ORIGINAL ARTICLE

The December 9, 2020, M$_w$ 5.5 Kudara earthquake (Middle Baikal, Russia): internet questionnaire hard test and macroseismic data analysis

Yan B. Radziminovich[1,2] · Nadezhda A. Gileva[2] · Tsyren A. Tubanov[3,4] · Olga F. Lukhneva[1] · Anna V. Novopashina[1] · Larisa R. Tcydypova[3]

Abstract

The article discusses the macroseismic data on the December 9, 2020, M$_w$ 5.5 Kudara earthquake which occurred in the Selenga River delta (Middle Baikal, Eastern Siberia, Russia). This is the strongest seismic event in the study area over a 50-year period. The bulk of macroseismic data was obtained with internet questionnaire posted on the website of the Baikal Branch of the Geophysical Survey of the Russian Academy of Sciences. In total, 1433 responses were received from 120 places (villages, towns and cities) in Eastern Siberia, with most of them was obtained from large cities. In addition, a field survey was carried out in the near-field, which revealed slight non-structural damage to buildings in several settlements. The maximum intensity assessed VI–VII MSK-64 or VI EMS-98 was observed in the Kudara village. Taking into account the macroseismic data obtained, we have prepared a map of intensity data points. The largely observed shakings (intensity IV MSK-64/EMS-98) were noted at epicentral distances of over 500 km; intensity II MSK-64/EMS-98 was noted at a distance of up to 980 km. The Kudara earthquake allowed us to test the internet questionnaire in real conditions of strong seismic impact. The results obtained confirm the rather high efficiency of the internet questionnaire in the conditions of the Baikal region, however, some limitations associated with the responses spatial distribution are exist. A detailed study of the Kudara earthquake allowed us to gain new experience useful for the further development of macroseismology in Eastern Siberia.

Keywords Earthquake · Macroseismic data · Internet questionnaire · Lake Baikal · East Siberia

✉ Yan B. Radziminovich
  ian@crust.irk.ru

1   Institute of the Earth's Crust, Siberian Branch of RAS, Irkutsk, Russia

2   Baikal Branch of the Geophysical Survey of RAS, Irkutsk, Russia

3   Geological Institute, Siberian Branch of RAS, Ulan-Ude, Russia

4   Buryat Branch of the Geophysical Survey of RAS, Ulan-Ude, Russia

1 Introduction

Despite the rapid improvement of instrumental methods in seismology, macroseismic data are still relevant and used, among other things, to seismic hazard assessment and develop preventive measures to reduce seismic risk. Information about the perceptible earthquakes effects is of importance in those world regions where network of seismic stations is insufficiently dense or completely absent. In particular, reliable intensity estimates can be converted into strong ground motions parameters via correlation equations and then used in works on seismic zoning (Lesueur et al. 2013; Caprio et al. 2015; Locati et al. 2017; Du et al. 2019; Zanini et al. 2019; Ahmadzadeh et al. 2020; Ardeleanu et al. 2020; Gomez-Capera et al. 2020; etc.). In turn, the accuracy of the equations linking the intensity, peak ground acceleration (PGA) and peak ground velocity (PGV) directly depends on both the quantity and quality of macroseismic data.

In Eastern Siberia, the macroseismic data are obtained using a limited number of traditional methods, including field survey, distribution of paper questionnaires using regular post, and also the use of regional mass-media materials. Over the past two decades, the collection of macroseismic data with internet questionnaires has been intensively practiced worldwide (Atkinson and Wald 2007; Sbarra et al. 2010; Wald et al. 2011; Bossu et al. 2015, 2017; Quitoriano and Wald 2020; Hough and Martin 2021). In the case of a major earthquake, the number of responses received with the internet questionnaire can reach several thousand or tens of thousands (Wald et al. 2011; Hough 2012). The materials obtained can be further used for a detailed analysis of diagnostic effects in urban and natural environment (Sbarra et al. 2020), as well as for the study of human behavioural reactions (Goltz et al. 2020). To date, the most advanced and globally operational internet questionnaire systems are developed and maintained by the United States Geological Survey (USGS) (Atkinson and Wald 2007) and European-Mediterranean Seismological Centre (EMSC) (Bossu et al. 2017; Steed et al. 2019). It is noteworthy that the efficiency of the EMSC system is provided, along with multilingual support, by the widespread use of smartphones for collecting macroseismic data (Bossu et al. 2015).

