UNCERTAINTIES OF EARTHQUAKE LOSS ESTIMATION AT GLOBAL SCALE IN EMERGENCY MODE

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Abstract

The paper addresses the reliability issues of strong earthquakes loss assessment following strong earthquakes with worldwide Systems' application in emergency mode. Timely and correct action just after an event can result in significant benefits in saving lives. In this case the information about possible damage and expected number of casualties is very critical for taking decision about search, rescue operations and offering humanitarian assistance. Such rough information may be provided by, first of all, global systems, in emergency mode. The experience of earthquakes disasters in different earthquake-prone countries shows that the officials who are in charge of emergency response at national and international levels are often lacking prompt and reliable information on the disaster extent. Uncertainties on the parameters used in the estimation process are numerous and large: knowledge about physical phenomena and uncertainties on the parameters used to describe them; global adequacy of modeling techniques to the actual physical phenomena; actual distribution of population at risk at the very time of the shaking (with respect to immediate threat: buildings or the like); knowledge about the source of shaking, etc. The paper analyzes the influence of different uncertainties on the reliability of expected loss estimations, special attention is paid to influence of regional peculiarities of shaking intentity attenuation.

Introduction

At present, among the global systems that allow to provide earthquake loss estimation just after an event, three stand out. They are: the Russian "EXTREMUM" System which allows to simulate the distribution of shaking intensity, damage to buildings of different types, number of casualties in damaged and destroyed buildings and, optionally, identify effective response measures in case of emergency; the "Global Disaster Alert and Coordination System" (GDACS), which allows in near real-time to monitor the seismic situation and provide estimation of expected number of inhabitants in the affected area based on population density

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data; and the "Prompt Assessment of Global Earthquakes for Response" (PAGER) System of the US Geological Survey which allows to simulate expected shaking intensity and estimate expected number of inhabitants in zones of different intensities based on population density information. Within the Global Earthquake Model (GEM) initiative a new similar system is under development. The paper analyzes the untertainties which influence the reliability of earthquake consequences simulation in emergency mode. Special attention is paid to one of the main factors such as the regional peculiarities of shaking intensity attenuation.

Brief description of existing global systems

The "EXTREMUM" System development started in 1990ies by joint efforts of Extreme Situations Research Center (ESRC) Ltd., Seismological Center, Institute of Environmental Geosciences, Russian Academy of Sciences, and Civil Defense and Disaster Management Research Institute, Emercom of Russia, within the framework of the Russian Federal Programs "Safety of Population, Buildings and Structures against Natural and Technological Hazards" and "Federal System of Seismological Observations and Earthquake Prediction". In 1999 – 2001, the system was further developed within the framework of EDRIM ("Electronic Discussions for Risk Managements") Program under the umbrella of the EUR-OPA Major Hazards Agreement ("Open Partial Agreement on the Prevention of, Protection Against and Organisation of Relief in Major Natural and Technological Disasters") of the Council of Europe.

The first implementation of "EXTREMUM" system in the Russian Federation has been done in 1995 for damage and loss assessment after the Neftegorsk earthquake. The first implementation at the global level has been done following the recommendations of Moscow Seminar on the "Contribution to the Decision-Making Process in Seismic Risk Management: Models for Earthquake Damage Assessment", held on 29 June – 01 July, 2000, within the framework of the EUR-OPA Major Hazards Agreement. Starting on 01 August 2000, a version has been run on an operational basis.

The "EXTREMUM" System databases and mathematical models used for simulation of shaking intensity, damage to buildings and structures, number of fatalities and injuries, are regularly updated by Extreme Situations Research Center, Seismological Center of IGE, Russian Academy of Sciences. The description of simulation models and data bases, as well as reliability issues is given (Bonnin et al., 2002a,b; Bonnin et al., 2004; Bonnin & Frolova, 2010; Larionov & Frolova, 2003a; Larionov *et al*. 2003b; Frolova *et al*., 2003a,b; Frolova *et al*., 2006; Frolova *et al*., 2007; Frolova *et al*., 2010).

