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Detailed Macroseismic Survey and Rational Approach to Seismic Intensity Assessment within the Territory of a Large City: Case Study of the Consequences of the September 21, 2020 Bystraya Earthquake in Irkutsk

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Abstract—The article discusses the advisability of conducting detailed macroseismic surveys within large cities and urban agglomerations. A retrospective analysis of information about earthquakes that occurred in the past decades and were felt in Irkutsk with an intensity of I = V or higher revealed the problem of preserving and availability of primary data on earthquake effects. Processing of the macroseismic data collected using internet-based questionnaires for the Irkutsk area after the September 21, 2020 Bystraya earthquake was carried out. The usage of online questionnaires has demonstrated high efficiency and information content, and also opened up certain possibilities such as improving the method with respect to the particular conditions of East Siberia. A large number of responses from earthquake eyewitnesses makes it possible to assess the shaking intensity separately in every administrative unit of Irkutsk, which in turn contributes to an increase in the detail of documenting the earthquake macroseismic field. The results allow us to consider assessment of the shaking intensity within certain parts of Irkutsk city as more rational versus assessment for the entire territory of the city.

Keywords: earthquake, macroseismic survey, shaking intensity, internet-based questionnaire

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INTRODUCTION

The first macroseismic investigations in East Siberia were carried out in the early 20th century and were related to start of the operation of the Irkutsk seismic station. The macroseismic effects of strong earthquakes, which implied, in particular, assessment of seismic shaking intensity on the Rossi–Forel scale, were investigated by A.V. Voznesenskii after a number of strong seismic events: April 12, 1902 in southern Baikal; November 26, 1903 in Middle Baikal; and the earthquakes of July 9 and 23, 1905, in Mongolia (Voznesenskii, 1903, 1905, 1908). Since that time, the main objective of macroseismic studies has traditionally become acquisition of information on perceptible earthquake effects for the maximum possible number of observation points. Virtually all macroseismic data are collected from reports from populated places, each of which is considered as single point with the known geographic coordinates and assigned shaking intensity. Eventually, the whole set of the observation points and their characteristics constitute the macroseismic field of an earthquake (Shebalin, 2003).

The common practice in Russian seismology is that shaking intensity is assessed on the basis of macroseismic data collected within the entire area of a populated place, independently of its size. However, it should be emphasized that areas occupied by a rural locality and a large city can differ by the factors of tens, if not hundreds. In this respect, a small village occupying an area of 1–2 km^2 can be considered as a point within the macroseismic field, whereas it is clear that a large city of up to several hundreds of square kilometers in area should not be considered so.

Shaking intensity assessment made for a large city on the whole a priori has a higher uncertainty and is therefore less reliable due to averaging of macroseismic data collected over a relatively large area. Thus, it is clear that partitioning of a large city into smaller areas (e.g., its administrative subdivisions) becomes an advisable solution. This problem has been particularly discussed in the guidelines for using the European Macroseismic Scale, EMS-98 (*European*..., 1998), and also in the methodological works (Musson and Cecić, 2002; Cecić and Musson, 2004). Effectiveness and utility of the detailed macroseismic surveys within urban and urbanized areas has been repeatedly confirmed by the worldwide practice (Cifelli et al., 1999a, 1999b, 2000; Tertulliani and Donati, 2000). One of the most important, in practical sense, applications of macroseismic data is related to revealing sites within a large city, where local amplification of shaking intensity is observed and, as a result, seismic hazard can be specified (Solonenko, 1962; Borisova et al., 1975; Sousa and Oliveira, 1996; Guidoboni et al., 2003; Giammarinaro et al., 2005; Sbarra et al., 2012).

The problem of an optimal size of an area, for which shaking intensity is assessed, is still debated. For example the EMS-98 scale recommends that the smallest place should be no smaller than a village, and the largest no larger than a moderately-sized European town (*European*..., 1998). On the contrary, the new Russian seismic intensity scale, SIS-17, explicitly states that the estimated macroseismic or instrumental intensity should not be extrapolated by a distance more than 0.5 km (*GOST*..., 2017).

Up until the second decade of the 21st century, methods of macroseismic surveys in East Siberia remained virtually unchanged and, more importantly, stayed uneffective. Strong earthquakes felt in such large regional cities as Irkutsk, Ulan-Ude, Angarsk, and others, were not always followed by detailed macroseismic investigations in the respective cities. Another problem is that some initial data appeared to be lost. However, the initial macroseismic data on earthquakes are of great value in terms of specifying seismic hazard within urban areas. Moreover, there may be a need to revise earlier assessments of shaking intensity with the use of modern seismic scales (Musson et al., 2010). Finally, the absence of the initial information makes it impossible to reproduce the results obtained by earlier researchers.

The situation has noticeably changed by now. In September 2008, the Baikal Branch, Geophysical Survey, Russian Academy of Sciences (BB GS RAS), published on its website (http://seis-bykl.ru) an online form (questionnaire) for local inhabitants to fill out in case of an earthquake; this allowed researchers to collect considerably larger amounts of macroseismic data than could be done before (Radziminovich et al., 2014). Since then, it has been established that the predominant majority of reports after tangible quakes is received from inhabitants of relatively large urban settlements. Among other aspects, this point offers a new opportunities to perform more, reliable assessment of shaking intensity within urban areas.

The strong (M_W = 5.5) Bystraya earthquake that occurred on September 21, 2020, in the southern Baikal region, in the eastern part of the Tunka rift system (Filippova et al., 2022), offered a unique opportunity to collect a considerable amount of macroseismic data, namely, several thousands of completed questionnaires (Gileva et al., 2021). About half these reports were received from people in Irkutsk. In the present work we will consider how these data can be used to assess shaking intensity within individual administrative units of the city of Irkutsk.

PREVIOUS MACROSEISMIC SURVEYS IN IRKUTSK

In the second half of the 20th and the first two decades of the 21st century, 12 earthquakes were felt within Irkutsk city with an intensity of at least I = V (Fig. 1) which were actively reacted to by many people. In case of each of these seismic events, a detailed macroseismic survey might be carried out; however, the respective research works were focused on different matters. Retrospective analysis of past publications suggests that their authors of were interested to a greater degree in investigation the epicentral zones of the earthquakes (e.g., (Ruzhich et al., 2002; Berzhinsky et al., 2010)) or outlining the tangibility areas in general; in contrast, considerably lower attention was paid to macroseismic effects within the city of Irkutsk. In a number of works there are no clear indications whether a macroseismic survey was performed within the city limits, and if yes, what was its degree of detail. The literature sources often provided the final assessment of shaking intensity for the entire territory of the city, although the results of macroseismic surveys were presented at best in the very brief. Let us consider several examples.

