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Seismic risk assessment for the infrastructure in the regions adjacent to the Russian Federation Baikal–Amur Mainline based on the Unified Scaling Law for Earthquakes

Anastasiya Nekrasova & Vladimir Kossobokov

Natural Hazards **116**, 1995–2010 (2023) | Cite this article

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Soil Dynamics and Earthquake Engineering

Peer review status

[1st revision] REGIONAL SEISMIC RISK ASSESSMENT BASED ON THE UNIFIED SCALING LAW FOR EARTHQUAKES: THE LAKE BAIKAL RAILWAY SYSTEM

Nekrasova A,
V. Kossobokov,
E. Podolskaia

1st revision

Under Review

Last review activity: 3rd November 2023

Watch to learn what we're doing behind the scenes

SJR Q1

ESC - S07: 1213

3rd EUROPEAN CONFERENCE ON

EARTHQUAKE ENGINEERING & SEISMOLOGY

BUCHAREST, ROMANIA, 2022

Nekrasova A., Kossobokov V. (2022) The Lake Baikal Region anisotropic seismic impact modelling for realistic assessment of associated risks and disaster scenarios. Proceedings of the Third European Conference on Earthquake Engineering and Seismology - 3ECEES: September 5-September 9, 2022, Bucharest, Romania / editors: Cristian Arion, Alexandra Scupin, Alexandru Ţigănescu. - Bucureşti: Conspress, 2022, ISBN 978-973-100-533-1, pp 3915-3921.

EGU General Assembly 2023

NH4.2/SM3.06 – Seismic Hazard and Disaster Risk: Assessment, Testing, and Implementation

Nekrasova, A., Kossobokov, V., Podolskaia, E. (2023) Seismic risk assessment of the Lake Baikal railway infrastructure based on Unified Scaling Law for Earthquakes and anisotropic seismic impact, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-1710, https://doi.org/10.5194/egusphere-egu23-1710

Republican Seismic Survey Center – Azerbaijan National Academy of Sciences

VII International Conference "Seismology and Engineering Seismology“
Republican Seismic Survey Center of the Azerbaijan National Academy of Sciences and the Ministry of Emergency Situations of the Republic of Azerbaijan
Dedicated to the 100th anniversary of the birth of Nationwide Leader H. Aliyev

Некрасова А. К., Кособоков В. Г. (2023) Общий закон подобия для землетрясений: оценка сейсмической опасности и ассоциированных рисков, Материалы VII Международной конференции «Сейсмология и инженерная сейсмология», организованной Республиканским Центром Сейсмологической Службы при Национальной Академии Наук Азербайджана и Министерством по Чрезвычайным Ситуациям Азербайджанской Республики, посвященной 100- летию со дня рождения Общенационального Лидера Г.Алиева, 6-9 июня 2023 г. Баку, Азербайджан.

Outline

- **The Unified Scaling Law for Earthquakes, USLE**
- **Scaling Coefficients Estimation algorithm, SCE**
- **Seismic hazard maps based on USLE**
- **Anisotropic seismic impact due to the dominant direction of the regional active fault system**
- **Seismic Hazard (SHA) and Risk (SRA) Assessment based on USLE: the most recent example – the Lake Baikal region**
- **Conclusions**

Seismic activity is self similar

Nekrasova A. K., Kossobokov V. G. (2020) The Unified Scaling Law for Earthquakes. Journal of Volcanology and Seismology 14(6): 353–372. https://doi.org/10.1134/S07420463200600
Nekrasova, A.K., Kossobokov, V.G., Parvez, I.A., Tao X. (2020) Unified Scaling Law for Earthquakes as Applied to Assessment of Seismic Hazard and Associate Risks. Izvestiya, Physics of the Solid Earth, 56 (1): 83–94. https://doi.org/10.1134/S1069351320010097

.

The Unified Scaling Law for Earthquakes generalizes the classical Gutenberg-Richter relationship accounting for the local fractal structure of the lithosphere as follows -

$$\log_{10}N = A + B\cdot(5 - M) + C\cdot\log_{10}L$$

where $N = N(M, L)$ is the expected annual number of earthquakes with magnitude M in an earthquake-prone area of linear dimension L.

Scaling Coefficients Estimation algorithm, SCE

Nekrasova A.K. 2013, Certificate of State Registration of Computer Software № 2013618171. Program for estimation of coefficients of the General Law of Similarity for earthquakes (SCE). Date of state registration in the Register of Computer Programs September 02, 2013

- A catalogue of earthquakes is used as initial input data source.
- A space-time-magnitude volume $S \times T \times M$ is considered, where S is the territory, T is time interval from T_0 to T_1, and M is the magnitude range above M_0 .
- Note: the events in the catalogue with magnitude m ≥ M_0 should be reasonably complete within S since T_0 .

Seismic hazard maps based on USLE

One can use the long-term estimates of the USLE coefficients to characterize seismic hazard in traditional terms of maximum expected intensity. Specifically, consider the values of A, B, and C obtained for seismic locus (e.g. at the grid points of a regular mesh).

For magnitude $M1 \le M \le M2$ calculate at these grid points the expected number of events in T years, $N_T(M) = T \times N(M)$ and find the maximum magnitude M_+ with the expected number $N_T(M)$ = p% or greater.

For grid points of a regular mesh compute the maximum of intensity produced by the ensemble of M_+ earthquakes.

Presumably, such an expected maximum magnitude map corresponds to “probability p% exceedance of in T years”, i.e. “**p% poe in T years**”.

isotropic seismic impact

Nekrasova A., Kossobokov V. (2022) The Lake Baikal Region anisotropic seismic impact modelling for realistic assessment of associated risks and disaster scenarios. Proceedings of the Third European Conference on Earthquake Engineering and Seismology - 3ECEES: September 5-September 9, 2022, Bucharest, Romania / editors: Cristian Arion, Alexandra Scupin, Alexandru Ţigănescu. - Bucureşti : Conspress, 2022, ISBN 978-973-100-533-1, pp 3915-3921.

Shebalin (1968) suggested the empirical estimate of macroseismic intensity *I* at distance Δ from of an earthquake epicentre of magnitude *M* originated at depth *h*,

$$I = b \times M - v \times \log_{10} \sqrt{\Delta^2 + h^2} + c$$

where b, v and c are the empirically estimated regional constants

Anisotropic seismic impact

We propose to use a modification depending on the dominant strike of the system of active faults in the Earth's crust:

$$I_e(M, \Delta, h, \varphi, \alpha, \beta, \gamma, \delta) = RAND(I(M, A(M), h), I(M, 0, h))$$

within the earthquake source zone of an elliptical shape with semi-axes $A(M) = ½\times10^{\alpha + \beta M}$ and $B(M) = ½\times10^{\gamma + \delta M}$ is randomly distributed values from $I(M, A(M), h)$ to $I(M, 0, h)$;

φ is the angle measured from the dominant strike ψ of the active fault system;