The results of computations are usually presented as maps and tables, where estimates of expected number of fatalities, injuries and homeless are given for the whole stricken area and for each settlement. Fig. 1 show maps with the results of expected damage and shaking intensity computations for the earthquakes occurred on 21 July 2013 in China. Dots of different size and color show the settlements in the stricken area; the dot size depends on the number of inhabitants in the given settlement; the dot color tells the expected "averaged" damage state of the buildings.

Fig. 1. Results of possible loss assessment caused by July 21, 2013 earthquake in China

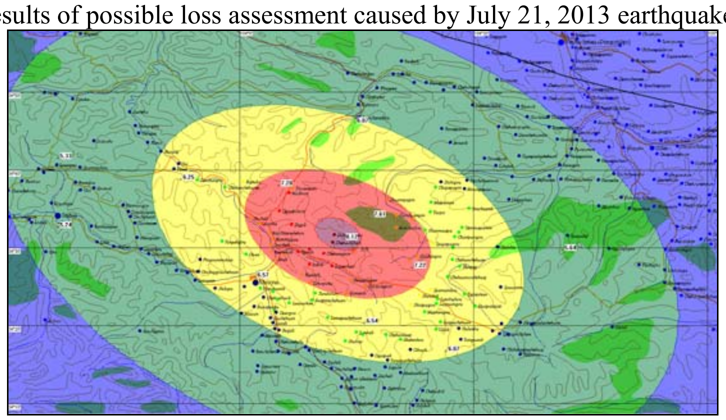
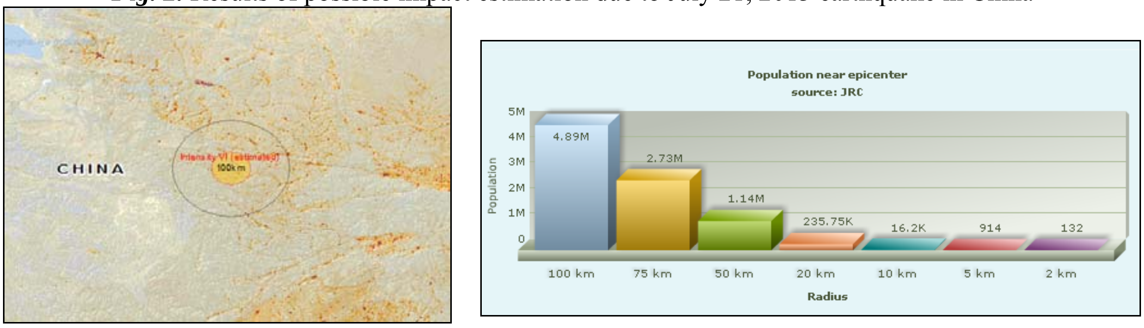


Fig.1 shows the result of loss computation with input data according to the variant 5 (tabl.2); dots are settlements in the stricken area; colour of dots shows the average damage state of building stock (black: total collapse, brown : partial collapse, red : heavy, yellow: moderate, green : slight damage, blue: no damage).

In 2012 the three-years' project under EMERCOM of the Russian Federation was started aimed at updating the "Extremum" System assigned for assessment of loss due to earthquakes and secondary hazardous processes in emergency mode at global scale.

The "Global Disaster Alert and Coordination System" (GDACS) was jointly developed by the European Commission's Joint Research Centre and the United Nations Office for Coordination of Humanitarian Affairs (OCHA) since 2005. The main aims of the system are to alert the international community in case of major sudden-onset disasters and to facilitate the coordination of international response during the relief phase of the disaster (de Groeve, 2006; de Groeve et al., 2008). The disaster alerts are based on automatic hazard information retrieval and real-time GIS-based consequence analysis. The GDACS earthquake impact model is built on the existing seismological infrastructure. Every 5 minutes, GDACS collects information on rapid estimations of earthquake location, magnitude and depth of source from different agencies, like NEIC, EMSC, GEOFON, JMA and others. By reporting the epicenter on the map of population density, GDACS estimates the total population in the affected area within radii of different sizes. Then, it estimates the likelihood need for international humanitarian intervention.
Fig. 2 shows fragments of the green alert event report for the earthquake in China on July 21, 2013 from the web site of the system (http://www.gdacs.org).