The earthquake of August 30, 1966, that occured at the southern basin of Lake Baikal, was felt in Irkutsk with I = V–VI; it was considered briefly in the monograph (*Seismotektonika*..., 1968) and in more detail in (Solonenko et al., 1970). Macroseismic effects within the city of Irkutsk were mentioned in only one paragraph of the latter, in particular, "...the character of shaking and its consequences were determined by the peculiarities of soil and hydrogeological settings in different parts of the city" (Solonenko et al., 1970, p. 186). The quoted fragment gives ground to suppose that a macroseismic survey was performed in Irkutsk, although no more details were given in the respective article. Another example can be given by the earthquake of March 28, 1970, which was described in the sole publication (Golenetskii et al., 1973). However, this work provided only the integrated assessment of shaking intensity in Irkutsk (I = V), with no information about macroseismic effects within the city boundaries.

The direct indication of a detailed macroseismic survey in Irkutsk after the January 25, 1973 earthquake was provided in the publication overviewing seismicity in the Baikal region in 1973 (the article appeared in the yearbook *Earthquakes in the USSR*): "Beyond the epicentral zone, the most complete macroseismic data were collected in different parts of the city of Irkutsk" (Golenetskii, 1976, p. 112). Shaking intensity for the entire city was assessed to be I = V, but later the same

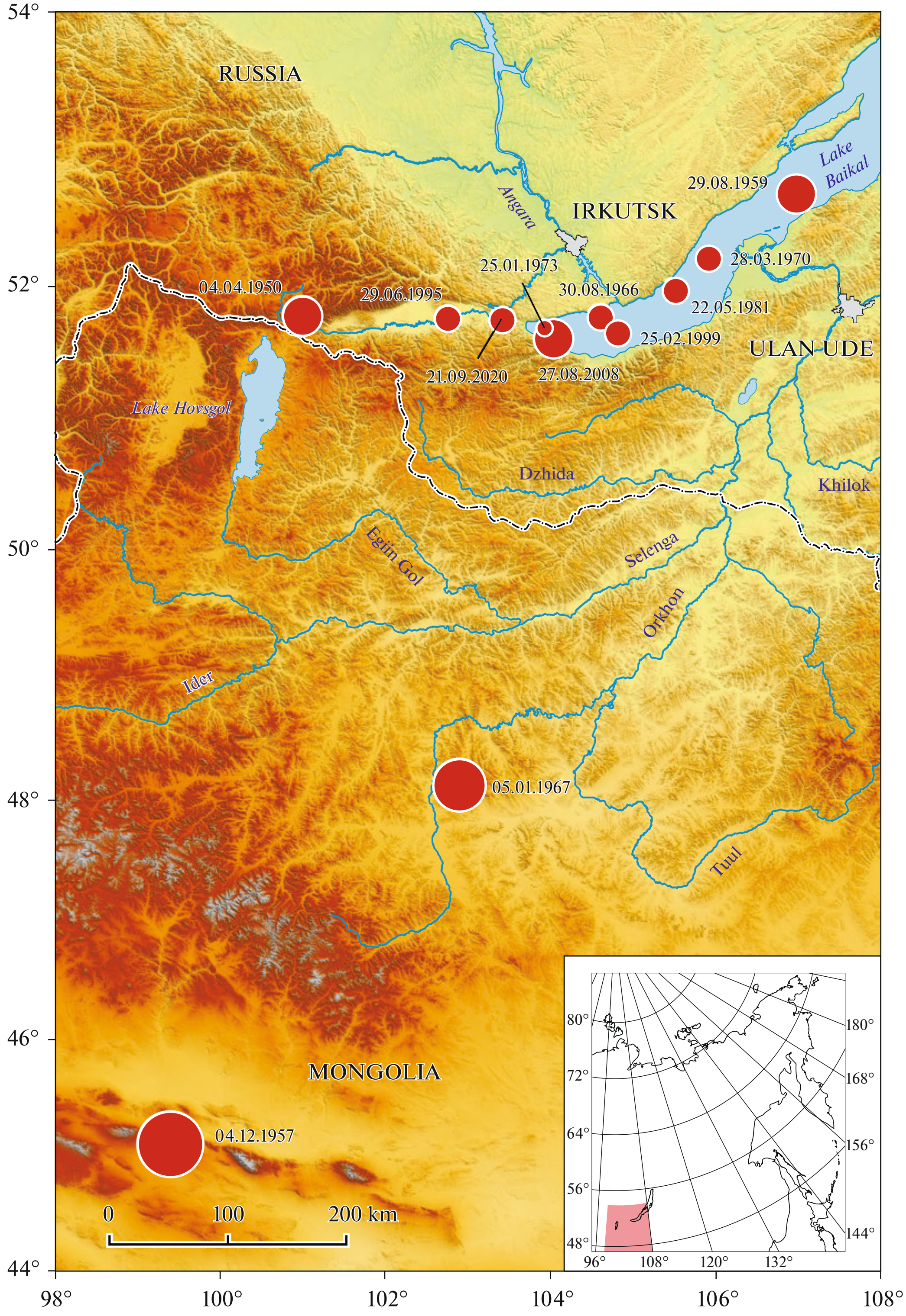

Fig. 1. Epicenters of earthquakes felt in Irkutsk with at least I = V. Magnitudes are indicated in Table 1. Inset: location of study region in East Eurasia.

author (Golenetskii, 1976) provided only brief information about the most typical effects, with no reference to the sites where they were observed and, moreover, without intensity values for different parts of the city.

The same is for the earthquake of May 22, 1981: S.I. Golenetskii et al. (1984) mentioned that a detailed survey of Irkutsk took place, but the initial macroseismic data had not been provided even in brief. Later, the earthquakes of January 25, 1973 and May 22, 1981 were considered in slightly more detail in the monograph (Golenetskii, 1997), with the initial archive materials from the BB GS RAS being used. In particular, analysis of the initial data (more than 200 observation points) allowed the author to establish the absence of differences between shaking intensity reported in different parts of Irkutsk during the May 22, 1981 earthquake (Golenetskii, 1997).

