]	2.25	Angle 302°

of more than 100 events for the country, was used to take into account the regional peculiarities of shaking intensity attenuation.

By accumulating the data on reported consequences of strong events the results of computation (simulation) according to different variants of input data are compared with observed ones. In the case of the event on July 21, 2013 the simulated by Global Extremum System intensity estimations were compared with observed macroseismic effect published by the Chinese seismological authorities (Fig. 6) in order to find the better agreement between simulated and observed effect. The map on Fig. 6 shows isoseists with different intensities I = VIII (dark red), VII (pink) and VI (light pink). The zone with I = VIII corresponds to huge destruction, I = VII – to very strong shaking and is also responsible for a lot of misery. The yellow dot is the epicenter or breaking point. The red lines on the map are the mapped faults (http://earthquake-report.com/2013/07/21/very-strong-earthquake-gansu-china-on-july-21-2013).

Figure 7 shows the comparison of observed shaking intensity values (Fig. 6) with simulated ones using Extremum System software (Table 3) and ShakeMap software of PAGER System.

In the case of the event on July 21, 2013 all simulated values of shaking intensity are in general underestimated in comparison with observed values. The greatest difference of simulated ant observed intensities is about two grades of intensity scale. Such estimations are not acceptable as will not allow the reliable loss estimations to be achieved.

The exception is variant 5 (Fig. 5, Table 3) for the epicentral distances $\Delta > 25$ km, it gives intensity values slightly above reported ones. In the case CEIC parameters of the event are used for loss computations, ΔI_{max} do not exceed one grade of intensity scale for all variant 5, 6, 10 11 and 12 (Table 4). For the variant 5 the values of $\Delta I_{average}$ is equal to 0.1.

Relatively good agreement of simulated and observed shaking intensity values is obtained when we use the regional intensity attenuation relationships (equations 2, 3) proposed for the eastern part of China in IASPEI publication [The Practice..., 1993].

Along major axis:

$$I = 6{,}045 + 1{,}480m - 2{,}081\ln(R + 25{,}0),\quad s = 0.49 \qquad (2)$$

Along minor axis:

$$I = 2{,}617 + 1{,}435m - 1{,}441\ln(R + 7{,}0),\quad s = 0.56 \qquad (3)$$

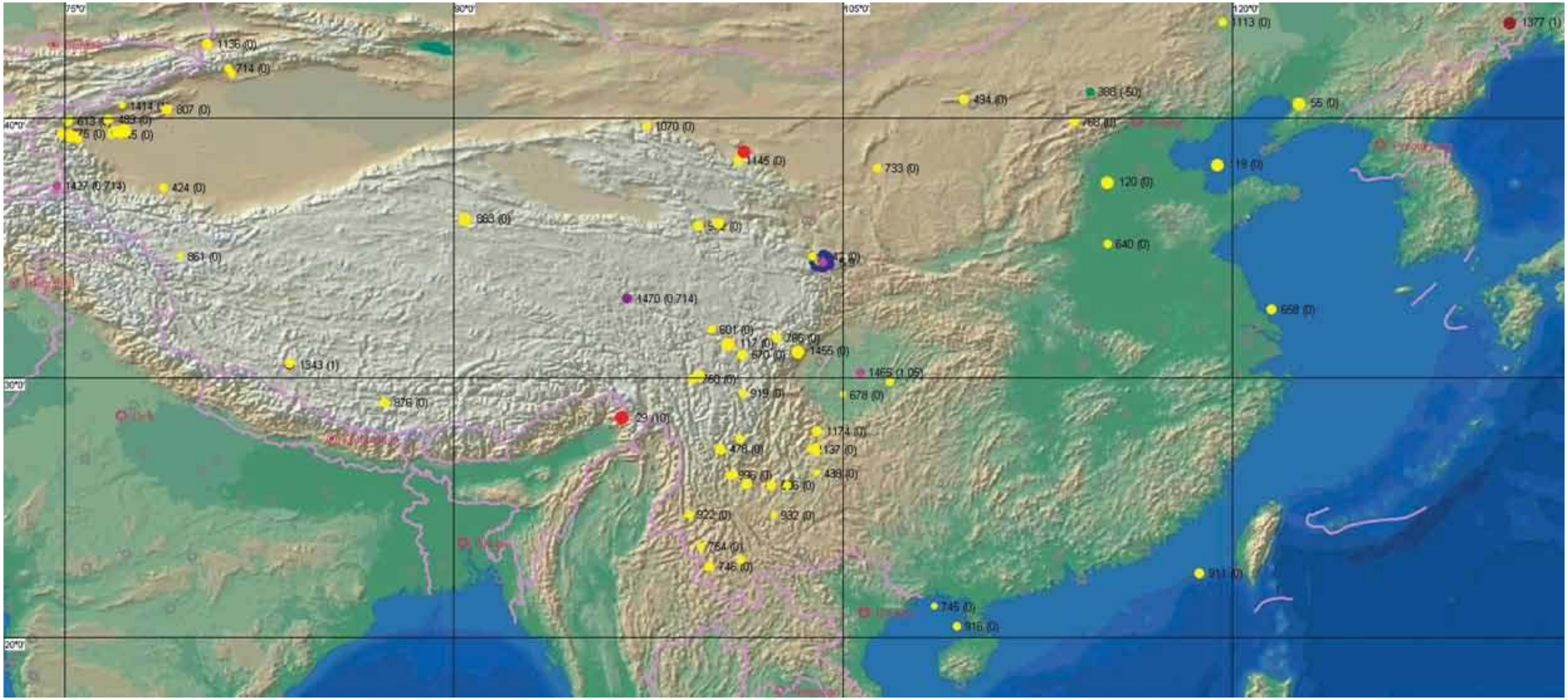

Fig. 5. Fragment of the "Extremum" System impact knowledge base about past events consequences for China