Fig. 2. Results of possible impact estimation due to July 21, 2013 earthquake in China



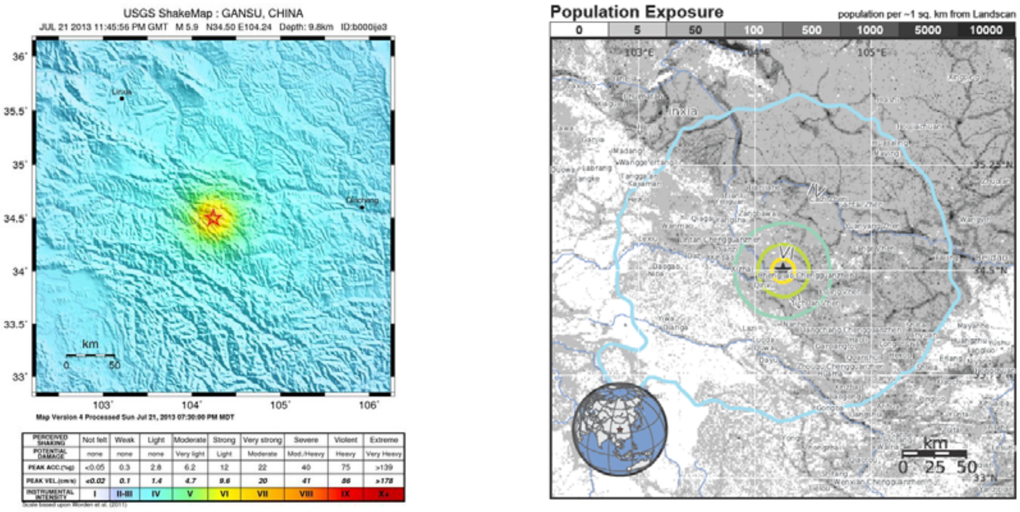
In the case critical facilities, such as airports, ports, nuclear plants and hydrodams are located near the epicenter the list of these facilities is given, if affected.

GDACS provides a platform allowing stakeholders in international disaster response to exchange disaster-related information in a structured and predictable manner, particularly in the response phase of disasters. It is not aimed at informing the potentially endangered population. GDACS collects news from various sources, including ReliefWeb and AlertNet. JRC contributes to the European Media Monitor system: a system that automatically gathers and classifies news from media and blogs and makes this available as RSS files.

The "Prompt Assessment of Global Earthquakes for Response" (PAGER) System of US Geological Survey allows to simulate expected shaking intensity by using the methodology and software developed for ShakeMap (http://earthquake.usgs.gov/shakemap). Then, the expected number of inhabitants within the zones of different level of shaking intensity *I* is estimated by using the information on population density from Oak-Ridge National Laboratory's Landscan population database. PAGER is an automated system; it monitors the NEIC near real-time detections of domestic and global earthquakes and issues alarm to emergency agencies and other end-users at national and international levels. Its estimations of exposed population could be revised in case subsequent information about event parameters becomes available and a replacement alarm is issued. Rapid estimates include the number of people and names of cities exposed to each shaking intensity level as well as the likely ranges of fatalities and economic losses. At present three PAGER earthquake loss models exist: empirical, semi-empirical and analytical one. The results of computation with last two models are not publicly available.

Fig. 3 shows an example of possible consequences estimation following the 21 July 2013 earthquake in China with empirical model application.