A slightly better situation took place in case of the February 25, 1999 earthquake, which is presently believed to be one of the most well studied (both instrumentally and macroseismically) seismic events in the South Baikal region (Golenetskii et al., 2001; Ruzhich et al., 2002; Radziminovich et al., 2005). Along with the information about the macroseismic effects of the earthquake within the entire tangibility zone, the large body of macroseismic data within Irkutsk was obtained. In total, more than 1000 questionnaires were collected, and, as a result, shaking intensity was estimated not only within the city on the whole, but also within its individual administrative units (Sherman et al., 2003).

Table 1 provides the main parameters of the earthquakes occurred in the second half of the 20th–early 21st centuries, which were felt in Irkutsk with at least I = V, and also the information about the detailed macroseismic surveys in the city territory and the current state of the initial macroseismic data. As one can see, the initial macroseismic data for earthquakes felt in Irkutsk are presently either hardly accessible or their storage place is unknown; some materials can even be considered to be irretrievably lost. Although the macroseismic data on earthquakes of the last decades are undoubtedly on demand and can be employed in modern works on assessment seismic risk (hazard) and seismic microzoning of the city area, the use of only resultant values of shaking intensity, without the initial data being available, seems to be insufficient. Thus, preservation and availability of the initial macroseismic data on strong earthquakes of the second half of the 20th century becomes a topical problem.

INITIAL DATA

The initial data used to assess shaking intensity within individual administrative units of the city of Irkutsk were macroseismic data collected through the online questionnaire published on the website of BB GS RAS (http://seis-bykl.ru). A questionnaire includes six units reflecting the main observed macroseismic effects of an earthquake: (1) place of observation; (2) date and time of observation; (3) human reaction; (4) reaction of a building and household items; (5) effects in the natural environment; (6) additional data on an earthquake (duration of shaking, character of earthquake effects, presence or absence of underground hum, animal behavior, presence or absence of felt aftershocks). Additionally, eyewitnesses can describe their personal impressions (as well as observations of their relatives, friends, and acquaintances) in the respective text fields. This online questionnaire has been tested on several moderate earthquakes and proved quite high effectiveness (Radziminovich et al., 2014, 2020, 2022).

Within seven days after the occurrence of the September 21, 2020 Bystraya earthquake, as many as 3012 questionnaires were received, of which 2737 contained minimal macroseismic information to be processed. The bulk of reports was received from large cities and towns, including 1452 ones from Irkutsk. Remarkably, 857 questionnaires indicated the names of streets, microdistricts, or administrative districts of the city, so that the questionnaires had been grouped to fit the administrative subdivision of Irkutsk; the rest 595 questionnaires from Irkutsk had mentioned only the city name. The majority of questionnaires contained both the characteristics of buildings (material and number of stories) and the story at which an eyewitness was located during the earthquake. The obtained macroseismic data can be generally considered as representative and, thus, they can be used to reveal differences between shaking intensity values (of absence of such differences) for different administrative units of the city.

RESULTS

Administrative subdivision of Irkutsk includes five city districts: Kirovsky, Kuybyshevsky, Leninsky, Oktyabrsky, and Sverdlovsky. There is also an alternative administrative subdivision into city okrugs, which almost completely coincides with the subdivision into city districts, excluding the Pravoberezhny city okrug that incorporates the Kirovsky and Kuybyshevsky urban districts (*Atlas*..., 2011). In the present work we employ the up-to-date subdivision into city okrugs; the reason for it is that the least number of questionnaires was received from the Kirovsky city district and, hence, it seems reasonable to unite this city district with the Kuybyshevsky one. The information about populations of administrative city okrugs and about numbers of questionnaires received from each of them is given in Table 2.

The numbers of questionnaires received from each administrative city okrug is no more than 1% of its population. One might expect more abundant feedback, but nevertheless, given that the total population of Irkutsk is about 617000, the obtained data can be considered representative. Given the total number of received questionnaires with specified spatial references, we can consider the Bystraya earthquake of September 21, 2020 to be one of the most extensively studied in East Siberia in terms of macroseismic effects within Irkutsk on the whole as well as within its individual administrative city okrugs.

Table 1. Earthquakes occurred since second half of 20th century until present, which were felt in Irkutsk with at least I = V

Date, DD.MM.YYYY	Time, hh:mm:ss	Epicentral coordinates		M	Δ, km	I, MSK-64	Detailed macroseismic survey in territory of Irkutsk and availability of initial materials	Source(s)
		φ, N	λ, E					
04.04.1950	18:44:14	51.77	101.00	6.9 (M_W)	235	V	Detailed macroseismic survey was not carried out. A small volume of macroseismic data on particular objects was collected within Irkutsk. Data are published in brief	(Treskov and Florensov, 1952; Golenetskii, 1997)
04.12.1957	03:39:48	45.10	99.40	8.1 (M_W)	875	V	Detailed macroseismic survey was not carried out. Only fragmentary macroseismic data were published. Initial data are not preserved	(*Gobi-Altaiskoe*..., 1963)
29.08.1959	17:03:14	52.68	106.98	6.8 (M_{LH})	187	VI–VII	Detailed macroseismic survey was carried out. Number of surveyed buildings varies, depending on source, from 3500 to 4275. Brief macroseismic data and general results of survey were published. Current state and storage place of initial materials are unknown	(Solonenko and Treskov, 1960; Rustanovich, 1961; Solonenko, 1962)
30.08.1966	06:10:31	51.76	104.61	5.5 (M_{LH})	59	V–VI	Detailed macroseismic survey was supposedly carried out. Brief results of macroseismic data interpretation, without any details, were published. Initial materials have not preserved	(*Seismotektonika*..., 1968; Solonenko et al., 1970)
05.01.1967	00:14:41	48.10	102.90	7.1 (M_W)	474	VI–VII	Detailed macroseismic survey was supposedly carried out. Brief results, including those on particular objects, were published. Initial materials have not preserved	(Golenetskii et al., 1970)
28.03.1970	09:44:57	52.20	105.92	5.5 (M_{LH})	108	V	No information about detailed macroseismic survey. Only resultant intensity value for Irkutsk was published. Current state of initial materials is unknown. Descriptions of macroseismic effects in Irkutsk were not published	(Golenetskii et al., 1973)

Table 1. (Contd.)