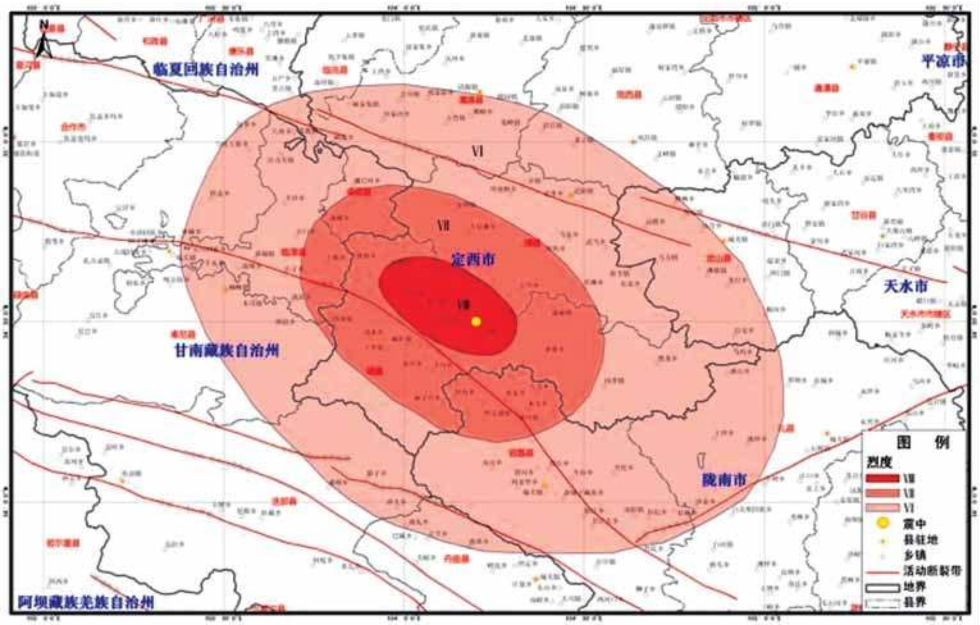

Fig. 6. The isoseismal map published by the Chinese seismological authorities for the event on July 21, 2013

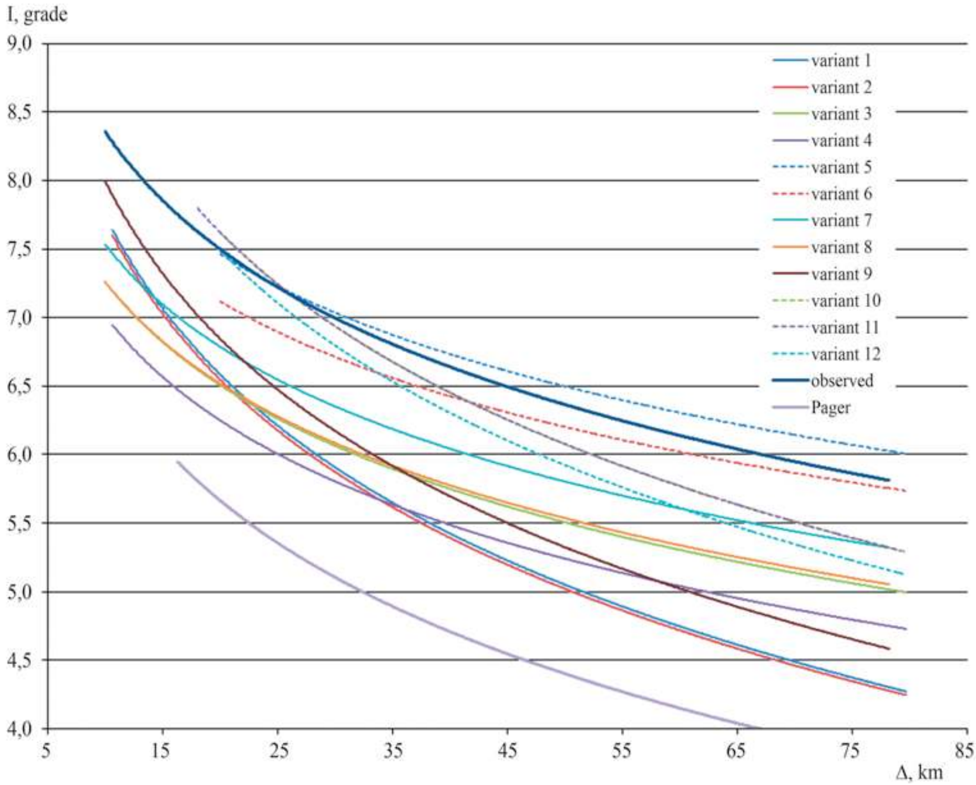

Fig. 7. Comparison of simulated shaking intensities for the event on July 21, 2013 with application of Extremum and PAGER Systems and reported values

Table 4. Comparison of intensities computed using CEPC parameters of earthquake with observed values of shaking intensity

Variant 5	Variant 6	Variant 10	Variant 11	Variant 12
ΔI_{max} = 1,0 $\Delta I_{average}$ = –0,1 σ = 0,3	ΔI_{max} = 1,0 $\Delta I_{average}$ = –0,4 σ = 0,3	ΔI_{max} = 1,0 $\Delta I_{average}$ = –0,4 σ = 0,2	ΔI_{max} = 1,0 $\Delta I_{average}$ = –0,3 σ = 0,2	ΔI_{max} = 1,0 $\Delta I_{average}$ = –0,5 σ = 0,3

In the case of variant 3, 5 and 7 (Table 5) ΔI_{max} varies from one intensity grade up to 1.5 and $\Delta I_{average}$ changes from 0.2 up to 0.3.

Table 5. Comparison of intensities computed using regional attenuation relationships (2 and 3) with observed values of intensity

Variant 3	Variant 5	Variant 7
ΔI_{max} = –1.5 $\Delta I_{average}$ = –1 σ = 0.3	ΔI_{max} = 1.0 $\Delta I_{average}$ = –0.1 σ = 0.3	ΔI_{max} = 1.0 $\Delta I_{average}$ = –0.6 σ = 0.2

Figure 8 shows the average residuals, binned in 5 km by epicentral distance, from observed and simulated shaking intensities for the variants 5 and 6, Fig. 9 – for the variants 10 and 11.