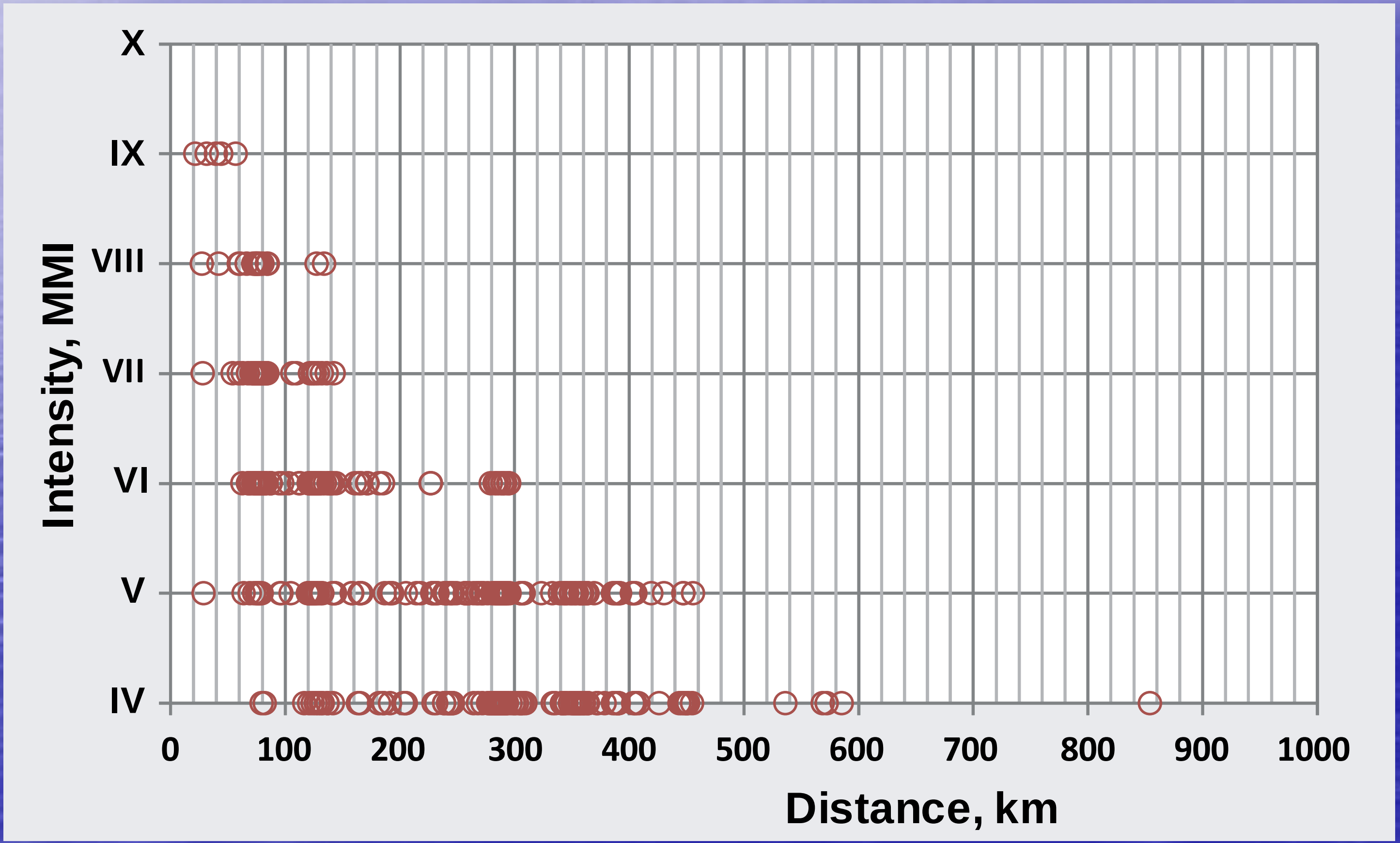
$\alpha, \beta, \gamma, \delta$ are the constants characterizing typical length and width of the source zone, which should be regional, if available, or determined by independent studies elsewhere, e.g.,

Wells and Coppersmith (1994) suggest the following mean values $\alpha = -2.29, \beta = 0.57, \gamma = -1.17, \delta = 0.34$.

Anisotropic seismic impact

M 6.8 - 54 km WSW of Oukaïmedene, Morocco

2023-09-08 22:11:01 (UTC) 31.073°N 8.407°W 18.0 km depth
https://earthquake.usgs.gov/earthquakes/eventpage/us7000kufc/shakemap/stations



Anisotropic seismic impact

We also assume that seismic waves propagate uniformly from the boundary of the earthquake source zone, so that outside it, macroseismic intensity follows equation

$$I_e(M,\ \Delta, h, \varphi,\ \alpha,\ \beta,\ \gamma,\ \delta) = I(M, A\left(M\right) + \Delta r(M, \varphi), h)$$

where $\Delta r(M,\ \varphi)$ is the minimum distance from the point $(\Delta \times cos\varphi,\ \Delta \times sin\varphi)$ to the boundary of the source zone, namely,
to the ellipse with semi-axes *A(M)* and *B(M)* centered at the earthquake epicenter.

Evidently, the dominant strike ψ of the regional active fault system may have a number of optional directions, in particular, at nodes and intersections of morphostructural lineaments. Therefore, a given epicentre of either real or model earthquake can be associated with one or even several directions for modelling its seismic impact. A reasonable choice of directions and their number to be made by analysing the empirical probability density distribution of the fault azimuths $\{\psi_i,\ p_i \mid i = 1, \dots n;\ \sum p_i = 1\}$ and picking the ψi with maximal p_i.

Sha and SRA, most recent example

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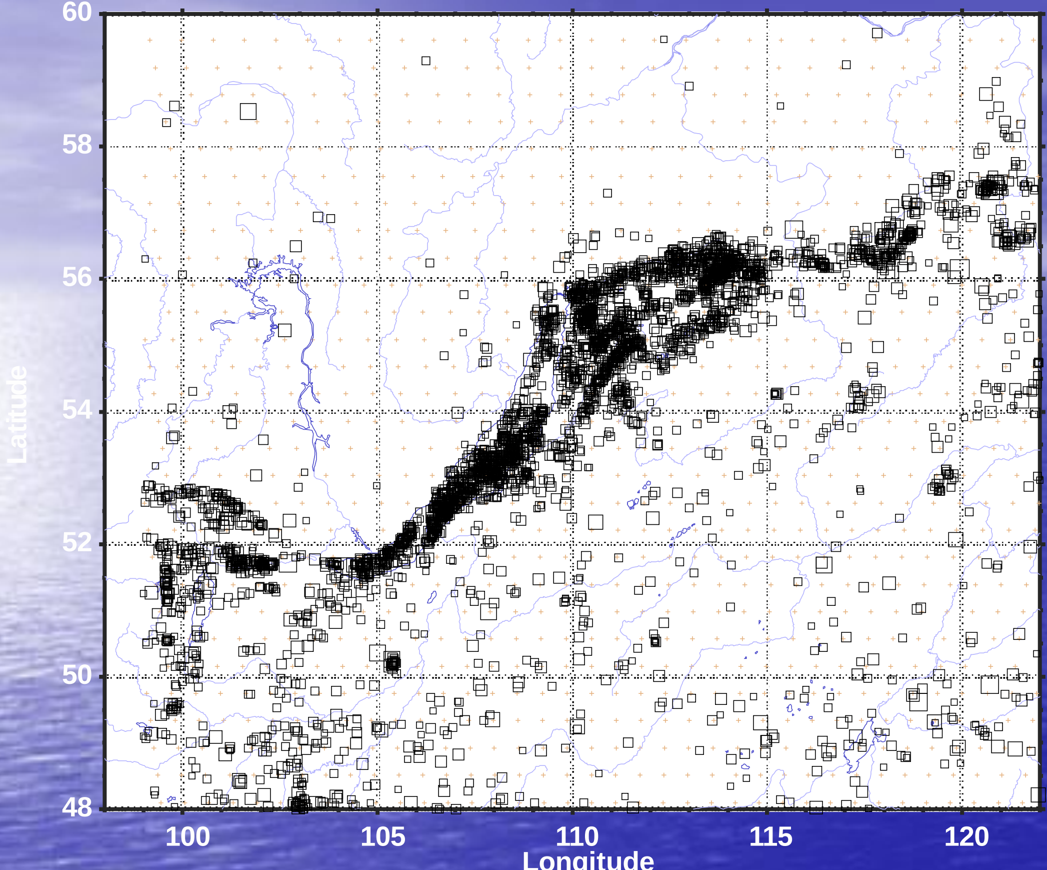
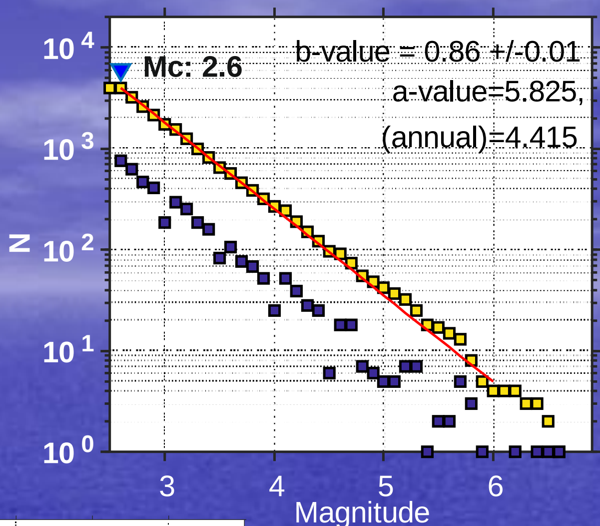
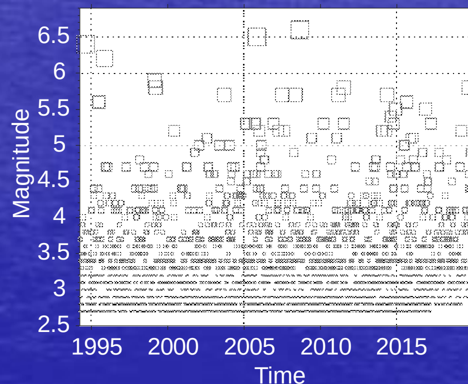
Natural Hazards **116**, 1995–2010 (2023) | Cite this article