Fig. 3. Results of possible consequences estimation following the July 21, 2013 earthquake in China according to application of PAGER System



The USGS is improving the PAGER system to include more comprehensive loss-estimate methodologies that take into account more detailed building inventories representing sub-country-level regional variations, more complete population demographics (including time of day population shifts), and better tools to compute building damage (Wald *et al*., 2008; Wald *et al*., 2009; Jaiswal et al., 2009; Jaiswal & Wald, 2012). PAGER development and maintenance are supported by the USGS under the Advanced National Seismic System (ANSS), with additional funding from the Global Earthquake Model (GEM) project. PAGER team is working in collaboration with Earthquake Engineering Research Institute's (EERI) World Housing Uncyclodediya (WHE) team to develop a country-specific, building-type library, taking existing information from WHE' house prototype and extending the coverage further by adding more countries.

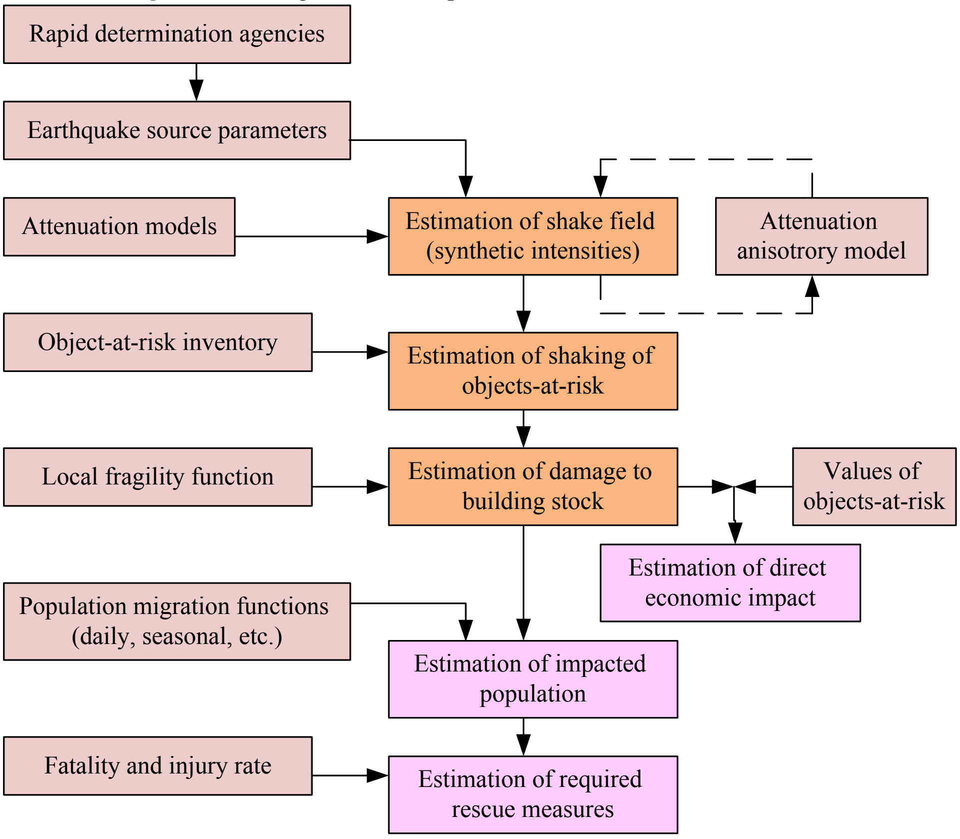
All three considered worlwide systems to different extent are based on imitation modeling.

Reliability of expected loss estimations applying the three global systems

The analysis of results of earthquake loss computations in emergency mode with different systems which make use of simulation models showed that their reliability strongly depends on many factors (fig.5). Among them, the main factors are the following:
• uncertainties in rapid determinations of event parameters by seismological surveys;
• uncertainty of mathematical models used for simulation shaking intensity, behabior 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 due to earthquakes and other secondary natural and technological hazards;
• lack of access to confidential sources of information.