The example of this event shows the importance of proper choice of macroseismic field model: regional intensity attenuation equation and its regional coefficients; orientation and ratio *k* of ellipse major and minor semi-axis.

This event also shows the previous calibration for the area under study was successful. It was based of the past events in the Global Extremum System data bases (Fig. 5).

Visualization of loss simulation results allows the time needed for system calibration to be reduced significantly.

Seismic risk assessment at country level in preventive mode

Fig. 10 shows example of seismic risk maps of the Russian Federation territory produced within the Federal Program "Natural and Technological Risk Assessment and Management in the Russian Federation until 2010" in order to identify the most vulnerable areas and develop the preventive measures' plan aimed at risk reduction. As input data

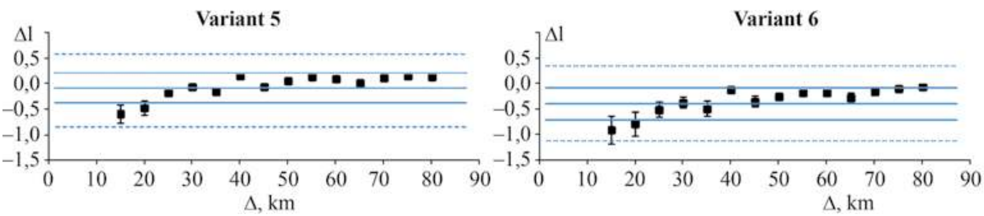

Fig. 8. Residuals for the simulated shaking intensities; residuals are binned in 5-kilometer windows and the median residual is plotted by grey dots

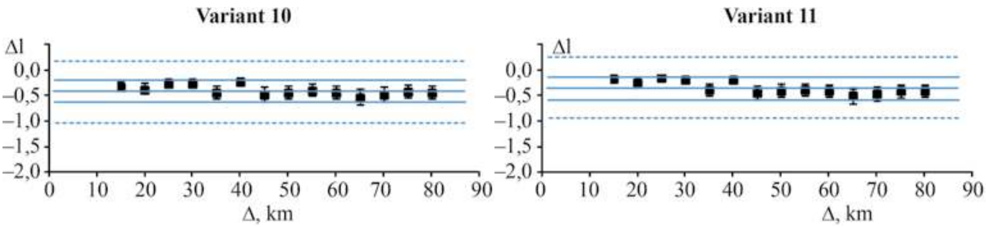

Fig. 9. Residuals for the simulated shaking intensities; residuals are binned in 5-kilometer windows and the median residual is plotted by grey dots

Fig. 10. Map of individual seismic risk $R_s 1$, 10^{-5}/year, for the territory of Russian Federation

about seismic hazard the set of review seismic zoning maps (scale 1:5 000 000) were used. They are the maps of review seismic zoning of the OSR-97 A, B and C, corresponding to 10 % (A), 5 % (B) and 1 % (C) probability of exceeding the calculated intensity for a fixed interval of time T = 50 years, or 90 % probability of not exceeding the values of intensity for the following fixed time intervals, respectively, T = 50 (A), 100 (B) and 500 (C) years [Set ..., 1998]. The built environment was presented by averaged settlements models: percent of building of different types according to MMSK-86 scale and their average height. On the whole within the Program six maps of individual risk R_s (Fig. 10) and collective risk R_{sc} have been constructed: R_s1, R_s2, R_s3; $R_{sc}1$, $R_{sc}2$, $R_{sc}3$. Values of seismic risk obtained for separate cities and settlements were averaged within the administrative regions of the country and are shown on the maps by different color. The color scale is usually chosen in order to pay attention of the end-users to the areas characterized by high risk level.

Obtained values of individual seismic risk R_s vary from negligible ones close to zero up to rather high values – more than $30 \cdot 10^{-5}$ for the probability of fatalities (map R_s1), more than $100 \cdot 10^{-5}$ for the probability of fatalities and injuries (map R_s2), more than $150 \cdot 10^{-5}$ for the probability of fatalities, injuries and economic loss to population caused by earthquakes per year (map R_s3).

Table 6 shows size of zones with different levels of individual seismic risk according to maps R_s1, R_s2 and R_s3.

Obtained values of collective seismic risk R_{sc} vary from negligible small ones – less than $0.1 \cdot 10^{-5}$ up to rather high values –

Table 6. Values of individual seismic risk and size of zones with different risk levels

Risk ranges, 10^{-5}, 1/year	Qualitative risk characteristics	Square of zones, map R_s1, %	Square of zones, map R_s2, %	Square of zones, map R_s3, %
Less than 0.1	small	53	49	46
0.1–1.0	moderate	15	17	13
1.0–5.0	average	14	9	11
5.0–10.0	high	7	8	5
10.0–30.0	rather high	7	9	11
30.0–100.0		3	7	10
100.0–150.0	extremely high	–	1	1
More than 150.0		–	–	2

Table 7. Values of collective seismic risk and size of zones with different risk levels

Risk ranges, persons/year km^2	Qualitative risk characteristics	Square of zones		
		map $R_{sc}1$, %	map $R_{sc}2$, %	map $R_{sc}3$, %
Less than 0.1	small	58.4	53.6	48.8
0.1–1.0	moderate	15.1	14.5	16.9
1.0–5.0	average	12.7	12.0	9.6
5.0–50.0	high	10.2	13.3	15.7
50.0–500.0	rather high	3.0	5.4	7.2
500.0–1,000.0		0.4	0.5	0.6
1,000.0–5,000.0	extremely high	0.4	0.5	0.6
More than 5,000.0		–	0.2	0.6

more than $1{,}000 \cdot 10^{-5}$ for expected number of fatalities (map $R_{SC}1$), more than $5{,}000 \cdot 10^{-5}$ for expected number of fatalities and injuries (map $R_{SC}2$) and for expected number of fatalities, injuries and number of persons who lost their property (map $R_{SC}3$). Table 7 shows size of zones with different levels of collective seismic risk according to maps $R_{SC}1$, $R_{SC}2$ and $R_{SC}3$.

