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SEISMOLOGY

Why Are New Approaches to Seismic Hazard Assessment Required?

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Abstract—For the first time, a numerical comparison of the General Seismic Zoning (GSZ) maps with the effect of earthquakes that actually occurred after the publication of the maps was carried out. The area of zones of expected intensity on the GSZ map is compared with the area of isoseists from actual earthquakes. It turned out that the isoseist area is on average by an order less than expected according to the GSZ. This paper describes possible reasons for such an overestimation and proposes ways to improve seismic hazard assessments.

Keywords: earthquake, seismic hazard, General Seismic Zoning, GSZ, isoseists, intensity

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INTRODUCTION

The solution to the problem of hazard mitigation from the impact of earthquakes earlier in the Soviet Union, and now in the Russian Federation, mainly comes down to the introduction of construction rules and regulations. In turn, such norms and rules are based on the General Seismic Zoning (GSZ) maps. In recent years, the GSZ maps have often been criticized ([3, 20] and others). The main concern is the subjective nature of many of the estimates on which the construction of these maps was based [6]. Until now, no quantitative assessments have been made on how optimally the GSZ maps assess the future seismic hazard, in terms of both underestimation and overestimation.

The first GSZ map of the territory of the Soviet Union was built in 1937. The GSZ-37 map was based on a deterministic approach to seismic hazard assessment and did not take into account the peculiarities of the seismic regime of the regions. Subsequently, the GSZ-49, GSZ-57, GSZ-68, and GSZ-78 maps were built. When creating the GSZ-78 map, the recurrence rate of seismic shaking once every 100, 1000, and 10000 years was taken into account. However, the seismic intensity indicated on this map was exceeded by an average of two points by a number of strong earthquakes that occurred on the territory of the Soviet Union in the next two decades: the Spitak earthquake, 1988; the Zaisan earthquake, 1990; the Racha-Java earthquake, 1991; etc.

The first GSZ map built on the international principles of probabilistic seismic hazard assessment (PSHA) [7] was the GSZ-97 map [19]. It actually formed part of the global seismic hazard assessment program (GSHAP) [9, 10].

Today, the global seismic hazard assessment program is the international project GEM (Global Earthquake Model) [15]. GEM aims to develop a global earthquake risk model as an open single source project driven by the scientific community. One of its main tasks is to develop realistic risk models for each country. This will make it possible to calculate potential losses and tangible benefits from loss reduction measures. It should be noted that the undoubted strength of the GEM project is the use of the ISC-GEM Global Instrumental Earthquake Catalogue. Its high-quality preparation is carried out by the International Seismological Center (ISC) [18]. Another strength of the project is the use of a single standardized methodology for the territory of all countries, minimizing the subjective nature of the assessments. However, this approach takes into account a single limited set of parameters, and therefore cannot be used as a final product for a single country.

GSZ maps constructed according to the PSHA methodology (GSZ-97*, GSZ-2012, GSZ-2014, GSZ-2015, GSZ-2016) largely repeat the GSZ-97. In fact, they only take into account those omissions of

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strong earthquakes that were allowed in the GSZ-97. The revision of the map in the direction of decreasing the expected intensity was carried out only for small areas, and on average the assessed seismic hazard changed very little.

FORMULATION OF THE PROBLEM AND CONTENT OF THE STUDY

Twenty-five years have passed since the publication of the GSZ-97 map, which already makes it possible to obtain a fairly reliable assessment of its accuracy. To this end, we assessed the impact of all earthquakes of magnitude 3.5 and higher on the territory of Russia and in the border areas and calculated the theoretical isoseists for them. For this, as well as in the building of the GSZ-97 map, the regional relationships between magnitude, hypocentral distance, and intensity on the MSK-64 scale (the macroseismic field equation according to N.V. Shebalin) were used [4].

As an initial list of earthquakes, we used the catalog for the period of January 1, 1997–December 31, 2021 (exactly 25 years), with hypocenter depths up to 70 km (more than 25000 events). The catalog was obtained by combining the Russian Earthquakes catalog (eqru.gsras.ru) and the USGS catalog (earthquake.usgs.gov/earthquakes/search/). The division into regions was carried out similarly to the division in [4].