Date, DD.MM.YYYY	Time, hh:mm:ss	Epicentral coordinates		M	Δ, km	I, MSK-64	Detailed macroseismic survey in territory of Irkutsk and availability of initial materials	Source(s)
		φ, N	λ, E					
25.01.1973	19:56:48	51.68	103.93	4.1 (M_W)	71	V	Detailed macroseismic survey was carried out. Brief results of survey and resultant intensity value were published. Initial materials are supposedly stored in holdings	(Golenetskii, 1976, 1997)
22.05.1981	09:51:20	51.96	105.52	5.4 (M_W)	88	V	Detailed macroseismic survey was carried out. Brief results of survey are resultant intensity value were published. Initial materials are supposedly stored in holdings	(Golenetskii et al., 1984; Golenetskii, 1997)
29.06.1995	23:02:27	51.75	102.76	5.7 (M_W)	122	V–VI	No information about detailed macroseismic survey. Current state of initial materials is unknown. Brief description of earthquake effects was published	(Golenetskii, 1997, 2001)
25.02.1999	18:58:29	51.64	104.82	5.9 (M_W)	77	V–VI	Detailed macroseismic survey was carried out. Brief description of earthquake effects was published. Initial materials are stored in holdings	(Golenetskii et al., 2001; Ruzhich et al., 2002; Sherman et al., 2003; Radziminovich et al., 2005)
27.08.2008	01:35:31	51.60	104.04	6.3 (M_W)	77	VI	Detailed macroseismic survey was not carried out. Brief description of earthquake effects was published. Initial materials are limited and stored in holdings	(Radziminovich et al., 2010; Mel'nikova et al., 2014)
21.09.2020	18:04:57	51.74	103.42	5.5 (M_W)	85	V	A detailed macroseismic survey was carried out using the internet-questionnaire. Initial materials are stored in holdings	(Gileva et al., 2021; Radziminovich et al., 2021; present work)

Dates and times are in GMT. Magnitudes M_{LH} are after (*Novyi*..., 1977). Moment magnitude M_W for earthquake of April 4, 1950 is after (Delouis et al., 2002); for earthquake of December 4, 1957, after (Okal, 1976); for earthquake of January 5, 1967, after (Huang and Chen, 1986). Moment magnitude for earthquake of January 25, 1973 was calculated from energy class K_P using relation from (Seredkina and Gileva, 2016). Moment magnitudes for earthquakes of May 22, 1981, June 29, 186, February 25, 1999, August 27, 2008, and September 21, 2020 are after Global CMT catalog (https://www.globalcmt.org).

Table 2. Characteristics of administrative city okrugs of Irkutsk and number of questionnaires received from them

Administrative okrug	Area, km^2	Population	Number of questionnaires	In per cent of okrug population
Sverdlovsky	49.00	206499	370	0.18
Oktyabrsky	23.64	146968	223	0.15
Leninsky	103.70	150689	176	0.12
Pravoberezhny	105.00	113359	88	0.08
Irkutsk city	281.34	617515	1452	0.24

Populations of administrative city okrugs are according to estimates of Russian Federal State Statistics Service as of January 1, 2021 (https://rosstat.gov.ru). Number of questionnaires for Irkutsk on the whole are indicated taking into account those (595 responses) without exact spatial referencing.

The largest number of questionnaires was received from people of the Sverdlovsky okrug. The observation points were quite uniformly distributed over the area of this okrug (Fig. 2), but still some more dense clusters, which corresponded to residential microdistricts or complexes, can be identified. The similar distribution was reported for the Oktyabrsky and Leninsky city okrugs. It should be noted that these three city okrugs are dominated by high-rise development, which are concentrated in microdistricts and novel high-rise residential complexes. This point might favor more intensive reaction of people and, hence, affect the locally higher number of responses.

A slightly different pattern is observed in the Pravoberezhny city okrug of Irkutsk, which occupies the larger area in comparison with the other ones, taken alone, while its population is smaller, and the various types of development (Table 2). The number of questionnaires received from the Pravoberezhny city okrug is considerably smaller than the one from any other city okrug; moreover, the observation points are not clustered and scattered over the area of the city okrug. Nevertheless, the number of received reports is quite sufficient to assess shaking intensity, in any case, the number of questionnaires exceeds the respective number for the entire area of Irkutsk in case of some strong earthquakes of the past decades (Table 1).

Figure 3 presents the column chart reflecting the frequency of various macroseismic effects reported in different city okrugs of Irkutsk according to the received questionnaires. The most frequently reported effects refer to reaction of people. A fright of eyewitnesses was mention in 75–79% of questionnaires received from each administrative city okrug of Irkutsk. Up to 30% of eyewitnesses left their homes and went outside (notably, 1–2% ran away in panic). From 43 to 61% of eyewitnesses stayed where they were during and after the earthquake.

The reactions of household items can be seen in most full in such macroseismic effects as: rattling of kitchenware and windowpanes (from 54 to 61% of questionnaires); trembling, swaying, and moving of furniture (from 54 to 63%); swaying, displacement, and collapse of unattached (or hanging) objects (from 11 to 17%). Thus, the macroseismic effects related to household items were the second most often mentioned after the reactions of people.

The reactions of buildings, mentioned in the received questionnaires, were (1) creak of such building parts as slabs and walls (reported in 32 to 46% of responses), and (2) formation of cracks in the plaster (near window apertures and near ceilings—walls intersections), mostly in stairwells of multi-apartment buildings (from 2 to 7%). In addition, up to 15% of eyewitnesses noticed the general shaking of a building, often characterized as quite intensive. This macroseismic effect is presently unavailable in the online questionnaire, but people mentioned shaking in the field describing personal accounts of eyewitnesses.

In addition to the reactions of people, household items, and buildings, eyewitnesses reported other macroseismic effects. In particular, the clearly heard underground hum during the earthquake was reported by 37 to 50% of eyewitnesses. Of special interest is the animal behavior associated to the earthquake (31–50% of questionnaires, depending on administrative city okrug); the detailed study of animal behavior with respect to the Bystraya earthquake was presented in (Radziminovich et al., 2021).