The computed values of individual seismic risk R_S1 are more than $30.0 \cdot 10^{-5}$, 1/year for all administrative divisions within Sakhalin area, Republic of Altaj, Tyva, Dagestan and Northern Osetiya. The highest values of individual seismic risk R_S3 are obtained for Kamchatka, near lake Baikal, Republic of Buryatiya, Irkutsk region, Altaj kraj, as well as for Krasnodar region and Chechen Republic. Table 8 shows the values of individual seismic risk R_S1 for some administrative areas of the Russian Federation.

Table 8. Individual seismic risk R_S1 for some administrative units of the Russian Federation

Administrative unit of RF	Name of municipal region	Population, persons	Population density, persons/km²	Seismic risk $R_S1, 1 \cdot 10^{-5}$, 1/year
Altajsky kraj	Petropavlovsky rajon	11,915	7.36	33.4
	Soloneshensky rajon	9,848	2.79	43.5
	Ust-Kalmansky rajon	14,450	6.28	31.7
	Xharyshsky rajon	11,728	1.7	30.2
Republic of Buryatiya	Barguzinsky rajon	22,738	1.23	43.7
	Ivolginsky rajon	42,665	15.8	30.4
	Kabansky rajon	58,340	4.32	44.3
	Kurumkansky rajon	14,376	1.15	46.1
	Mujsky rajon	11,218	0.45	47.6
	Okinsky rajon	5,395	0.21	45.0
	Pribajkalsky rajon	26,840	1.73	42.7
	Severo-Bajkalsky rajon	13,181	0.24	49.6
	Tunkinsky rajon	21,778	1.85	43.2
Zabajkalsky kraj	Kalarsky rajon	9,600	0.17	55.1
Republic of Ingishetiya	Malgobeksky rajon	52,038	77.67	34.2
	Nazranovsky rajon	94,254	134.65	31.3
	Sunzhensky rajon	121,079	80.03	34.8
Irkutsk oblast	Olkhonsky rajon	9,998	0.57	46.7
	Sluydyansky rajon	42,331	8.25	39.8
	Shelekhovsky rajon	63,876	30.42	31.7
Kamchatsky kraj	Elizovsky rajon	64,262	1.57	60.4
Krasnodarsky kraj	Town-resort Anapa	167,095	170.16	32.5
	Town-resort Gelendzhik	104,439	85.05	31.6
	Novorossijsk City	313,307	375.22	31.8
	Tuapsinsky rajon	129,066	53.7	33.3
Chechen Republic	Achkhoj-Martanovsky rajon	83,604	76	36.8
	Vedensky rajon	38,378	40.14	39.8
	Itum-Kalinsky rajon	5,888	2.94	40.0
	Novolaksky and Nozhaj-Yurtovsky	53,821	85.57	38.3
	Urus-Martanovsky rajon	130,997	201.53	37.7

Seismic risk maps of the Russian Federation are usually produced every 10–15 years taking into account updated estimations of seismic hazard level for the country territory and amortization of built environment. Such maps are used for creating schemes of territorial planning of preventive measures and their implementation. Risk visualization with such details allows the regions to be identified (Table 8), where more detailed information on hazard level and buildings inventory is needed for risk assessment at regional level.

Seismic risk and vulnerability assessment and mapping at regional level

Regional maps of seismic risk are usually constructed for the territories with high level of risk (more than $1 \cdot 10^{-5}$) in order to verify averaged estimations obtained at country level. As input data about seismic hazard the maps of review (scale 1:5,000,000) and regional detailed seismic zoning (scale 1: 500,000 or 1:200,000), as well as the shaking intensities' matrixes for the area under study are used. The built environment for cities and large settlements are verified and updated averaged settlements models (percent of building of different types according to MMSK-86 scale and their average height) are created.

To construct the regional seismic risk R_S1 maps for the population of the Irkutsk oblast, the Republic of Buryatiya and the Chita oblast two types of data about seismic hazards level were used. They are the set of maps of review seismic zoning of the OSR-97 A, B and C [Set ..., 1998] and the the shaking intensities' matrixes provided by the Institute of the Earth's Crust, Siberian Department of RAS.

The following procedure [Bonnin et al., 2002b; Bonnin & Frolova, 2004; Bonnin & Frolova, 2010; Frolova et al., 2003b; Frolova et al., 2006; Frolova et al., 2010; Larionov & Frolova, 2003a; Larionov et al., 2003b] was implemented to determine the risk indexes: identification of the quantitative characteristics of the seismic hazard for each settlement; computation of the damage states probability distribution for buildings of different types for various values of shaking intensity; computation of the possible social losses – the distribution of fatalities for each settlement; computation of the probability of fatalities per definite time period and per one year for each settlement. For computation of expected social losses for large towns and cities they were divided into elementary units, and their coordinates were represented by a point located in the center of the unit. Then the risk values obtained for individual unit sites were summarized. Fig. 11 and 12 show the examples of individual seismic risk zoning R_S1 maps for the Irkutskaya oblast, the Republic of Buryatiya and the Chitinskaya oblast produced using the map of review seismic hazard and shaking intensities' matrixes.

The regional maps of risk zoning (Fig. 11–12) includes two elements: risk for settlements with number of inhabitants less than 1,000, shown by "hypsometric" contours, and risk for settlements with number of inhabitants more than 1,000 shown by symbols (circles of different sizes and colors). The "hypsometric" scale is used to represent both elements on the map.

For the majority of settlements the seismic risk values R_S1 obtained using the shaking intensities' matrixes are less than the values obtained with the use of map OSR-97 (Table 9). On the whole, the values of seismic risk are still rather high for the considered area.