- **Catalogue**
- **Maps of the USLE coefficients A, B, and C**
- **SHA map in terms of MX**
- **Dominant directions of the Lake Baikal active foults**
- **SHA maps in terms of macroseismic intensity**

Catalogue





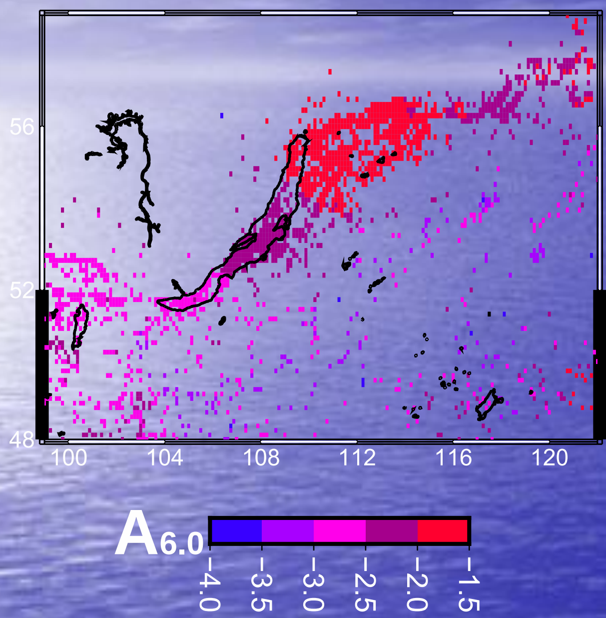


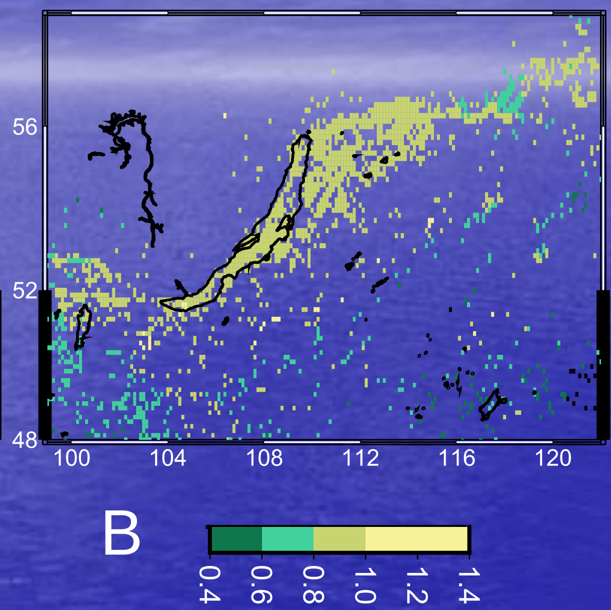
To analyse seismicity in the Lake Baikal Region, we make use of local catalogue compiled at Baikal Division of the Geophysical Survey, Federal Research Centre of the Russian Academy of Sciences from 1994 to 2019. Data available at https://seis-bykl.ru/modules.php?name=Data&da=1

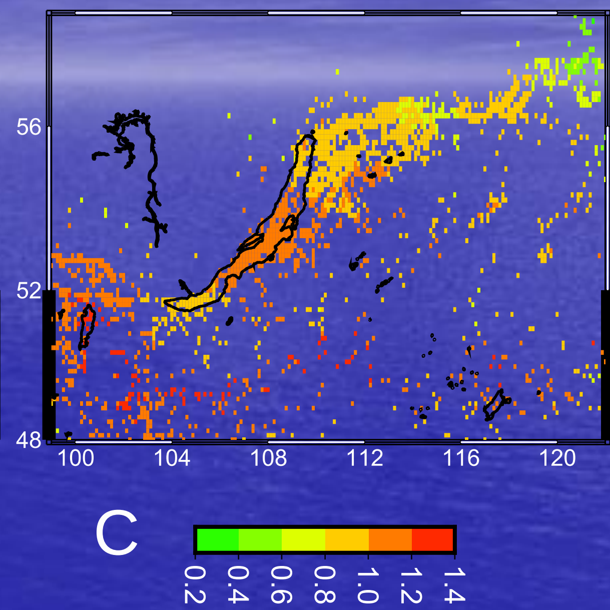
The catalogue is sufficiently complete at least for energy class K above 8.6 (K = 4 + 1.8×M).

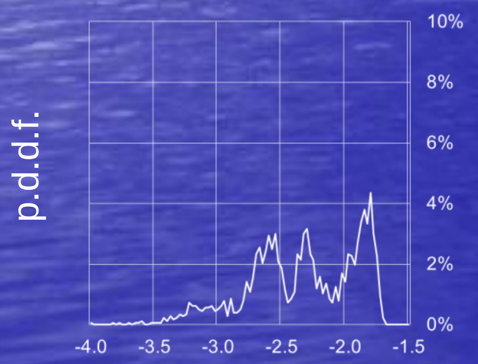
Maps of the USLE coefficients – A, B, C

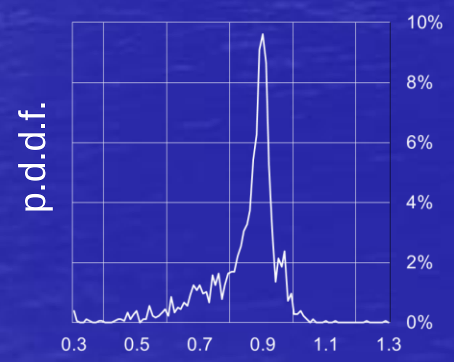
The calculations by the SCE algorithm (Nekrasova et al. 2015) performed using the hierarchy of enclosed square cells with linear sizes of 2°, 1°, 1/2°, 1/4° and 1/8° for 1813 earthquake-prone cells of a regular grid.