As follows from Fig. 3, there are almost no essential differences between the displays of most macroseismic effects of the Bystraya earthquake from one city okrug to another. The Pravoberezhny city okrug is remarkable for a more frequently reported "creak of floors and ceilings," as well as for more intensive reactions of animals, but this can be explained by the abundance of one-story wooden private houses in this city okrug—creak and cracking of constructive elements of these buildings is generally more easily perceived by eyewitnesses. Moreover, owners of private houses more often have domestic animals (chiefly dogs and cats), in comparison with people living in apartment buildings; accordingly, the areas of private residential buildings are naturally expected to have a larger number of reports about animal behavior during an earthquake.

As a result, the shaking intensity within every administrative city okrug of Irkutsk during the

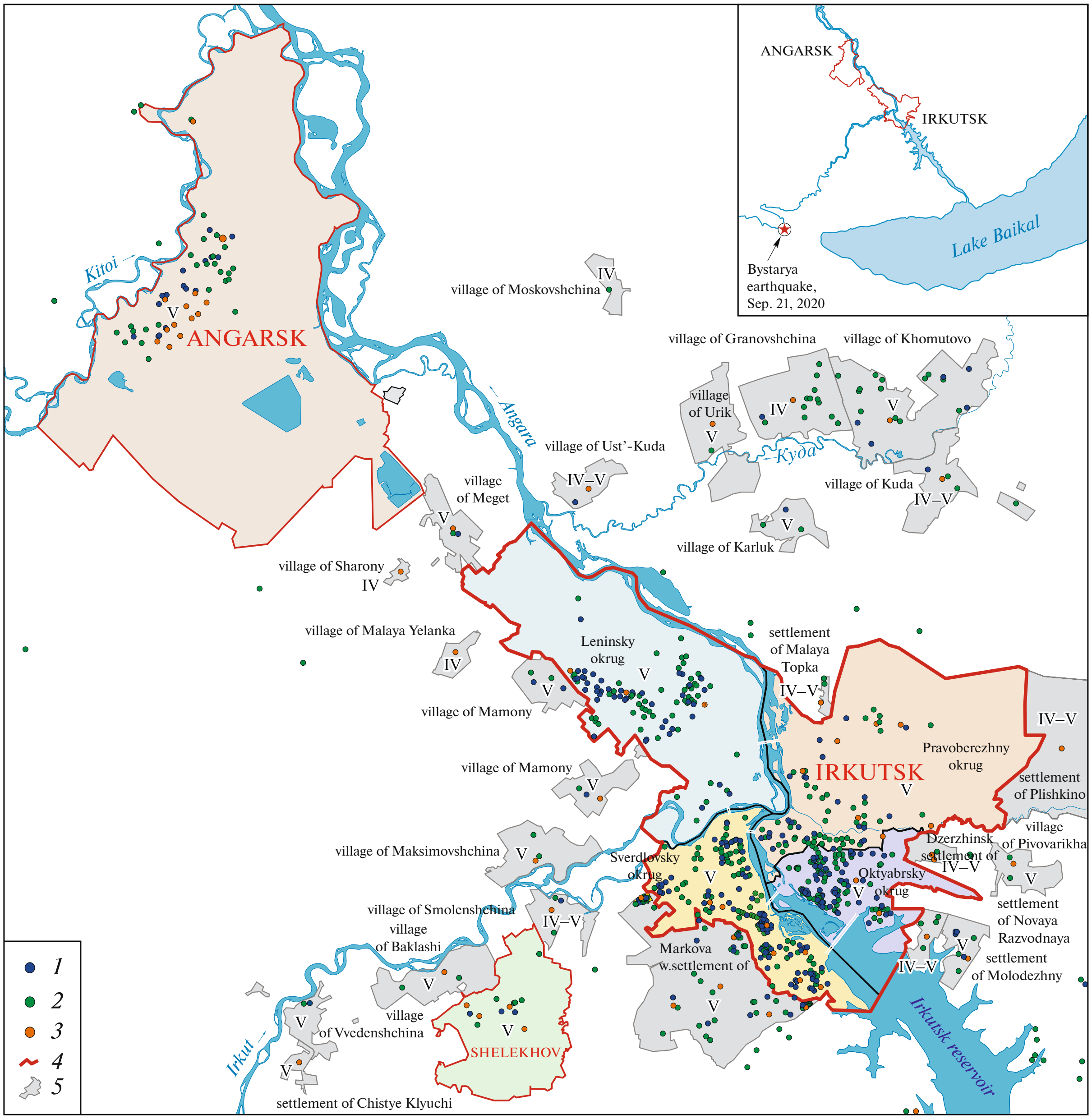

Fig. 2. Observation points of macroseismic effects from Bystraya earthquake of September 21, 2020 in Irkutsk and its vicinities: (*1*) observation points with most accurate spatial reference (administrative city okrug, street or microdistrict, and house number); (*2*) observation points with quite accurate spatial reference (administrative okrug and street/residential complex); (*3*) observation points with insufficiently accurate spatial reference (administrative okrug and microdistrict/quarter); (*4*) city borders; (*5*) areas of other settlements. Roman numerals correspond to shaking intensity on MSK-64 scale.

Bystraya earthquake can be reliably assessed at I = V on the MSK-64 scale. No damage to buildings during the earthquake were reported in the city; rare cases of cracked plaster were caused, most likely, by the absence of full repairs and by the general state of these buildings.

Interestingly, quite a large number of reports were received from the suburbs of Irkutsk, giving ground to obtain reliable shaking intensity estimates for the localities in the city neighborhood (Fig. 2). Some of these populated places are of significant area; e.g., the Markova work settlement (industrial township) is comparable in area to any of administrative okrugs of Irkutsk and spatially adjoins the city border. There are relatively small distances between Irkutsk and such cities as Angarsk and Shelekhov. If we consider Irkutsk together with its nearest vicinities, including rural localities, as a united area (agglomeration), then assessment of shaking intensity within each administrative city okrug becomes of special importance in the