Fig. 13–15 presents the examples of regional maps of seismic vulnerability for the Northern Caucasus. As input data about seismic hazard the map of review (scale 1:5,000,000) seismic zoning OSR-97B is used. Maps include two elements: percent of different damage states for settlements with number of inhabitants less than 1,000 and vulnerability for cities and towns with number of inhabitants more than 1,000. Physical vulnerability $V_{ph}(I)$ is presented as circle (Fig. 13) and bar charts (Fig. 14).

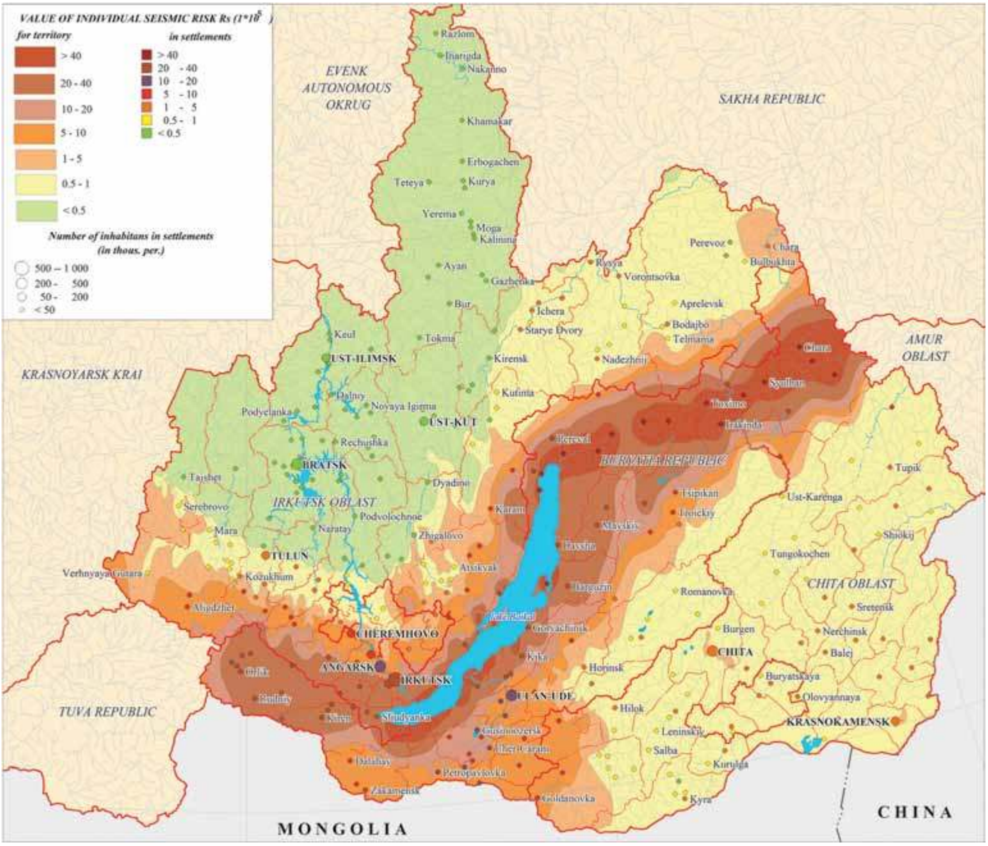

Fig. 11. Seismic risk map using the maps OSR-97

Table 9. Values of individual seismic risk R_s1 using shaking intensities' matrixes and maps OSR-97 for some cities and towns of the Baikal region

Name of settlement	Administrative unit of the Russian Federation	Population, thousands persons	R_s1 using matrices, 10^{-5} 1/year	R_s1 using OSR-97 maps, 10^{-5} 1/year
Irkutskк	Irkutsk oblast	583	13.1	42.1
Ulan-Ude	Republic of Buryatiya	367	19.1	28.3
Chita	Chita oblast	300	0.9	6.51
Angarsk	Irkutsk oblast	247	17.2	30.6
Shelekhov	Irkutsk oblast	48	20.5	61.2
Gusinoozersk	Republic of Buryatiya	28	14.2	28.3
Severobajkalsk	Republic of Buryatiya	27	78.2	56.6
Sludyanka	Irkutsk oblast	19	65.4	61.2
Kyakhta	Republic of Buryatiya	18	17.8	28.28
Selenginsk	Republic of Buryatiya	17	60.51	56.55
Bajkalsk	Irkutsk oblast	14	58.92	61.24
Toksimo	Republic of Buryatiya	12	72.25	56.55