We compared the calculated theoretical isoseists with the GSZ-97A map. The results of such a comparison are shown in Fig. 1. Taking into account the small size of the theoretical isoseists, we increased the scale of the presentation of the results by dividing the map into four parts. For each intensity level, starting from 6, only those isoseists or their parts are shown that correspond to the intensity of the zone on the GSZ-97A map or exceed it. Thus, intensity 5 calculated isoseists are not shown at all; intensity 6 isoseists are shown only in 6-point intensity zones of the GSZ-97A; intensity 7, in 7-intensity zones, etc. “Target omissions”, i.e., 6-point intensity isoseists in the intensity 5 zones of the GSZ-97A, 7-point intensity isoseists in 5- and 6-ipoint ntensity zones, etc., are shown with blue hatched figures, and isoseists corresponding to the intensity zone of the GSZ-97A are marked with lilac empty figures (Fig. 1). It should be noted that the calculated intensity of the Olyutorsk earthquake, the Ilin-Tas (Abyi) earthquake, the Bachatskii earthquake, the earthquake near the border of Kamchatka and Chukotka, and some other weaker earthquakes exceeded the intensity of the corresponding GSZ-97A zones by two points. Figure 1 does not show theoretical isoseists within the zones of a higher intensity of the GSZ-97A, since they did not reach the expected intensity excess.

CALCULATION RESULTS AND THEIR ANALYSIS

The GSZ-97A map represents the expected exceedance of a given intensity over a period of 50 years with a probability of 10%. This means that, in each zone of a certain intensity, the area within the isoseists of the corresponding and exceeding intensity from earthquakes over a 50-year period should be 10%. Even if future earthquakes in the period up to 2046 will occur where they did not yet occur in 1997–2021, the expected increase in the isoseist area will be approximately twice. Thus, in the case of correct estimates on the GSZ-97A map, the areas of isoseists from earthquakes over a 25-year period should be about 5% for the corresponding intensity zones. Taking into account the fact that isoseists from future earthquakes will partially intersect with each other and with isoseists from earthquakes of 1997–2021, to achieve a 10% probability of exceeding the given intensity over 50 years, this value should be even greater.

Figure 1 shows that isoseists of calculated intensity in each of the 6-, 7-, 8-, and 9-point zones of the GSZ-97A occupy a very small fraction of the area in each region, except for Kamchatka. We have estimated the ratio of isoseist areas and intensity zones in each region. In Table 1, for each region separately, for Russia as a whole, and for the territory of Russia excluding Kamchatka, the results of calculations are given using the formula:

$$r_i = \frac{\left\| \bigcup_{\substack{k=i,\ldots,12,\\ j=1,\ldots,N}} g_{kj} \right\|}{S_i}, \quad (1)$$

where i is the calculated intensity according to the MSK-64 scale, g_{kj} is the isoseist of the corresponding intensity k within the considered region from an earthquake with the index j (N is the number of such earthquakes), and S_i is the area of the i-intensity zone on the GSZ-97A map. A union is built for all earthquakes j. Formula (1) reflects the ratio of the area on which, according to the calculations, an excess of intensity was achieved for the area of the i-intensity zone on the GSZ-97A map for 25 years, calculated on the basis of earthquakes that actually occurred in the period of 1997–2021. Dashes in the cells of Table 1 mean that there is no zone with the corresponding intensity in the region on the GSZ-97A map.

As can be seen from Table 1, in all regions except for Kamchatka, Altai, and Sayan, the value r_i is at least by an order less than the 5% expected intensity excess. The large relative area of isoseists in Kamchatka is actually due to just one Olyutorsk earthquake that occurred on April 20, 2006, with $M = 7.6$, which was an omission for the GSZ-97 maps. In the Altai and Sayan region, the value r_i excluding isoseists from the Bachatskii earthquake in Kemerovo oblast on June 18,