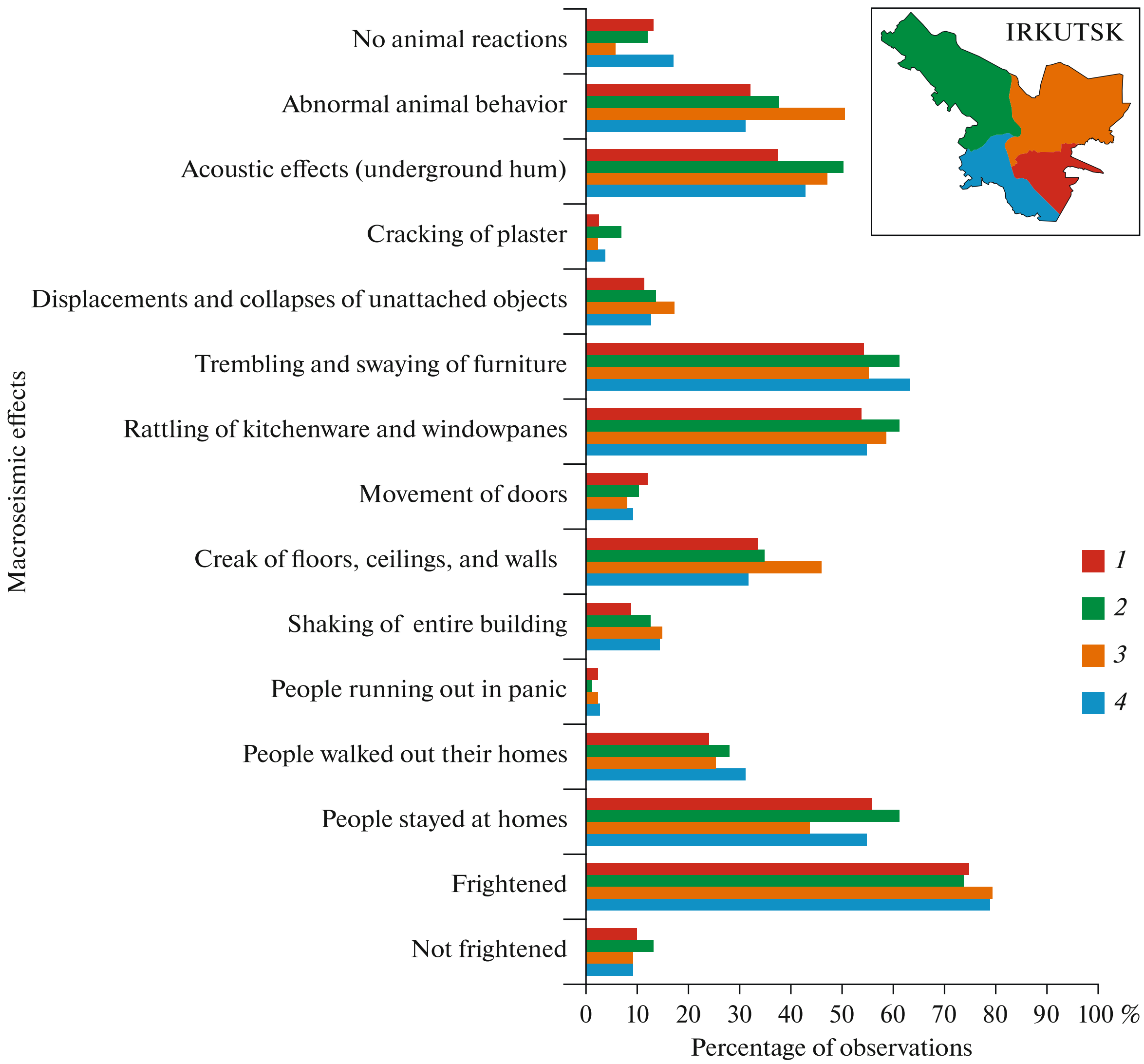

Fig. 3. Number of observed macroseismic effects (in % from total number of questionnaires) during Bystraya earthquake of September 21, 2020 within administrative city okrugs of Irkutsk: (*1*) Oktyabrsky, (*2*) Leninsky, (*3*) Pravoberezhny, (*4*) Sverdlovsky.

light of obtaining a more detailed macroseismic field and revealing variations of this field.

In this respect, it is also interesting to note that shaking intensity in some villages and settlements near Irkutsk was assessed to be lower by one intensity point in comparison with the city. This may be related to local engineering geological settings; however, different intensity values can also be explained by a higher perceptibility of the urban environment to seismic shaking. R.E. Tatevossian and his co-authors determined the influence of such parameters as area, population, and other ones typical of urban areas on the shaking intensity assessment as a "large city factor" (Tatevossian et al., 2003). It seems that this factor took place, at least partially, within the Irkutsk "agglomeration" during not only the September 21, 2020 Bystraya earthquake, but also other strong seismic event of the recent decades.

DISCUSSION

Analysis of macroseismic data on the Bystraya earthquake of September 21, 2020 revealed no significant difference between macroseismic effects within the territory of Irkutsk: shaking intensity in all administrative city okrugs can be reliably assessed at I = V. Probably, analogous to the earthquakes of May 22, 1981 (Golenetskii, 1997) and February 25, 1999 (Sherman et al., 2003), whose shaking intensity corresponded to I = V and I = V–VI, respectively, macroseismic effects had not been at the level, at which the differences in shaking intensity within different city okrugs could have been noticeable. Probably, the threshold intensity, above which local variations in macroseismic field can be identified, is I = VI. This supposition is supported by the results of macroseismic surveys after the Middle Baikal (Solonenko and

Treskov, 1960; Solonenko, 1962) and Mogod (Golenetskii et al., 1970) earthquakes, for which shaking intensity in Irkutsk was up to I = VI–VII (Table 1), but demonstrated spatial variations over the city area.

Nevertheless, we can consider the obtained results as a very useful experience. Such an "interactive" macroseismic survey of the city area and, first of all, its individual administrative okrugs has allowed us to obtain representative data which are necessary for updating seismic hazard and seismic risk assessment. Let us provide some thoughts on this matter.

First, urban environment is a dynamically developing system that gradually involves new areas, including those with unfavorable engineering geological settings. In terms of geomorphology, Irkutsk and its nearest vicinities are situated in the transitional zone between a platform flatland to the Baikal mountain region (Logachev et al., 1964). The majority of the city is located on the high flood plains and terraces of the Angara, Irkut, Ushakovka, Kaya, Topka, and other rivers. River terraces are composed of alluvium of 5 to 15 m thick, locally covered with slope detritus; the most clearly expressed are the flood-plain terrace (0.75–2.00 m), and those above flood plain: first (4–6 m), second (6–12 m), third (16–25 m), and fourth (26–35 m) (Kadetova and Rybchenko, 2003; *Atlas*..., 2011).