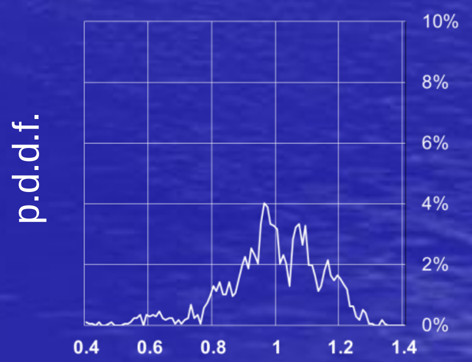






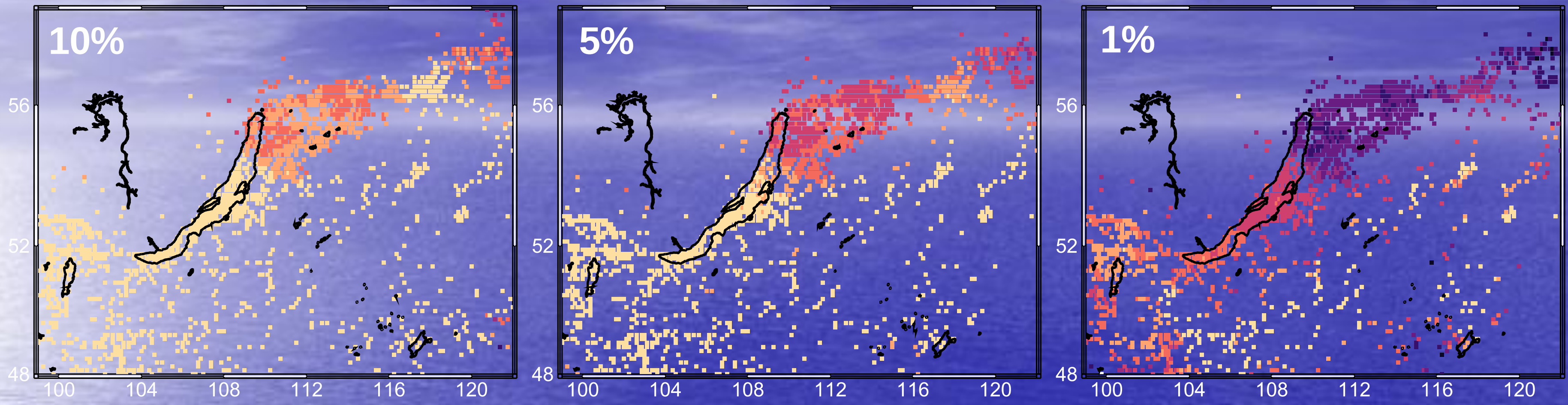


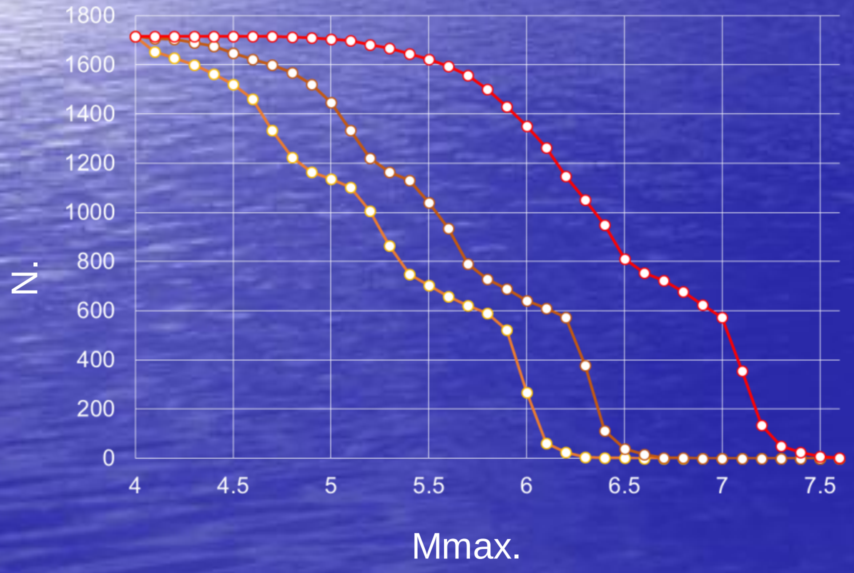


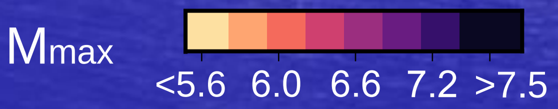


SHA map in in terms of M_{max}

The objective of the analysis is to evaluate probability of damaging seismic events for the purposes of assessing loss in performance of the major railway networks.



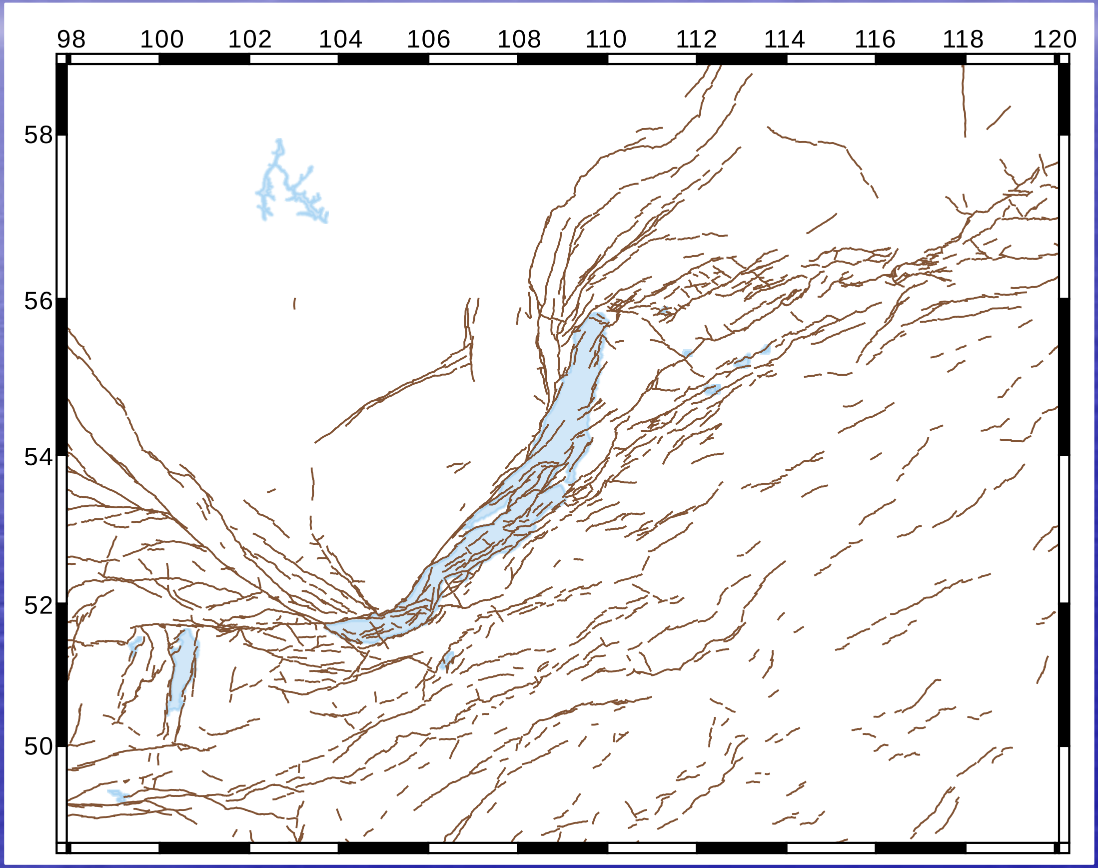




The number N of the regular grid earthquake-prone cells 1/8° x 1/8° in the Lake Baikal region with 10%, 5% and 1% *chance of exceedance* of Mmax in 50 years

Active faults of the Lake Baikal Region

The three values ψ_1, ψ_2, and ψ_3 of dominant directions supplied with the empirical p_1, p_2, and p_3 probabilities were estimated by averaging the azimuths of faults reported in Active Faults of Eurasia Database*



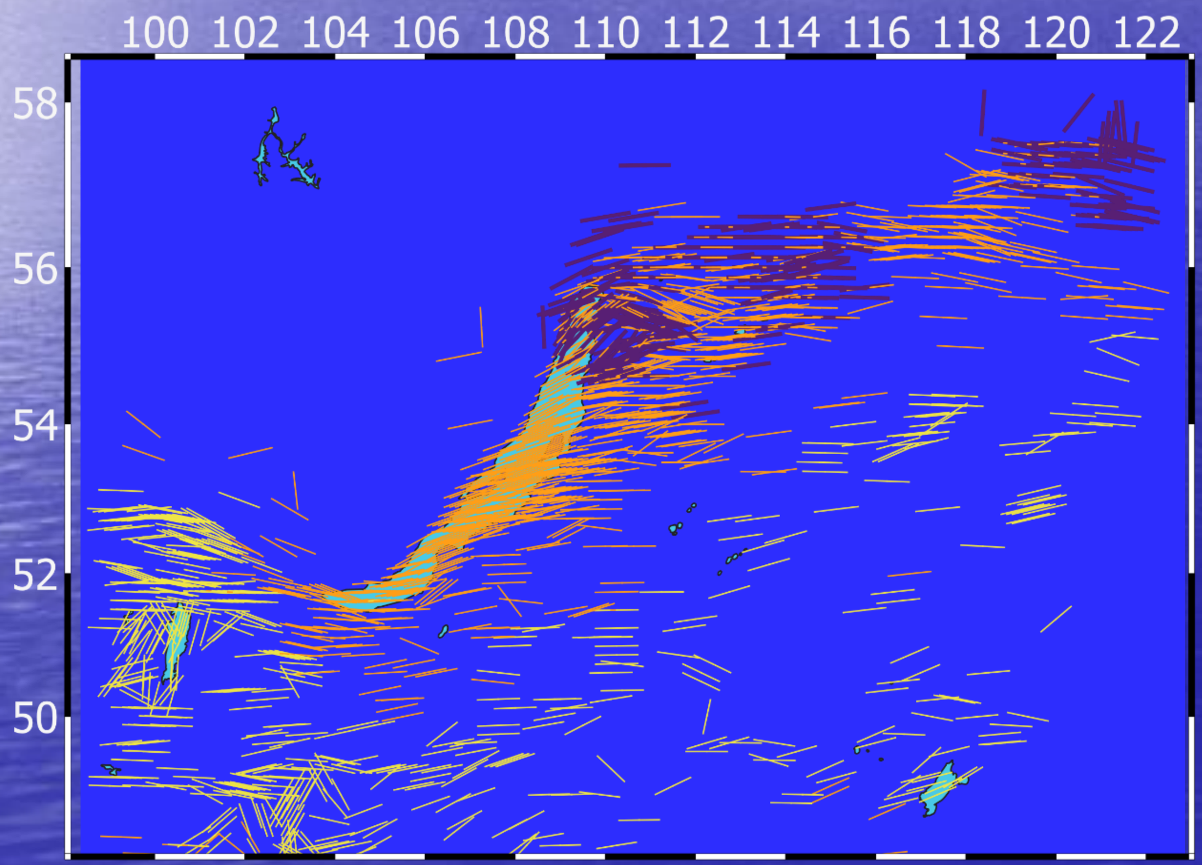
* Bachmanov, D.M., Kozhurin, A.I., Trifonov, V.G. (2017) The Active Faults of Eurasia Database. Geodynamics and Tectonophysics 8 (4): 711–736. https://doi.org/10.5800/GT-2017-8-4-0314