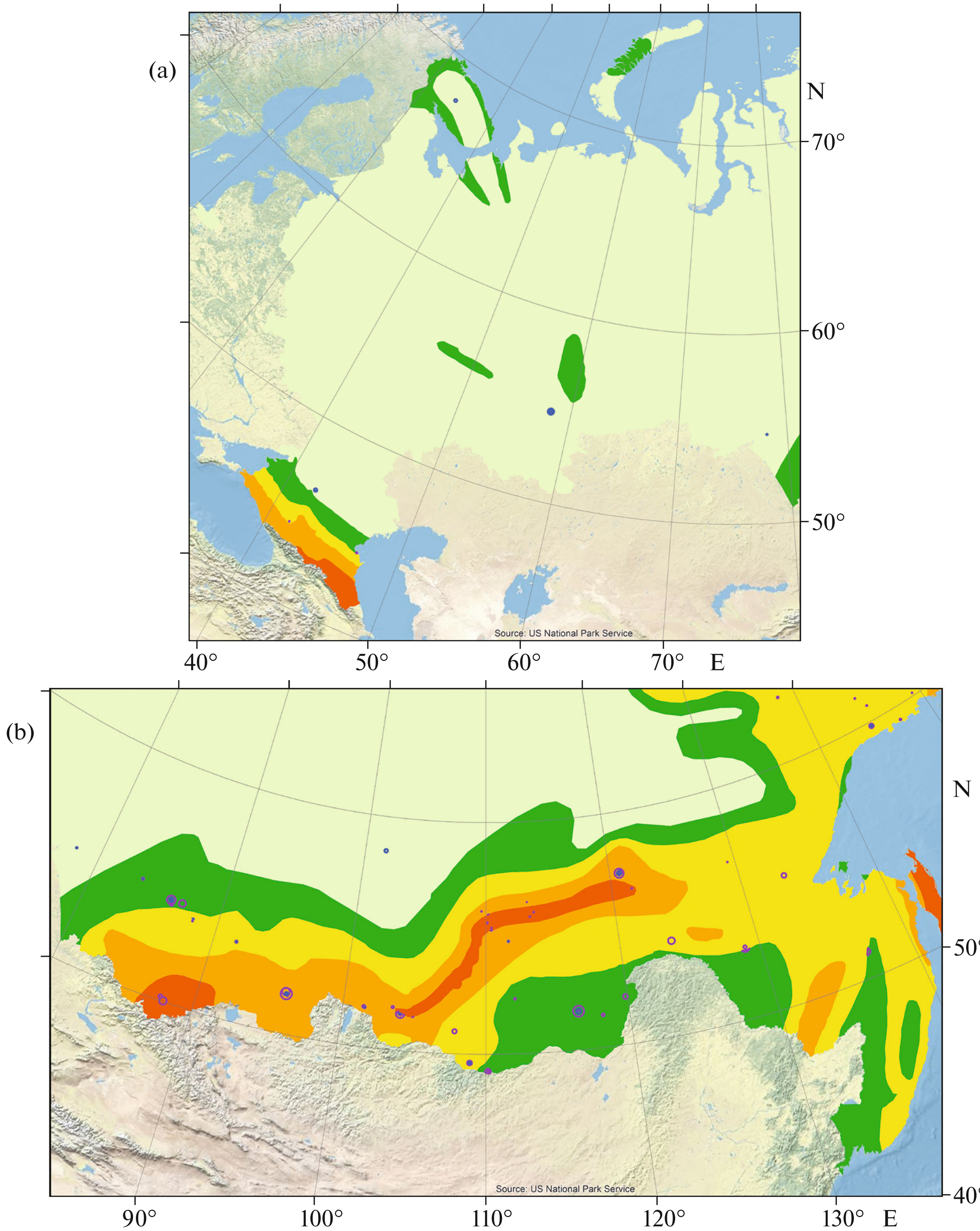

Fig. 1. GSZ-97A map and calculated theoretical isoseits.

2013, with $M = 5.6$ would also be less than 0.5%. Formally, this earthquake is also an omission, since, having a 7-points intensity intensity at the epicenter, it occurred in the 6-points intensity zone according to the GSZ-97A map. However, this earthquake, as most seismologists believe, was man-made and should hardly be taken into account on par with tectonic earthquakes.

Thus, in most regions of Russia, the assessment of the seismic hazard is, on average, overestimated by at least ten times. This is especially true of the Arctic zone of the Russian Federation, where significant areas of the Kola Peninsula, the Novaya Zemlya and Severnaya Zemlya archipelagos, the New Siberian Islands, the Taimyr Peninsula, and the north of Yakutia and Chukotka are assigned to zones with an intensity of 6 or higher. At the same time, the GSZ-97 allows significant omissions of strong earthquakes, in particular, the Olyutorsk earthquake, the Tuva earthquake with $M = 6.7$ (February 26, 2012), the Ilin-Tas (Abyi) earthquake with $M = 6.6$ (February 14, 2013),