During the 20th–early 21st centuries, the territory of Irkutsk considerably expanded (*Atlas*..., 2011), primarily due to the development of new microdistricts (Fig. 4). Additionally, the clear tendency toward taller high-rise buildings is observed. Intensive expansion and evolution of the urban development unavoidably leads to the changes in engineering geological settings (Kadetova et al., 2007) and hydrogeological conditions (Shen'kman et al., 2011), which in turn directly affects seismic properties of soils within local sites. In this respect detailed macroseismic data become of special value to reveal and assess the scales of these changes not only at the modern stage, but also retrospectively.

Second, detailed macroseismic survey offers an opportunity to compare the effects of a strong earthquake within different administrative city units, and if the data volume is big enough, then the detailed information can be obtained for individual microdistricts. This constitutes the basis for zoning of the urban area based on the observed shaking intensity and for further comparison of the obtained intensity values and seismic microzoning maps in order to update the latter. Note that this was one of the goals of the work by V.P. Solonenko and his colleagues when investigating the effects of the Middle Baikal earthquake of August 29, 1959 (M_{LH} = 6.8) (Solonenko and Treskov, 1960; Solonenko, 1962).

Third, macroseismic data on strong earthquakes, if they have exact spatial reference, allow researchers to follow the "seismic history" of individual buildings, both historical and recent ones. Thorough documenting of macroseismic effects and, moreover, the damages observed in every building during every strong earthquake, can become a basis for making adequate decisions to initiate reinforcement works and to reduce the vulnerability of any particular building.

The abovesaid is completely applicable not only to the territory of Irkutsk, but also to other large cities of East Siberia. For example, earthquakes occurred in the highly seismoactive northeastern flank of the Baikal Rift Zone (Melnikova et al., 2020; Novopashina and Lukhneva, 2020, 2021) are often and clearly felt in Chita city. Depending on earthquake magnitude and epicentral distance (up to several hundreds of kilometers), shaking intensity in Chita can range from I = IV to I = VII (Solonenko et al., 1958; Golenetskii et al., 1970, 1996; Seredkina et al., 2020). It is worth noting that the clear difference between macroseismic effects (with I varying from V to VII) had been reported within the territory of Chita during the Muya earthquake of June 27, 1957 (M_{LH} = 7.6) (Solonenko et al., 1958), although the area of this city was considerably smaller at the time. The shaking intensity in Ulan Ude can be I = V and more in case of either earthquakes with epicenters located within the Lake Baikal basin (Golenetskii et al., 1973), or seismic events in West Transbaikalia (Golenetskii et al., 1982) and Mongolia (Golenetskii et al., 1970).

Detailed macroseismic surveys can also be considered reasonable for smaller cities having populations from 50000 to 250000 (e.g., Angarsk, Shelekhov, and Bratsk). If a small city is characterized by a clear spatial structure and is subdivided into microdistricts or quarters, and if representative macroseismic data are available for its area, then reliable shaking intensity values can be obtained for small areas within the city limits. This, on the one hand, considerably increases the degree of detail of macroseismic field owing to a large number of intensity data points and, on the other hand, allows specialists to visualize macroseismic effects of an earthquake on a larger scale, especially taking into account the information from suburbs and nearest localities (Fig. 2).

Analysis of the information about the effects of strong earthquakes (including relatively recent ones) within Irkutsk has raised the problem of preservation of the initial macroseismic data. Detailed macroseismic surveys were carried out in Irkutsk after most earthquakes that were felt in the city with at least I = V, but the collected materials had almost never been published in full. The articles published predominantly in yearbooks (*Earthquakes in the USSR* and *Earthquakes in Northern Eurasia*) mentioned, at best, a brief description of macroseismic effects observed in Irkutsk and the resultant value of seismic shaking intensity.

The primary information about certain earthquakes, which was contained in paper-based question-