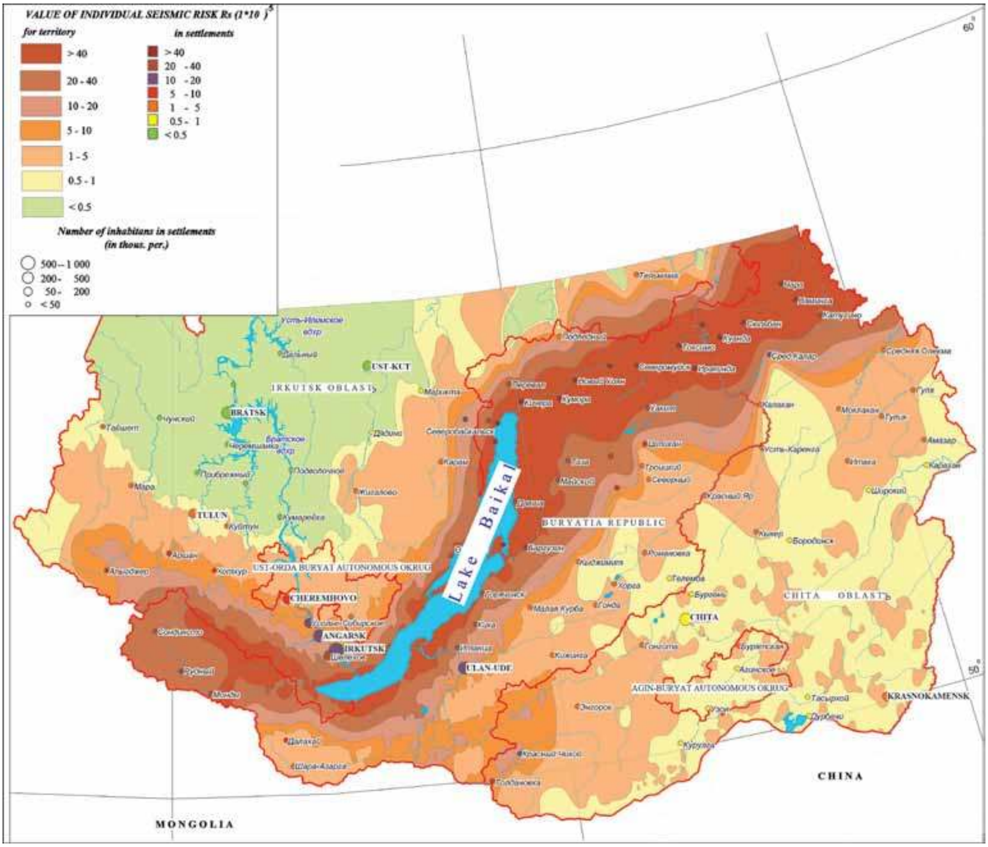

Fig. 12. Seismic risk map using the shaking intensities' matrixes

Maps of physical vulnerability may be used for preventive measure plans development and implementation at region level (Fig. 13) and for taking decision about population evacuation as it takes into account 3 damage states which result in estimation of homeless people (Fig. 15). Visual analysis of these maps give an evidence that the percent of damage states equal to 3–5 is rather high for some settlements. This fact allows making a conclusion that the preventive measures in these settlements are not sufficient.

Fig. 15 shows the map of economic vulnerability $V_e(I)$ for the Northern Caucasus, which is characterized by ratio between the cost of buildings repair and the initial cost of their construction. As previous maps, it also includes two elements: ratio between the cost of buildings repair and the initial cost of their construction for settlements with number of inhabitants less than 1,000 is shown by zones of different colors and the ratio for cities and towns with number of inhabitants more than 1,000 is shown by figures.

Tables 10–11 show the average values of damage states $d_{average}(I)$ to build environment and average values of economic vulnerability $V_e(I)$ for the administrative areas in the Northern Caucasus.

Regional maps of seismic risk and vulnerability allow settlements to be identified when additional study should be undertaken. First of all, the maps of seismic microzoning of the settlement territory should be compiled. The data on built environment inventory should be verified by visual inspection or by a joint analysis of high-resolution space images and photo panoramas of settlements.

Fig. 13. Fragment of the physical vulnerability map for the Northern Caucasus Federal region of the Russian Federation and Krasnodar area: percent of buildings in settlements which may survive damage states *d* = 1, 2, 3, 4, 5 in the case of earthquakes according to the seismic hazard map OSR-97B:

light blue – no damage; blue – light damage; green – moderate; yellow – heavy; brown – partial collapse; pink – total collapse

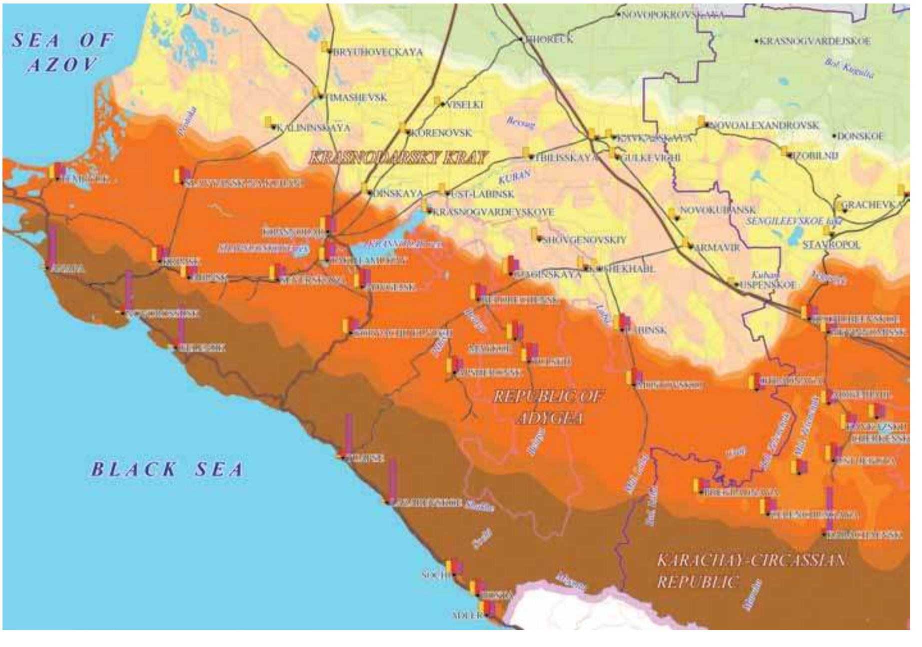

Fig. 14. Fragment of the physical vulnerability map for the Northern Caucasus Federal region of the Russian Federation and Krasnodar area: percent of buildings in settlements which may survive damage states *d* = 3, 4, 5 in the case of earthquakes according to the seismic hazard map OSR-97B:

light blue – no damage; blue – light damage; green – moderate; yellow – heavy; brown – partial collapse; pink – total collapse

Fig. 15. Fragment of economic vulnerability map in relative units:

figures – ratio between the cost of building repair and the initial cost of its construction

Table 10. Average damage states to buildings and structures in the administrative units