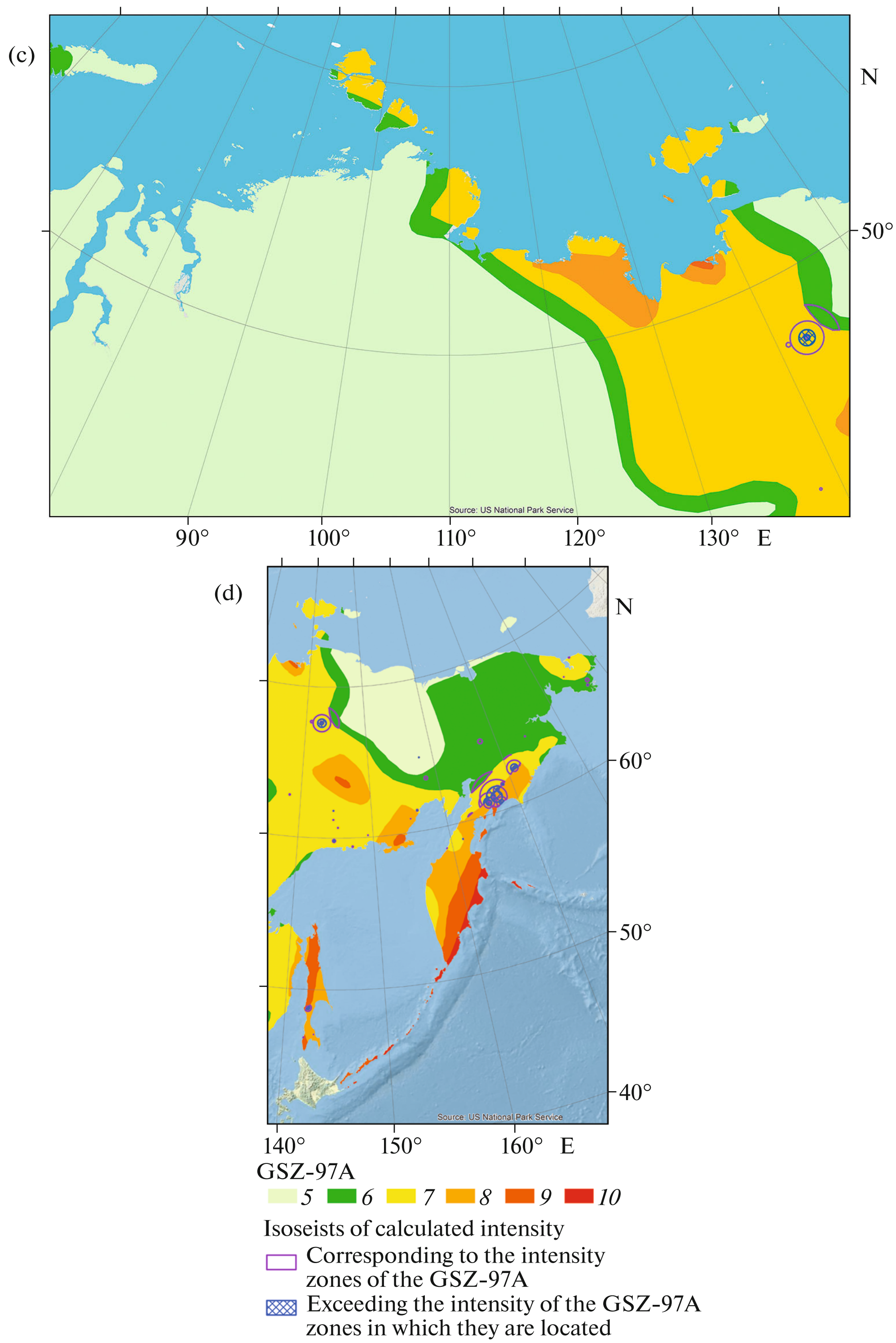

Fig. 1. (Contd.)

and the earthquake in the Urals with $M = 5.0$ (September 4, 2018), an earthquake near the border of Kamchatka and Chukotka with $M = 6.4$ (January 9, 2020), etc.

The presence of omissions of strong earthquakes for the GSZ maps of the territory of Russia, as well as maps of other regions of the world within the framework of the GSHAP program has been repeatedly noted by various researchers [3, 6, 20]. At the same time, the fact of a significant overestimation (at least on average) of the seismic hazard on the GSZ maps has been numerically established for the first time. We compared the impacts from real earthquakes with the expected intensity zones on the GSZ-97A map in order to take into account only those events that occurred after it was built.

After the GSZ-97 map, two maps, GSZ-2015 and GSZ-2016, were successively adopted as normative. On them, the area of 6-point intensity zones and above changed by no more than 20% (Table 2), while the 9- and 10-point intensity zones almost doubled on the GSZ-2016. Thus, these maps, in fact, give a significant overestimation of the seismic hazard.