On the whole, uncertainties on the parameters used in the earthquake loss estimation process are numerous and large: knowledge about physical phenomena and uncertainties on the parameters used to describe them; global adequacy of modeling techniques to the actual physical phenomena; actual distribution of population at risk at the very time of the shaking (with respect to immediate threat: buildings or the like); knowledge about the source of shaking, *etc.*

Fig. 5. Flow diagram of earthquake loss simulation uncertainties



All simulation models, used for earthquake consequences estimation, bring in their own uncertainties and propagate the uncertainties of the previous steps of the estimation procedure. Actually, the problems of accuracy are considerably more complex than it is suggested in the previous sentence; in addition, to the classical behaviour of uncertain input data through each step of the procedure, the simulation models introduce biases whose influence on the final results is not easy to assess; this cannot be thoroughly discussed here.

In the present study we consider in details the influence of simulation models for shaking intensity, regional peculiarities in shaking intensity attenuation and their influence on reliability of loss computations. Among three considered above worlwide systems, Extremum and PAGER Systems make use of simulation model to estimate shaking intensity distribution.

Influence of uncertainties in regional shaking intensity attenuation

The section describes the models for shaking intensity simulation. Data about event source parameters are input for computation of the probable shaking field, in terms of "intensity". Authors follow the traditional way of expressing the shaking; progress is badly needed to improve the situation and think in terms of true acceleration responsible for the damage observed. The formula often used is taken from Shebalin (Shebalin, 1968).

$$I = bM - \nu \lg\sqrt{\Delta^2 + h^2} + c, \qquad (1)$$

where Δ - epicentral distance (km); h - source depth (km); M - magnitude. Coefficients in the formula are estimated taking into account empirical data. In the research for the Balkan

Catalogue the sets of these coefficients were proposed by Sbebalin and Karnik (Shebalin et al. 1974) for rather detailed division of the territory under study. The estimations made by Shebalin for the former USSR were more general (Kondorskaya and Shebalin, 1977). Long experience of the equation application (Shebalin, 2003) showed that the region under consideration should be divided into minimum number of sub-regions. Attenuation law parameters proposed for Europe are obtained in the report (Shebalin et al., 1998). They are listed in Table 1.

Table 1. Macroseismic field coefficients for the Europe by (Shebalin et al. 1998)

Region	*b*	*ν*	*c*
Southern part $\varphi \leq 47^{\circ}$ N	1.5	4.0	3.8
Northern part $\varphi > 47^{\circ}$ N	1.5	3.5	3.6

For other territories, these coefficients may be taken from literature or derived from statistical analysis of available data sets; one could alternatively use the average values: b = 1.5; ν = 3.5; c = 3 proposed by Shebalin (Shebalin, 1968).
Sometimes when other regional attenuation laws are accessible they are integrated into global systems. There was the case of the 2006 Mozambique earthquake when Shebalin equation gave overestimation of shaking intensity and the equation (2) obtained on the basis on empirical data about the event in May 1940 in Mozambique (personal communication by A. Kijko) was used.

$$I_0 - I = a_1 - a_2 \ln(r) - a_3 r, \qquad (2)$$

where a_1=1.4, a_2= -0.44, a_3= -0.0064, r is hypocenteral distance in km, I is intensity and I_0 is the maximum intensity at the epicentre.

In emergency mode just after the event it is common practice to start earthquake loss computation with application of formula (1) and default regional coefficients. Then the obtained circular isoseists are stretched along the active tectonic faults in order to take into account anisotropy of the medium and source line extension. Different orientation of ellipse axis may be estimated taking into account source mechanism solution, as well as empirical data about ratio k of ellipse major and minor semi-axis (for different value of k) may be also taken into account.

In the case of the 2008 Kurchaloj earthquake in Russia twelve variants of input data were used for consequences computation in order to take into account regional peculiarities of shaking intensity attenuation. Different values of regional coefficients in formula (1) obtained by different researchers for the region under study (Shebalin, 1977; Bystritskaya, 1978; Aver'yanova et al., 1996) and different values of k were used (table 2). For all variants the macroseismic field oriented was along active tectonic faults.