Administrative unit	Population, persons	Population density, persons/km^2	Average damage states $d_{average}$ (*I*)
Krasnodar kraj	5,404,273	71.59	2.2
Republic of Dagestan	2,963,918	58.96	3.9
Republic of Adygeya	446,406	57.29	3.1
Republic of Ingushetiya	453,010	124.86	4.5
Kabardino-Balkar Republic	858,397	68.84	3.5
Karachaevo-Cherkessk Republic	469,837	32.91	3.6
Republic of North Osetiya – Alaniya	703,977	88.14	4.7
Stavropol kraj	2,794,508	42.24	2.1
Chechen Republic	1,346,438	86.05	3.9

Table 11. Average values of economic vulnerability in the administrative units

Administrative unit	Population, persons	Population density, persons/km^2	Average value of economic vulnerability $V_e(I)$
Krasnodar kraj	5,404,273	71.59	0.4
Republic of Dagestan	2,963,918	58.96	0.8
Republic of Adygeya	446,406	57.29	0.5
Republic of Ingushetiya	453,010	124.86	0. 9
Kabardino-Balkar Republic	858,397	68.84	0.7
Karachaevo-Cherkessk Republic	469,837	32.91	0.7
Republic of North Osetiya – Alaniya	703,977	88.14	0.9
Stavropol kraj	2,794,508	42.24	0.3
Chechen Republic	1,346,438	86.05	0.7

Seismic risk assessment at urban level

In the case of medium-term earthquake prediction for urbanized area, such as Petropavlovsk-Kamchatsky, or in the case of large investment projects in areas characterized by high level of seismic hazard, such as the Olympic Games Complex in City Big Sochi, the maps of seismic risk are constructed for definite cities. As input data about seismic hazard the maps of seismic microzing (scale 1:10,000) are used. The building inventory for cities is verified and updated averaged city districts models (percent of buildings of different types according to MMSK-86 scale within city district and their average height) or building by building inspection is undertaken in order

Fig. 16. Fragment of high-resolution space image for City Big Sochi, Kirova street

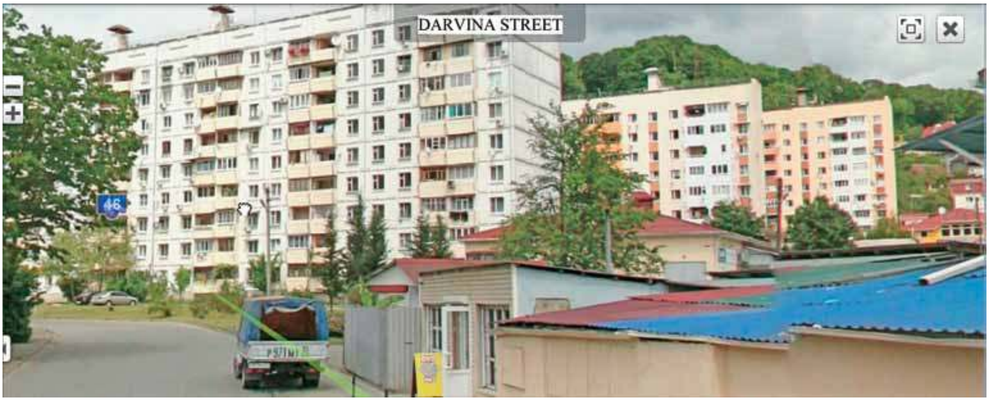

Fig. 17. Fragment of photo panorams from http://maps.yandex.ru/ for City Big Sochi, Darvina street

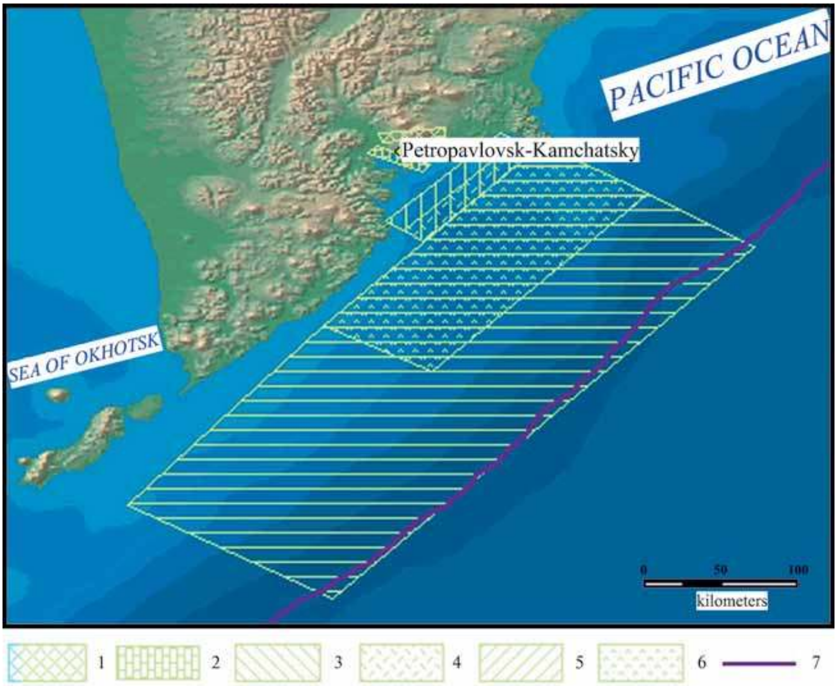

Fig. 18. Location of scenario earthquakes' source zones:

1 – VUL; 2 – PET; 3 – AVG; 4 – AVS; 5 – FZ9; 6 – FZ8; 7 – axis of the Pacific Ocean deep-water trough

to collect information about each building. Together with land inspection, decoding of high resolution space images and web-mapping may be applied (Fig. 16 and 17) for verification data on built environment inventory.

As an example of seismic risk computations at urban level the Petropavlovsk-Kamchatsky City is used. The Kamchatka Peninsula territory is one of the most seismically active regions of the Russian Federation. The land inspection was undertaken to verify the data on each building in the city. The Institute of Physics of the Earth, Russian Academy of Sciences, identified six possible earthquake source zones (VOZ). The values of M_{max} and return periods for the possible events in these zones VOZ (Fig. 18) are given in Table 12.