Table 1. Estimates of the ratio r_i of areas of calculated isoseists and intensity zones of the GSZ-97A map

Region	$I = 6$	$I = 7$	$I = 8$	$I = 9$
Caucasus	0.0005	0.0004	0	0
Altai and Sayan	0.0073	0.0007	0.0092	0.0224
Baikal	0.0068	0.002	0.0037	0.0005
Yakutia and Northeast	0.009	0.0093	0.0059	0.0007
Primorye and Amur River Region	0.002	0.0022	0	–
Sakhalin	–	0	0.0222	0.0057
Kuriles	–	–	–	0
Kamchatka	0.2337	0.2203	0.0873	0
Chukotka	0.002	0.0006	–	–
Arctic basin	0	0	–	–
Baltic shield	0	–	–	–
European part of the Urals, and Western Siberia	0	–	–	–
Russia	0.0079	0.0132	0.0178	0.0045
Russia excluding Kamchatka	0.0057	0.0055	0.0059	0.0062

Table 2. Share of the area occupied by zones of expected intensity on the GSZ maps

	GSZ-97A	GSZ-2015A	GSZ-2016A
$I = 5$, %	57.94	57.94	60.17
$I = 6$, %	15.01	17.78	12.24
$I = 7$, %	17.73	16.53	19.32
$I = 8$, %	7.11	8.55	6.90
$I = 9$, %	2.03	2.04	1.26
$I = 10$, %	0.18	0.16	0.11

DISCUSSION

What is the reason for the overestimation within the GSZ? In our opinion, the main reason is that, within the GSZ-97 and subsequent methods (GSZ-2012, GSZ-2014, GSZ-2015, GSZ-2016), the recurrence of strong earthquakes and the maximum possible magnitude were estimated locally and independently for different structures. In reality, the accumulation of stresses and the preparation of strong earthquakes occur in volumes many times greater than the size of earthquake sources [8]. For this reason, estimates should not be considered independently. In addition, local estimates are subject to significant errors, which increase with summation. It should also be noted here that, when building the GSZ-97 maps, the calculations of earthquake recurrence were based, among other things, on the hypothesis of characteristic earthquakes, which was subsequently refuted [13].

The second reason, which is often noted, including by builders, is the subjective nature of the estimates used, which are only slightly compensated by the method of expert assessments. It should also be noted that the administrative resource is often used when individual structures are interested in changing the estimates made by seismologists and geologists [14]. The third possible reason is that simplified models of seismic wave attenuation are taken into account, which for some regions of Russia have not been updated over the past decades, despite the emergence of new instrumental data.

In modern conditions, the errors in the GSZ are dangerous and fatal. They create the erroneous feeling that the whole system of seismic zoning is not working. Actually, it does work. The presence of errors on the GSZ-97 map in both directions does not mean that the existing zoning system should be completely abolished. However, the system requires significant modernization.

In the conditions of the modern economy, market mechanisms for regulating economic processes are becoming increasingly important. This also applies to the struggle to reduce damage from devastating earthquakes. Under any circumstances, the life and health of people is an absolute priority. Therefore, in the part where the standards during construction are necessary precisely for the preservation of life and health (we are talking about areas where intensities of 8 or more are expected), the existing standards should be preserved.

For cases of a less strong impact of earthquakes, in our opinion, building codes should be revised in the direction of situationality. Many buildings are constructed for a short period of operation, during which the probability of damage from an earthquake is extremely small. Here it is advisable to give the developer the right to decide whether to invest additional funds in increasing the seismic resistance of the building or pay a smaller amount to the insurance company, which will cover the losses in the event of such an impact. Thus, the damage mitigation system should be a flexible combination of building codes and a disaster insurance system.

What is the role of seismology and related branches of other geosciences in the transition to a new flexible system? Firstly, when it comes to the strongest earthquakes, it is necessary to improve the methods for predicting such events. The recurrence of strong earthquakes should be assessed at the regional level. Determining where such rare events can take place is the classic problem of strong earthquake-prone areas recognition. Significant progress in this direction has been achieved using the methods of system analysis and pattern recognition [1, 2, 5, 12].

Secondly, it is necessary to improve the methods for modeling the seismic regime [14, 17]. Furthermore, estimates of the maximum possible magnitude play an important role in assessing the recurrence of the strongest earthquakes [14]. It is necessary to find a reasonable balance between the maximum magnitude estimates based on event statistics and geological data [16].

Thirdly, it is necessary to improve the models of attenuation of the earthquake intensity at different distances from the epicenters (including separately for the near zone), in the engineering frequency range, taking into account the anisotropic properties of the medium and the complexity of the earthquake source, if it is required according to seismological and geological data ([11], and others).

Many of these steps can be taken now. The integration of existing methods and algorithms for earthquake-prone areas recognition, stochastic models of the seismic regime, and modern methods for estimating model parameters can give the effect of a multiple improvement in the quality of seismic hazard assessments. At the same time, an essential element should be the creation and application of mathematical methods for evaluating the quality of such assessments, taking into account not only “target omission” errors, but also “false alarm” errors.

This article is a very modest first step. It determines the quantitative level of overestimation of the seismic hazard on the existing GSZ maps, names the possible causes of this effect, and also outlines possible ways to improve seismic hazard assessments.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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