The simulated estimations of expected shaking intensities and losses are usually compared with observed macroseismic effect and reported damage.

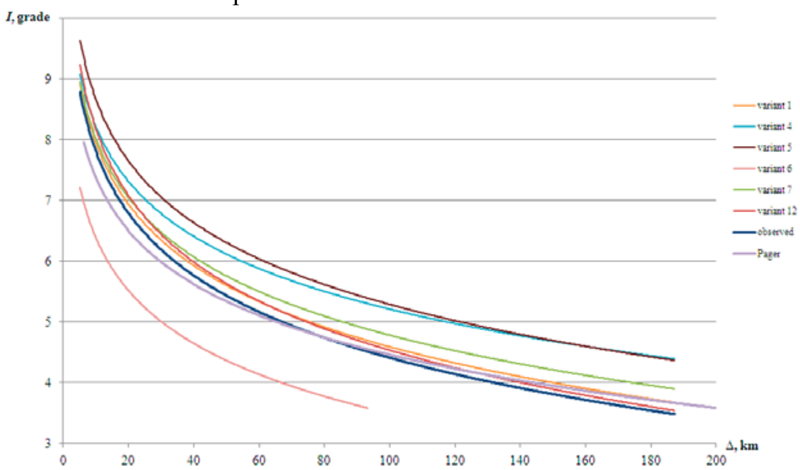
Table 2. Input data for simulation of the Kurchaloj event consequences

No	**Survey**	**Lat., Log.**	**M**	**h, km**	**Regional coefficients in formula (1)**	**Ratio *k***
1	**2**	**3**	**4**	**5**	**6**	**7**
1	GS RAS	43.276; 46.229	M=5.6	h=15	b=1,5; ν=3,6; c=3,1 for Dagestan; (Shebalin, 1977)	k=1.5
2	GS RAS	43.276; 46.229	M=5.6	h=15	b=1,5; ν=3,6; c=3,1 for Dagestan; (Shebalin, 1977)	k=2
3	GS RAS	43.276; 46.229	M=5.6	h=15	b=1,5; ν=3,6; c=3,1 for Dagestan; (Shebalin, 1977)	k=4
4	GS RAS	43.276; 46.229	M=5.6	h=15	b=1,6; ν=3,1; c=2,2; for NorthernCaucasus; (Shebalin, 1977)	k=1.5
5	GS RAS	43.276; 46.229	M=5.6	h=15	b=1,4; ν=3,5; c=4,2 for Caucasus; (Shebalin, 1977)	k=1.5

1	2	3	4	5	6	7
6	GS RAS	43.276; 46.229	M=5.6	h=15	*b*=1.52; *ν*=3.6; *c*=1.6 for Dagestan;(Bystristkaya, 1978)	*k*=1.5
7	GS RAS	43.276; 46.229	M=5.6	h=15	*b*=1.593; *ν*=3.41; *c* = 2.44 for Groznyj City; (Aver'yanova et al., 1996)	k=1.5
8	NEIC	43.3; 46.3	M=5.9	h=10	*b*=1,5; *ν*=3,6; *c*=3,1 for Dagestan; (Shebalin, 1977)	k=1.5
9	CSEM	43.47; 46.34	M=5.9	h=15	*b*=1,5; *ν*=3,6; *c*=3,1 for Dagestan; (Shebalin, 1977)	k=1.5
10	GS RAS	43.37; 46.35	M=5.6	h=10	*b*=1,5; *ν*=3,6; *c*=3,1 for Dagestan; (Shebalin, 1977)	k=1.5
11	GS RAS	43.15; 46.10	M=5.6	h=15	*b*=1,5; *ν*=3,6; *c*=3,1 for Dagestan; (Shebalin, 1977)	k=1.5
12	GS RAS	43.276; 46.229	M=5.6	h=15	*b*=1,5; *ν*=4; *c*=3,8; (Shebalin, 2003)	k=1.5

Figure 6 shows the comparison of observed values of shaking intensities with simulated values obtained by Extremum and PAGER Systems application. The example for the 2008 Kurchaloj earthquake shows that more general parameters (variant 12) allow to simulate shaking intensity which is close to observed values (fig. 6).