Dominant directions of the active faults

Емельянов И.В., Некрасова А.К. (2022) DDLAFS — плагин QGIS для оценки доминирующих направлений системы локальных активных разломов // Геоинформатика. —— No 4. — С. 54–62. https://doi.org/10.47148/1609-364X-2022-4-54-62

The direction ψ_i is defined as the azimuths of the maximum empirical probability determined by making use of the number of active fault azimuths in non overlapping 10-degree sectors of a 30-km radius circle centred at each epicentre g_i

estimated by averaging the azimuths of faults reported in Active Faults of Eurasia Database (Bachmanov et al., 2017; http://neotec.ginras.ru/database.html)



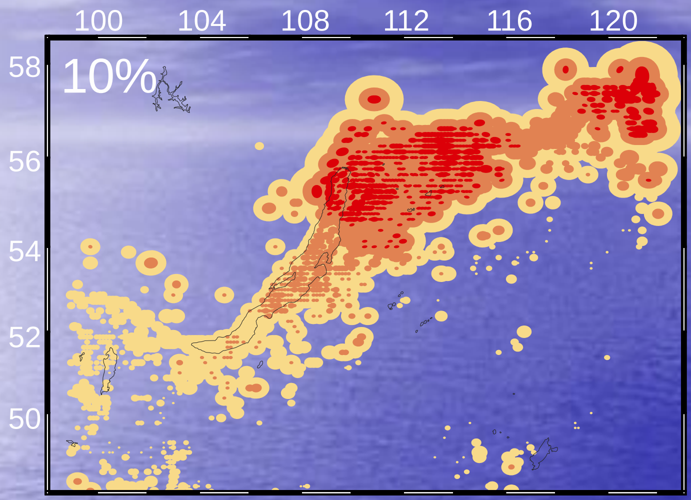
$\{\psi_i\}$ color-coded in respect to MX

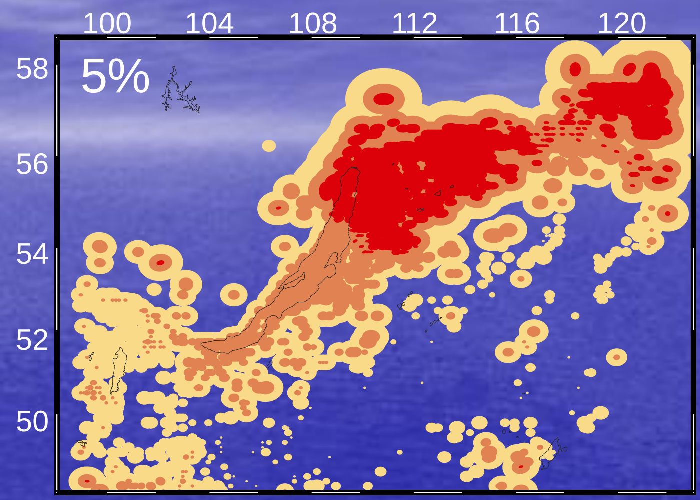
4.0 - 4.9

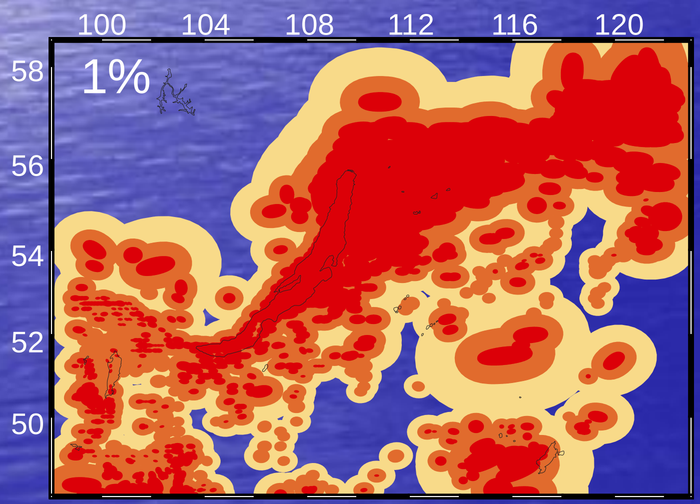
5.0 - 5.9

> 6.0

SHA maps in terms of macroseismic intensity based on USLE approach

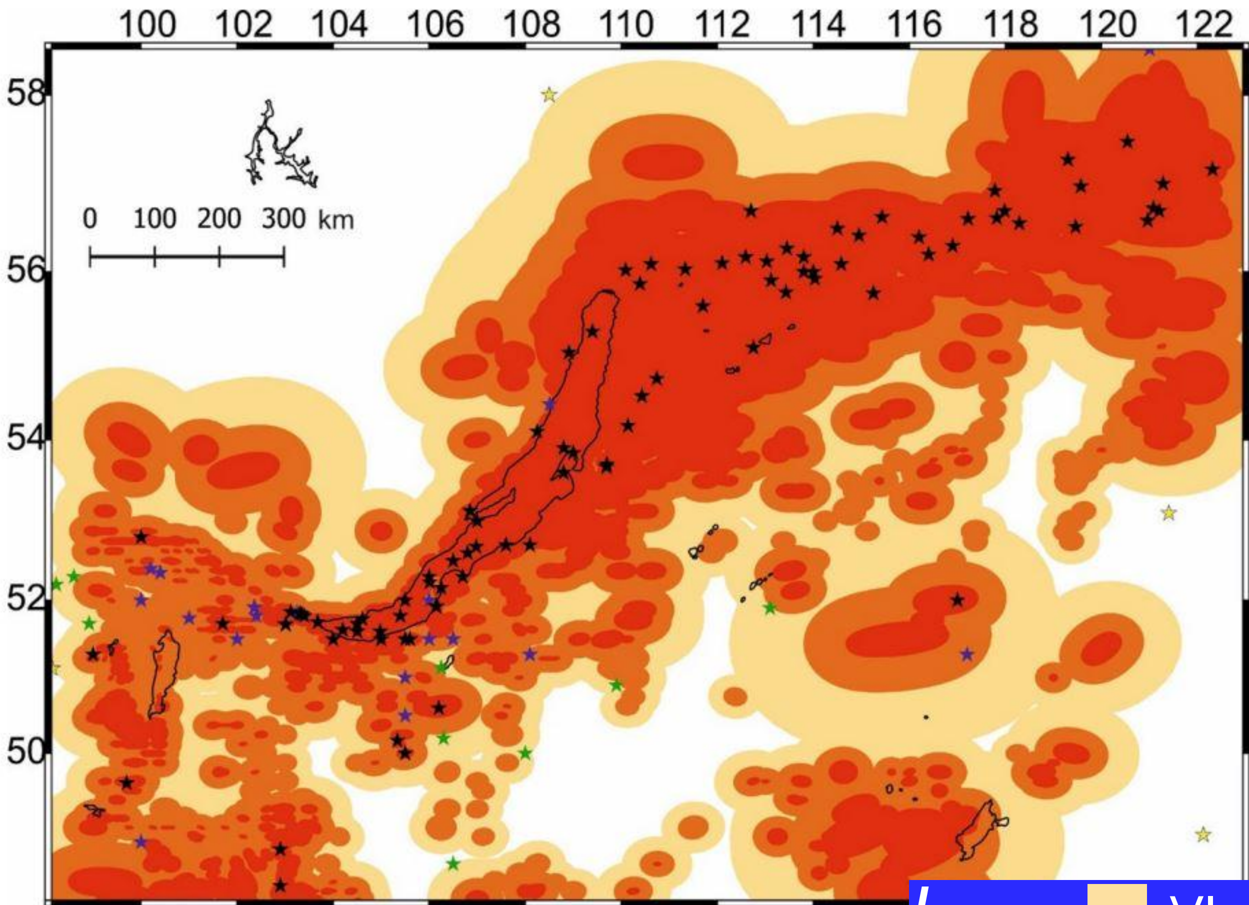






The set of triplets { (g_i, M_i, ψ_i) } allows us to design the elliptical seismic source zones for the Lake Baikal Region.
This resulted in consideration of 1136, 1448 and 1705 cells with expected 10%, 5% and 1% of exceedance of *MX* in 50 years.