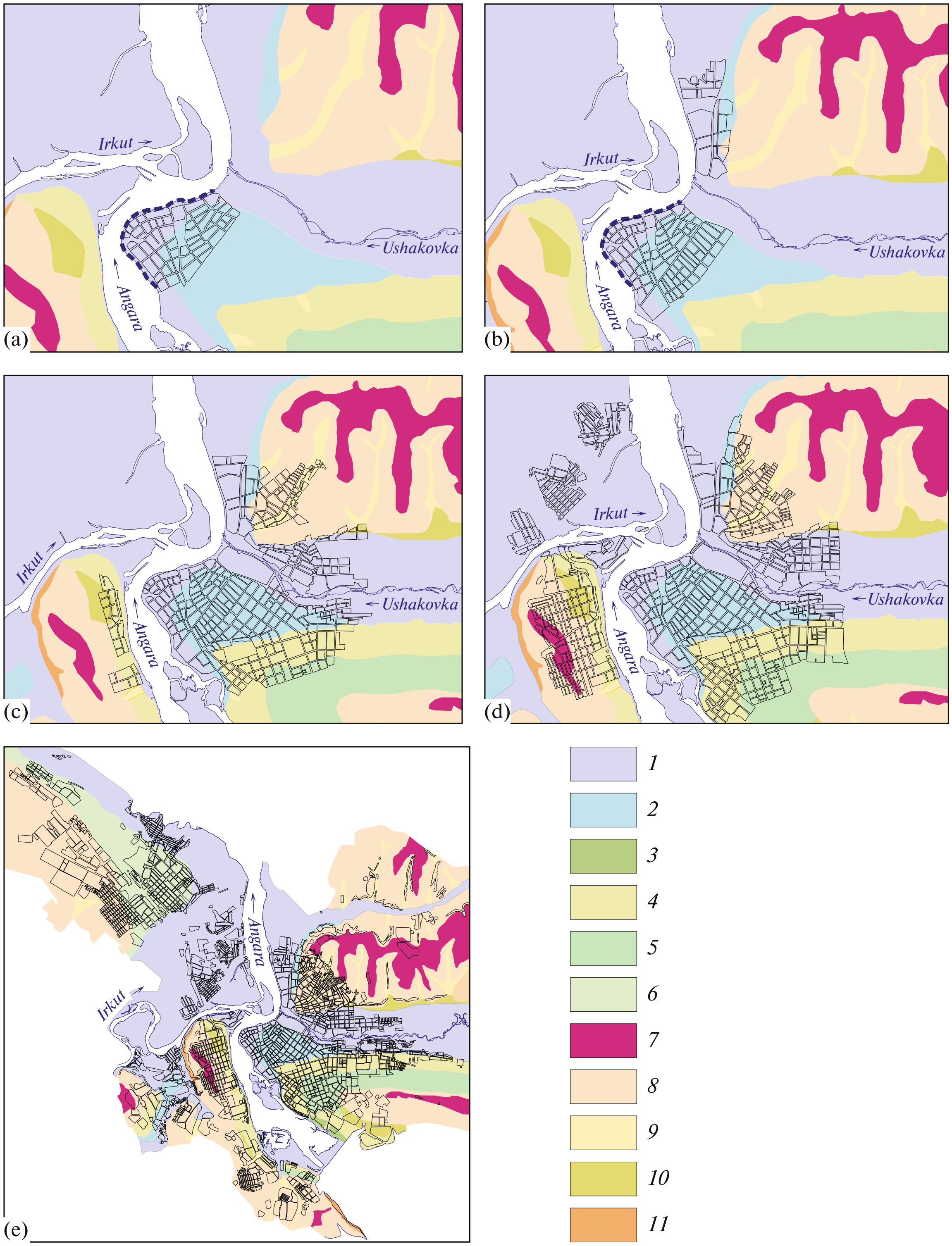

Fig. 4. Main stages of development of Irkutsk, modified after (Kadetova et al., 2007), combined with geomorphic zoning scheme: (a) 1652–1750; (b) 1750–1879; (c) 1879–1903; (d) 1903–1950; (e) 1950–present. Legend: (*1*) flood plain of Angara, Irkut, and Ushakovka rivers (0.2–2.5 m); (*2*) first terrace above flood plains of Angara, Irkut, and Ushakovka rivers (4–8 m); (*3*) second terrace above flood plain of Angara River (10–15 m); (*4*) third terrace above flood plain of Angara River (16–25 m); (*5*) fourth terrace above flood plain of Angara River (25–35 m); (*6*) third and fourth terraces above flood plain of Angara River (22–35 m) in Novo-Lenino microdistrict area; (*7*) flat water-divide surfaces and flat gentle slopes (up to 10°); (*8*) moderately inclined (up to 20°) slopes; (*9*) bottoms of dry valleys and intermittent stream valleys; (*10*) near-valley slopes; (*11*) non-terraced slopes inclined at more than 15°.

naires, field notes, and in holdings, has not preserved by present and can be considered irretrievably lost; therefore, the modern and future researchers cannot employ these data for applied purposes. Such situation is of high concern, and should be a least partially fixed by a thorough revision of the remained materials. In addition, the aimed collection and archiving of the detailed macroseismic information should be carried out in case of the future strong earthquakes.

At present, the problem about the minimum number of questionnaires necessary for reliable assessment of shaking intensity (in particular, in large cities) remains disputable. This number is determined, on the one hand, by the size of a city and its population, and, on the other hand, by general capabilities of performing a macroseismic survey in this area. According to the cases of the last two decades in Russia, shaking intensity in rural settlements is often estimated on the basis of as many as five to ten reports or questionnaires (Tatevossian et al., 2002, 2003; Verkholantsev et al., 2021). R.E. Tatevossian et al. analyzed the results of macroseismic survey of the Lower Kuban earthquake of November 9, 2002 to note that such an amount is sufficient to quite accurately assess shaking intensity, but it cannot be considered statistically representative; in addition, these authors point out the necessity of full-scale macroseismic surveys in large cities (Tatevossian et al., 2003). However, this last point is not always implementable due to various reasons, and, thus, macroseismic surveys in large cities is not a regular practice. For example, macroseismic survey of the Middle Uralian earthquake of October 18, 2015 had resulted in obtaining 8 questionnaires from Yekaterinburg and 17 from Perm (Verkholantsev et al., 2021). Given that the population of either city exceeds 1 000 000, such a small number of responses can hardly be considered representative. On the contrary, international practice indicates that questionnaires collected within an urban area during a detailed macroseismic survey can number hundreds and several thousand (Cifelli et al., 1999a, 2000; Tertulliani and Donati, 2000; Ripperger et al., 2009). Such number of questionnaires can be considered sufficient for a reliable assessment of shaking intensity for a city area on the whole, and for its individual administrative units.

The large number of collected reports (1452 questionnaires) containing the descriptions of effects from the Bystraya earthquake of September 21, 2020 in Irkutsk can be considered as a remarkable advance in macroseismic studies of urban areas in East Siberia. The use of the Internet-based questionnaire has proven its high effectiveness, although certain shortcomings have been revealed as well. Presently, the Internet-based questionnaire is a simplified version of the standard paper-based questionnaire, which was developed several decades ago. Since then, the typical urban development (more high-rise buildings, more modern construction materials and design conception), apartment interiors (stretched and suspended ceilings, more modern and diverse floor pavements, window glass units, built-in furniture), and characteristics of domestic appliances essentially changed.

All these changes have led to that some macroseismic effects, which were frequently used in the past and, in particular, mentioned in macroseismic scales, become presently obsolete. For example, LCD and LED televisions, which became widespread recently, are of smaller weight and often more prone to shaking (due to weak fixation), in comparison with old tube TV sets; therefore, they demonstrate a clearer reaction to earthquakes; the same is applicable to many other modern household items. In this respect, we can state the necessity of updating the questionnaire taking into account the modern conditions.

CONCLUSIONS

Based on our experience, the use of an Internet-based questionnaire makes it possible to collect a considerable amount of reliable macroseismic data within a short time interval. The majority of responses are usually received from inhabitants of highly urbanized areas, offering new opportunities to assess shaking intensity within sites that are considerably smaller in area than an entire city. In this case, macroseismic data can be grouped by individual administrative units or even microdistricts, thus increasing the number of intensity data points. This allows specialists to significantly enhance the detail of macroseismic field or at least the part that covers large urban agglomerations.

Detailed macroseismic survey makes it possible to reveal sites within urban areas at which shaking intensity demonstrates local amplification during strong and moderate earthquakes. These studies can improve the maps of seismic microzoning and assist the more accurate assessment of seismic risk; however, they require a large amount of reliable initial data.

The present study has also demonstrated the need to carefully preserve and systematize macroseismic data, both modern and past. These materials should be considered an important element of the informational background when planning further development of urban areas and their infrastructure.

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CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest.

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