Fig. 6. Comparison of simulated shaking intensities with application of different attenuation law parameters and observed values



In the case of recent deadly earthquake on July 21, 2013 near Minxian, Gansu, China, which resulted in at least 95 killed and 2,395 injured (http://earthquake-report.com/2013/07/21/very-strong-earthquake-gansu-china-on-july-21-2013/) the estimations of consequences in emergency mode were made using different input data about event parameters determined by USGS, CEPC and GS RAS, different shaking intensity attenuation relationships, different orientation of the macroseismic field and different ratio *k* of macroseismic ellipse major and minor semi-axis (table 3), 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. 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***	**Orientation of ellipse**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
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°

1	2	3	4	5	6	7	8
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°

The simulated intensity estimations were compared with observed macroseismic effect published by the Chinese seismological authorities (fig. 7) in order to find the better agreement between simulated and observed effect. The map 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)**.

Fig. 7. The map published by the Chinese seismological authorities

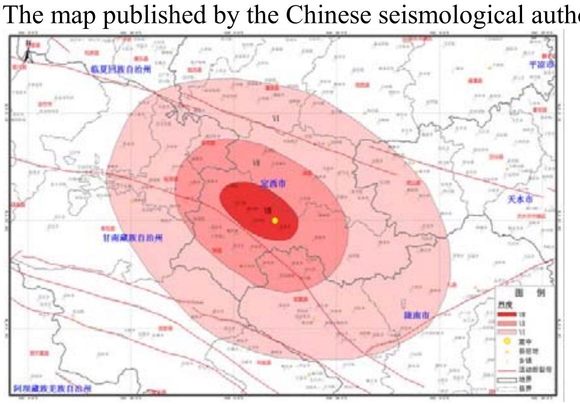
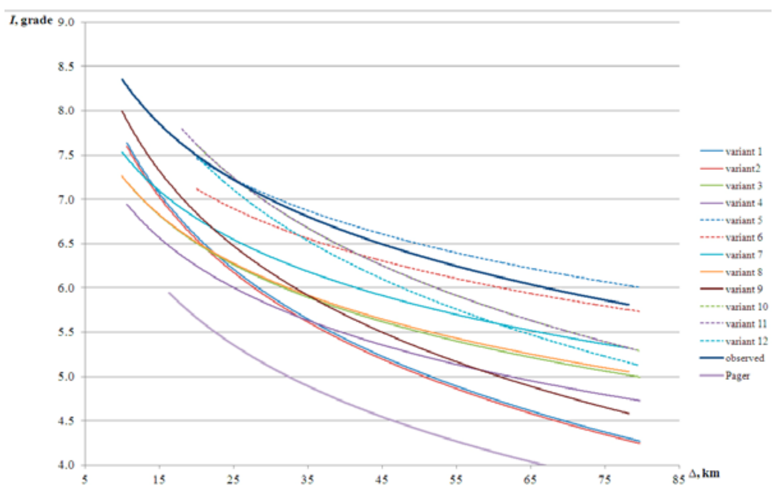


Figure 8 shows the comparison of observed shaking intensity values (fig. 7) with simulated ones using Extremum System software (tabl. 3) and ShakeMap software of PAGER System.

Fig. 8. Comparison of simulated shaking intensities with application of Extremum and PAGER Systems and observed values



In general all simulated values of shaking intensity are 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 to get reliable loss estimations. The exception is variant 5 (fig. 8, tabl. 3) for the epicentral distances Δ>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 (tabl. 4). For the variant 5 the values of $\Delta I_{average}$ is equal to 0.1.