The catalogue contains 124 earthquakes of magnitude MLH≥5.5 that occurred from 3000 BC to 2013 AD in the Lake Baikal Region.



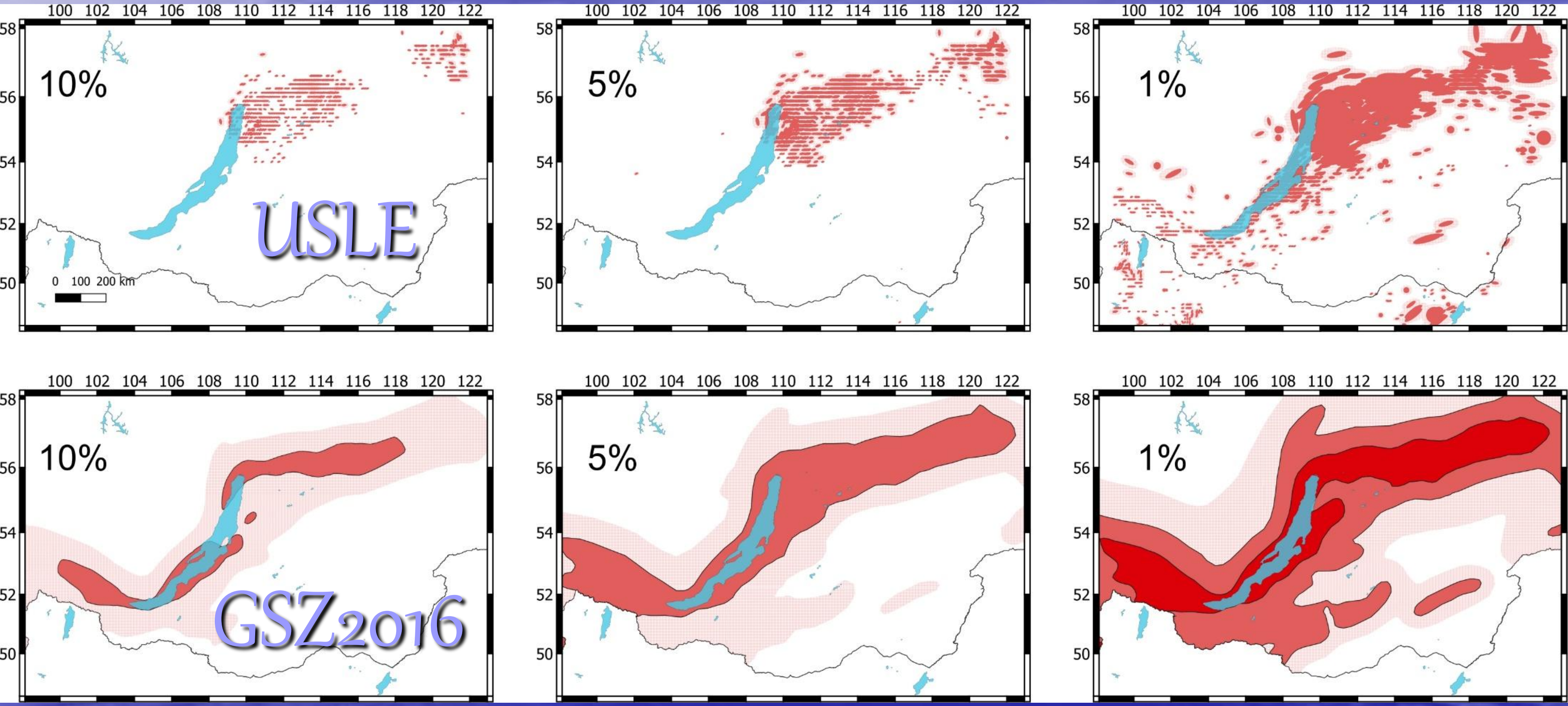
95 earthquakes (77% of the total 124 earthquakes) are located in the area of expected intensity VIII, 22 (18%)—in area of intensity VII, and only 6 (5%) within the area of intensity VI

Imax VI VII VIII

Fig. 10 Epicentres of the magnitude MLH ≥ 5.5 earthquakes from Ulomov and Medvedeva (2014) on top the USLE-based seismic hazard map of *I*max with 1% chance of exceedance in 50 years given in Fig. 7. Epicentres within the areas of macroseismic intensity VIII, VII and VI are marked with black, blue and green stars, respectively. Three epicentres fall outside the area of expected strong ground shaking (yellow stars) including the two outside the territory of the Russian Federation

macroseismic high intensities
based on USLE and GSZ2016 models

Nekrasova, A., Kossobokov, V. Seismic risk assessment for the infrastructure in the regions adjacent to the Russian Federation Baikal–Amur Mainline based on the Unified Scaling Law for Earthquakes. Nat Hazards 116, issue 2, 1995–2010 (2023). https://doi.org/10.1007/s11069-022-05750-9



I

VIII IX X

Zavyalov A, Peretokin S, Danilova T, Medvedeva N, Akatova K (2019) General Seismic Zoning: from Maps GSZ-97 to GSZ-2016 and New-Generation Maps in the Parameters of Physical Characteristics. Seismic Instruments 55(4):445–463. https://doi.org/10.3103/S0747923919040121

macroseismic high intensitiesbased on USLE and GSZ2016 models

Natural Hazards

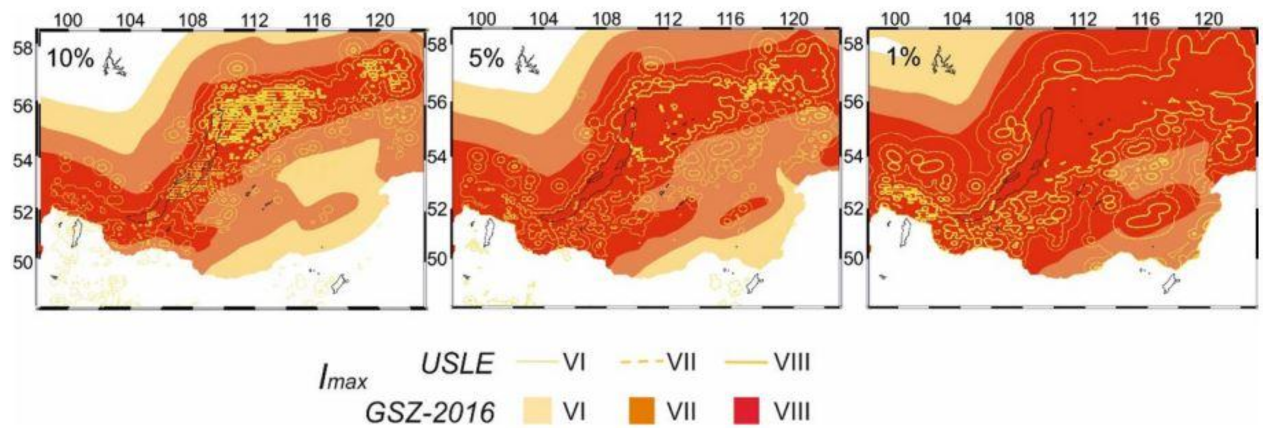


Fig. 9 GSZ-2016 and USLE-based macroseismic intensity maps for the Lake Baikal region for 10%, 5% and 1% probability of *I*max exceedance in 50 years

Table 2 The lake Baikal Region macroseismic intensity area for a period of 50 years with 10%, 5% and 1% probability of exceedance (in per cent to the total area within the borders of Russian Federation)