The results of seismic risk computation for different VOZ zones (Table 12) show that the highest values of risk for population are reached for an event in zone AVS

Table 12. Expected social losses and individual risk R_s1 for the Petropavlovsk – Kamchatsky city due to events in different zones VOZ

Zone index	M_{max}; Return period, years	Seismic Individual Risk, 10^{-5}	Expected Losses	
			Fatalities, persons	Injuries, persons
PET	6.8–7.0; 3 000–30 000	1.0–8.0	7,260–15,460	16,180–33,120
VUL	6.8–7.0; 2 000–20 000	1.0–10.0	5,590–12,860	12,580–32,310
FZ9	9.0–8.5; 100–500	8.0–50.0	44–290	250–1 320
FZ8	8.4–8.25; 50–500	10.0–45.0	220–810	720–3,270
AVS	7.8–7.9; 30–100	30.0–300.0	850–2,610	2,450–8,150
AVG	7.8–7.9; 300–3 000	4.0–15.0	570–1,760	1,650–6,330

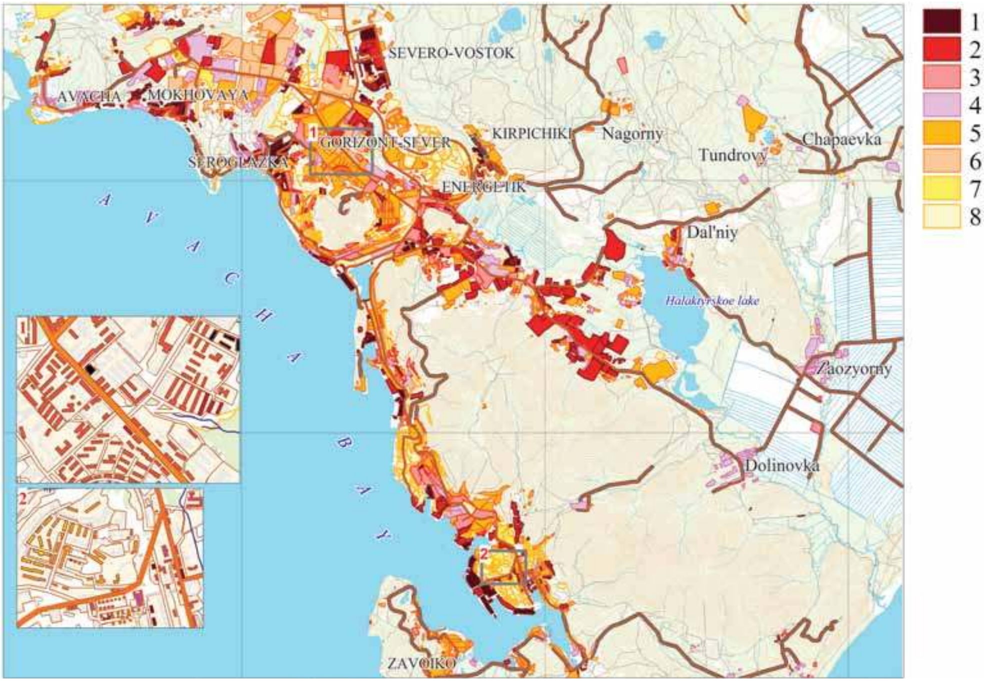

Fig. 19. Individual seismic risk R_s zonation for the Petropavlovsk-Kamchatsky City for a scenario event in zone AVS; values of risk for city districts:

1 – < $2 \cdot 10^{-3}$; 2 – $5 \cdot 10^{-4} \div 2 \cdot 10^{-3}$; 3 – $2 \cdot 10^{-4} \div 5 \cdot 10^{-4}$; 4 – $1 \cdot 10^{-4} \div 2 \cdot 10^{-4}$; 5 – $5 \cdot 10^{-5} \div 1 \cdot 10^{-4}$; 6 – $1 \cdot 10^{-5} \div 5 \cdot 10^{-5}$; 7 – $5 \cdot 10^{-6} \div 1 \cdot 10^{-5}$; 8 – > $5 \cdot 10^{-6}$

(Table 12, Fig. 19). Using possible source zones as input data on seismic hazard level, as well taking into account the influence of ground conditions, allows to get more detailed differentiation of risk values at urban level.

Taking into account the fact that maximum values of risk for Petropavlovsk-Kamchatsky City are related to earthquakes in zone AVS and maximum expected losses are typical of a scenario event in zone PET, which is characterized by low risk values, the following conclusions were drawn that programs, plans and preventive measures aimed at risk reduction should be developed and implemented in two stages. For long term planning maximum expected losses should be taken into account: expected fatalities = 15,000 persons; injuries = 33,000 persons. For short term planning the measures should be implemented which take into account expected losses: fatalities = 2,600 persons; injuries = 8,000 persons.

CONCLUSIONS

In the paper the influence of input data about seismic hazard on ambiguity of seismic risk assessment at different levels has been shown. The practice of crisis management shows that the reliability of risk or loss computations strongly depends on many factors [Bonnin & Frolova 2010; Frolova et al. 2011]. Among them, the main factors are the following: uncertainty on mathematical models used for simulation shaking intensity, behavior of building, population and other elements at risk; completeness and reliability of databases on elements at risk (population and built environment) and hazard sources; reliability of regional shaking intensity attenuation relationships; reliability of regional vulnerability functions for different elements at risk caused by earthquakes and other secondary natural and technological hazards; uncertainties on rapid determinations of event parameters by seismological surveys; lack of access to confidential sources of information.

On the whole, uncertainties on the parameters used in seismic risk estimation process are numerous and large. Taking into account the present situation the expert participation in earthquake risk estimation is very vital. Visualization of seismic risk and vulnerability assessment on the maps of different details facilitate expert estimation of the obtained results and their acceptability. ■

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