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

Variant 5	Variant 6	Variant 10	Variant 11	Variant 12
ΔI_{max}=1.0	ΔI_{max}=1.0	ΔI_{max}=1.0	ΔI_{max}=1.0	ΔI_{max}=1.0
$\Delta I_{average}$= -0.1	$\Delta I_{average}$ =-0.4	$\Delta I_{average}$ =-0.4	$\Delta I_{average}$ =-0.3	$\Delta I_{average}$ =-0.5
σ=0.3	σ=0.3	σ=0.2	σ=0.2	σ=0.3

Relatively good agreement of simulated and observed shaking intensity values is obtained when we use the regional intensity attenuation relationships (equations 3, 4) proposed for the eastern part of China (IASPEI, 1993).

Along major axis $I = 6.046 + 1.480m - 2.081\ln(R + 25.0)$, s=0.49 (3)

Along minor axis $I = 2.617 + 1.435m - 1.441\ln(R + 7.0)$, s=0.56 (4)

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

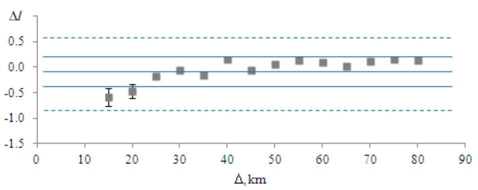
Table 5. Comparison of intensities computed using regional attenuation relationships (3 and 4) with observd values of shaking intensity

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

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

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

Variant 5



Variant 6

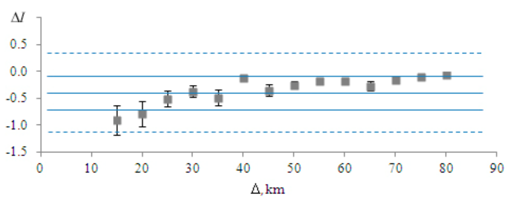
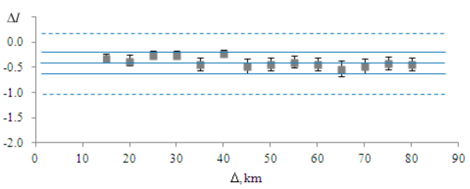
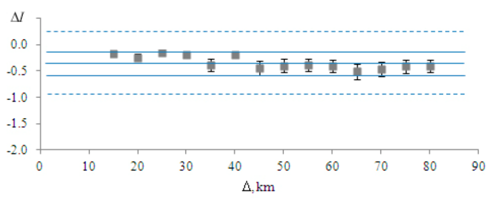


Fig. 10. Residuals for the simulated shaking intensities; residuals are binned in 5-kilometer windows and the median residual is plotted by grey dots

Variant 10



Variant 11



The above considered examples for tow earthquakes in Russia and China show that it is possible to choose the proper regional characteristics of shaking intensity (relationship and its regional coefficients, orientation and ratio *k* of ellipse major and minor semi-axis). Namely, these three parameters are essential for reliable loss computations.

Conclusions

The present paper describes briefly existing global system used for earthquake loss estimations in emerdency mode. The uncertainties in simulation models and data bases used for loss computations are analyzed.

Special attention is paid to uncertainties in shaking intensity simulation. Three groups of characteristics responsible for reliable estimation of regional peculiarities of shaking intensity distribution (relationship and its regional coefficients, orientation and *k*, are identified. In order to increase the reliability of earthquake loss estimations in emergency mode it is proposed to undertake zoning of the earthquake prone territories of the world according to these paprameters.

Similar studies are under way within the GEM project and PAGER, as well as the authors started to investigate the issue within the contract with EMERCOM of Russia.

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Dr. Valery Larionov is Vice General Director of Extreme Situations Research Center. He has contributed to research on emergency response since 1972. He is an expert in assessment and management of natural and technological risk; organization of management and response to emergency situations; industrial safety, assessment and management of seismic risk. The Russian Federation government awarded Dr. Valeri Larionov, along with others, the prizes in 1999 and 2001 for the work on development of the Russian Federal system for monitoring and forecast of emergency situations.

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