I class	USLE	GSZ-2016/A	USLE	GSZ-2016/B	USLE	GSZ-2016/C
	10% of exceedance		5% of exceedance		1% of exceedance	
VI+	32.3	87.2	42.5	91.9	72.5	100.0
VII+	15.2	63.8	23.1	76.6	48.9	90.3
VIII+	3.8	31.1	16.0	45.1	24.9	71.4

Nekrasova, A., Kossobokov, V. Seismic risk assessment for the infrastructure in the regions adjacent to the Russian Federation Baikal–Amur Mainline based on the Unified Scaling Law for Earthquakes. Nat Hazards 116, issue 2, 1995–2010 (2023). https://doi.org/10.1007/s11069-022-05750-9

Zavyalov A, Peretokin S, Danilova T, Medvedeva N, Akatova K (2019) General Seismic Zoning: from Maps GSZ-97 to GSZ-2016 and New-Generation Maps in the Parameters of Physical Characteristics. Seismic Instruments 55(4):445–463. https://doi.org/10.3103/S0747923919040121

Seismic risk estimates

Any kind of risk estimates result from a convolution of the hazard with the exposed object under consideration along with its vulnerability –

$$R(g)=H(g) \otimes O(g) \otimes V(O(g)),$$

where H(g) is natural hazard at point g, O(g) is the exposure of objects of risk at point g, and V(O) is the vulnerability of objects of risk. Note that distribution of risks, as well as objects of concern and their vulnerability could be time-dependent.

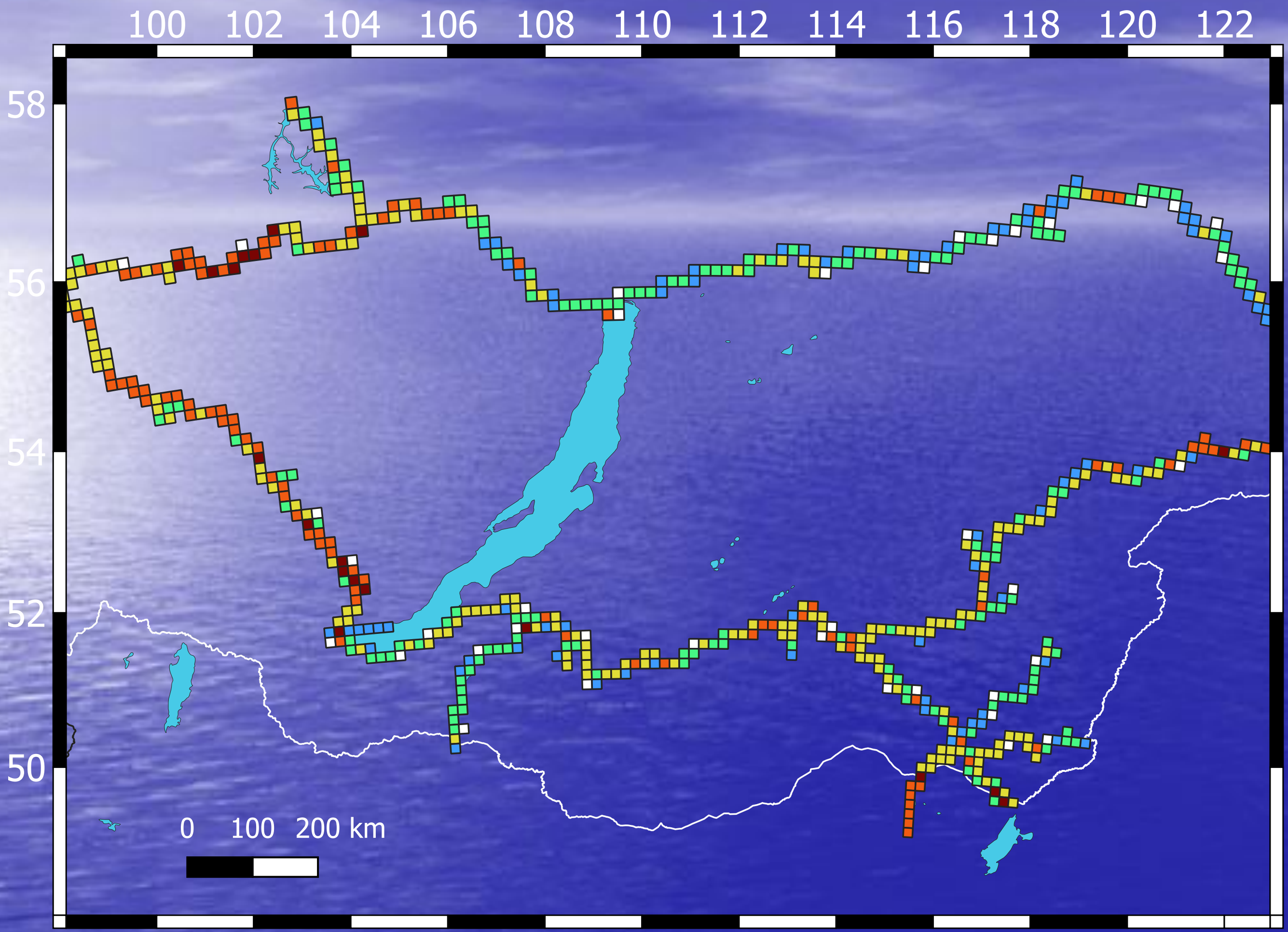
damage state standards

HAZUS Damage State	ds_2	ds_3	ds_4	ds_5
	Slight/Minor	Moderate	Extensive	Complete
Tracks/Roadbeds				
PGD (in)	6-12	12-24	24-60	same as ds_4
I (GOST R 57546-2017)	8-8.5	8.5-9.0	9-9.5	9-9.5
Bridges (Seismically Designed and Conventionally Designed)				
PGA (median, g)	0.3-0.67	0.7-0.86	0.8-1.4	1-1.4
I (GOST R 57546-2017)	7.5-8.0	8.0-8.5	8.5-9.0	8.5-9.0
Tunnels (Rock and Cut & Cover)				
PGA (median, g)	0.5-06	0.7-0.8	>0.8	>0.8
I (GOST R 57546-2017)	7.5-8.0	8.0-8.5	8.5 and more	8.5 and more

Federal Emergency Management Agency (FEMA), Hazus Earthquake Model Technical Manual Hazus 5.1. Retrieved from https://www.fema.gov/sites/default/files/documents/fema_hazus-earthquake-model-technical-manual-5-1.pdf on April 04, 2023, 14:34 EST.

GOST R 57546-2017 National Standard of the Russian Federation. Earthquakes. Scale of seismic intensity.
Date of introduction 2017-09-01 (in Russian)

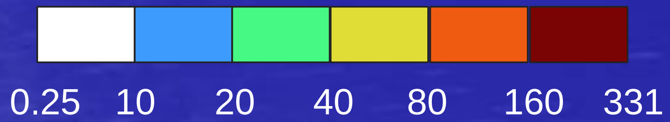
Elements of Lake Baikal railroad system …



We use Open Street Map data to obtain information on railroad tracks, bridges, and tunnels in the Lake Baikal Region (https://www.openstreetmap.org).

The OSM data revealed the presence of 13,999 railroad tracks…

RF State Border



km, Total length

Vulnerability of railroad elements

Pre-cast concrete (PCC) railroad ties & stone track repairs/Improvements cost based on *Railway Engineering & Construction Cost ..., 2023*

Macroseismic intensity	VIII	IX	X
$\times 10^6$, a.u. per route km, mean value	0.250	0.333	0.416

Railway Engineering & Construction Cost Benchmarks USA Location - 2023 Cost Basis:New & Refurbished Railroad Cost Benchmarks per mile & Km, includes Traffic Control Systems, Detailed Design/Construction Management costs. COMPAS international inc , 2023 (*https://compassinternational.net/wp-content/uploads/2023/02/CompassInternational_RailwayEngineering_11x8.5_Draft2-1.pdf*)

Benchmark cost, based on P50-value, *New Main Lines Cost, 2021*

Macroseismic intensity		VIII	IX	X
$\times 10^6$, a.u. per route km	Tunnels	15.275	30.550	45.825
	Bridges	11.7	23.4	35.2

New Main Lines Cost Benchmarking Study March 2021

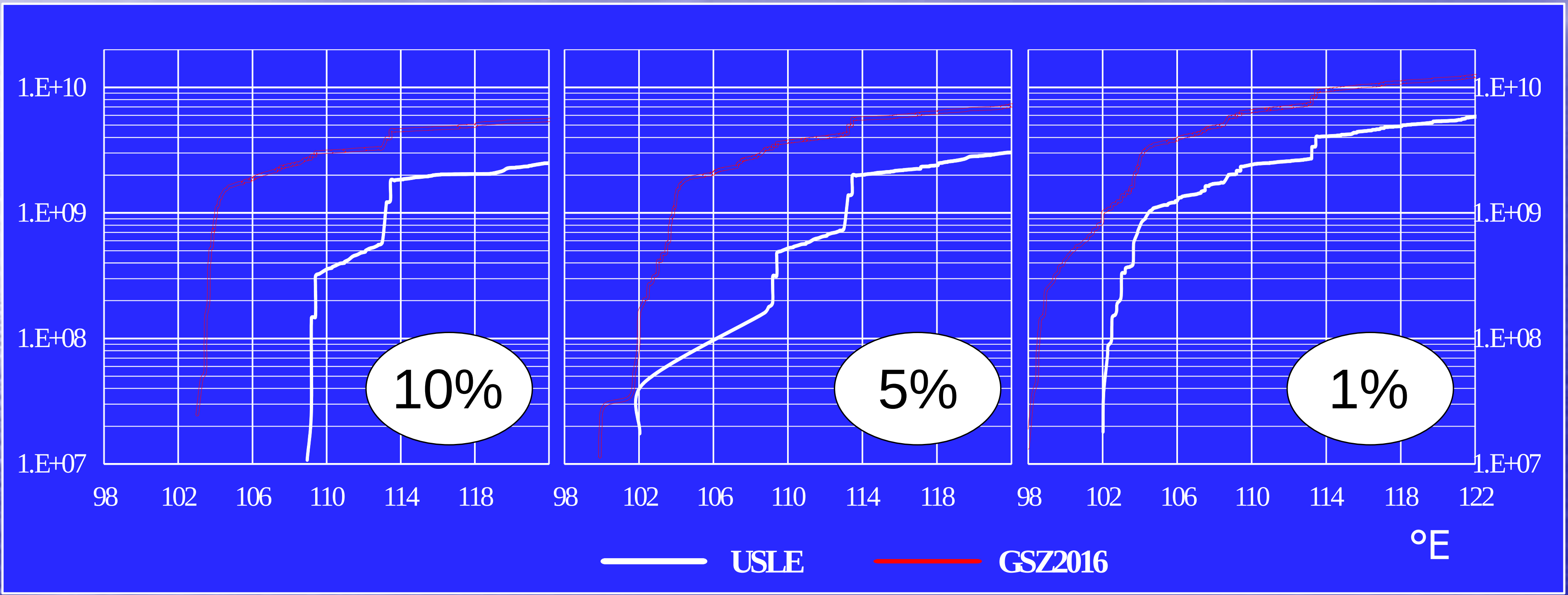
Seismic risk for Lake Baikal railroad system

SR = I ⊗ (railway elements [km] in regular grid cells) ⊗ V

Probability of exceedance	Models							
	USLE				GSZ2016			
	N_c	Λ, km	λ %	Cr, 10^6 a.u.	N_c	Λ, km	λ, %	Cr, 10^6 a.u.
Tracks/Roadbeds								
10%	68	2059	6.7	0.7	191	7858	25.6	2.5
5%	92	2707	8.1	0.9	305	14083	45.8	4.0
1%	207	8773	28.5	2.7	395	19449	63.3	7.0
Bridges (Seismically Designed and Conventionally Designed)								
10%	57	22.7	15.7	0.5	153	53.0	36.7	1.0
5%	79	28.7	19.9	0.7	228	71.7	49.7	1.4
1%	164	52.6	36.5	1.1	293	85.6	59.3	2.5
Tunnels (Rock and Cut & Cover)								
10%	6	42.1	57.4	1.3	18	65.0	88.5	2.0
5%	9	51.9	70.6	1.5	20	65.1	88.5	2.0
1%	19	65.1	88.5	2.0	23	66.6	90.6	3.2

Seismic risk for Lake Baikal railroad system

SR = I ⊗ (railway elements [km] in regular grid cells) ⊗ V



Total risk (in a.u.) along longitude estimated for the Lake Baikal railroad tracks, tunnels, and bridges

Conclusions

Using the USLE approach (although limited by seismic data available) can provide

- **A reasonable estimation of the seismic hazard map in different terms of ground shaking for a particular time interval and fixed probability of exceedance level.**
- **The preliminary estimation of seismic risk for various types of spatial objects with point, linear, or planar shapes that can be useful for decision-makers to gain a better understanding of expected losses.**

The USLE approach provides a practical and realistic evaluation of seismic risks. It also reveals the tendency of underestimating the seismic effect at exposures and overestimating it at regional and national scales.

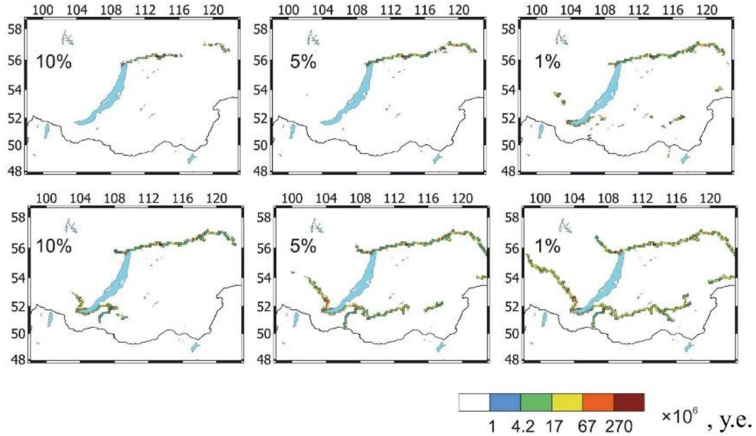
Thank you!

Let us emphasize that our estimates of seismic hazard and risks for Lake Baikal Region are presented here for academic purposes only highlighting the general problem-oriented approach based on USLE. Evidently, these estimates do not use more adequate though complicated procedures of convolutions of seismic hazard, objects of risks, and their vulnerability.
The studies addressing realistic and practical kinds of seismic risks should bring together seismologists and experts in earthquake engineering, social sciences, and economics.

Nekrasova, A., Kossobokov, V. (2023) Seismic risk assessment for the infrastructure in the regions adjacent to the Russian Federation Baikal–Amur Mainline based on the Unified Scaling Law for Earthquakes. Natural Hazards 116: 1995–2010 https://doi.org/10.1007/s11069-022-05750-9 (SJR 2022 Q1)

Nekrasova A, V. Kossobokov, E. Podolskaia, Regional seismic risk assessment based on the unified scaling law for earthquakes: the Lake Baikal railway system. Soil Dynamics and Earthquake Engineering (SJR Q1) Статья на рецензировании.

Выполнена оценка рисков потери работоспособности объектов инфраструктуры в регионах, прилегающих к Байкало-Амурской и Транссибирской магистралям, из-за сейсмических событий максимальной макросейсмической интенсивности, ожидаемой в течение 50 лет с вероятностью 10%, 5% и 1%. Использованы данные о землетрясениях, собранные в Байкальском отделении Российской геофизической службы, которые позволяют достаточно полно определить землетрясения с M = 2.5 и более за период 1994–2019 гг. для надежного рассчета коэффициентов A, B и C Общего закона подобия для землетрясений. На основе оценок A, B и C составлены карты максимальной магнитуды, ожидаемой в течение 500, 1000 и 5000 лет с учетом модели анизотропного сейсмического воздействия на объекты инфраструктуры региона. Постороены карты сейсмической опасности в традиционных терминах макросейсмической интенсивности и связанного с нею сейсмического риска для объектов инфраструктуры Байкало-Амурской и Транссибирской магистрали.
Выполнено сравнение полученных оценок сейсмического риска с сейсмическим риском по данным вероятностных карт ГСЗ-2016. Отношение максимально накопленного ущерба для восстановления объектов инфраструктуры прилегающих к Байкало-Амурской и Транссибирской магистралям, по модели ГСЗ-2016 к максимальному ущербу по модели на основе Общего закона подобия для землетрясений составляют 3.3, 4.0 и 2.8 для карт с 10%, 5% и 1% вероятностью превышения в 50 лет, соответственно.



Региональный сейсмический риск для железнодорожного полотна с 10%, 5% и 1% вероятностью превышения в 50 лет по модели Общего закона подобия для землетрясений (вверху) и ГСЗ-2016 (внизу).