In Eastern Siberia, the internet questionnaire has been used since 2008, but until now we could not fully assess its potential and efficiency due to the absence of relatively strong $M > 5$ earthquakes. During the period 2020 – early 2021, several strong seismic events took place in the Baikal Region. One of them is the M_w 5.5, December 9, 2020 Kudara earthquake occurred at 21^h44^m UTC (December 10 at 05^h44^m local time) at Middle Baikal near the Selenga River delta (Table 1). The earthquake was felt over a large area and caused serious fright and concern for the population of the Southern Baikal region, as well as minor damage to buildings in villages within the near-field. The material loss and a wide public outcry among the population of Eastern Siberia made this earthquake a significant event in the life of the region, that, in turn, gave reason to expect large number of eyewitnesses responses. Thus, the December 9, 2020 Kudara earthquake is of considerable interest in terms of testing the internet questionnaire under conditions of a relatively strong seismic impact. Moreover, the currently available macroseismic data sets on earthquakes within the Selenga River delta is rather limited; therefore, the collected data can be considered as a significant addition to our knowledge in this respect.

Table 1 Main parameters of the December 9, 2020 Kudara earthquake according to international seismological agencies

Agency	T_0, h:min:s	Hypocenter			Magnitude
		$\varphi°$, N	$\lambda°$, E	h, km	
BYKL	21:44:33.70	52.36	106.60	23.0	
MOS	21:44:33.10	52.46	106.78	10.0	mb 5.3
NEIC	21:44:33	52.420	106.721	17.0	M_w 5.4
GCMT	21:44:34.90	52.48	106.52	20.3	M_w 5.5

BYKL Baikal Branch of the Federal Research Center 'Geophysical Survey of RAS' (Irkutsk, Russia, http://seis-bykl.ru); *MOS* Federal Research Center 'Geophysical Survey of RAS' (Obninsk, Russia, http://www.ceme.gsras.ru); *NEIC* National Earthquake Information Center (USA; https://earthquake.usgs.gov); *GCMT* The Global Centroid-Moment-Tensor Project (USA, https://www.globalcmt.org)

2 Tectonic settings and seismicity of study area

The Middle Baikal including the Selenga River delta is considered one of the most seismically active areas of the intracontinental Baikal rift zone (Figs. 1, 2). Geodynamically, the Selenga delta region is a historical core of the rift zone and is characterized by a rather long evolution (Logachev 2001, 2003). There are different opinions on the rift zone age, as well as geodynamic processes leading to the formation and development of the rift (Tapponnier and Molnar 1979; Logatchev and Zorin 1992; Zorin et al. 2003; Petit and Déverchère 2006; Zhao et al. 2006; San'kov et al. 2011; Buslov 2012; Mats 2012). However, it is generally accepted that the modern rifting processes and the Lake Baikal basin opening are caused by southeast motion of the Amurian plate relative to the Eurasian plate. According to GPS data, at the present stage the Amurian plate moves southeast at rates from 0.5–1.4 mm·yr^{-1} in the western flank of the rift zone (Lukhnev et al. 2021) to 3.2 mm·yr^{-1} in the central part of the rift (Lukhnev et al. 2010, 2013). As the central link of the rift zone, the Middle Baikal is characterized by a pure extension (Calais et al. 2003; Mel'nikova and Radziminovich 2007; Mel'nikova et al. 2010; Novopashina and Lukhneva 2020, 2021). The overwhelming majority of the focal mechanism solutions within the middle Baikal are characterized by normal fault kinematics (Radziminovich et al. 2013). The hypocenters are located mainly at depths from 10 to 22 km, which suggests the presence of a seismically active layer in this depth range (Suvorov and Tubanov 2008). The depth of the Moho boundary within the Middle Baikal is estimated to be approximately 40 km (Ten Brink and Taylor 2002; Mordvinova et al. 2016). The area is distinguished by a rather dense active faults pattern (Levi et al. 1997; Lunina 2016; Kuz'mina and Novopashina 2018) with a maximum seismic potential of up to M 7.5 (Ulomov 2014).

The strongest seismic event known in the study area is the January 12, 1862, M 7.5 Tsagan earthquake (Kondorskaya and Shebalin 1982; Golenetskii 1996). This earthquake was accompanied by seismogenic subsidence of a tectonic block with an area of more than 200 km^2 and the formation of Proval Bay in the northeastern part of the Selenga delta (Golenetskii 1996), which, in turn, can be considered as a separate episode in the evolution of the Baikal basin (Shchetnikov et al. 2012). Macroseismic effects of the Tsagan earthquake were observed over a vast area; the epicentral intensity is IX–X MSK-64 (Golenetskii 1996). Less strong earthquakes with M≥6.5 occurred in 1839, 1871, 1885, 1903 and 1959 (Kondorskaya and Shebalin 1982). From this, we can conclude that during the nineteenth century there was
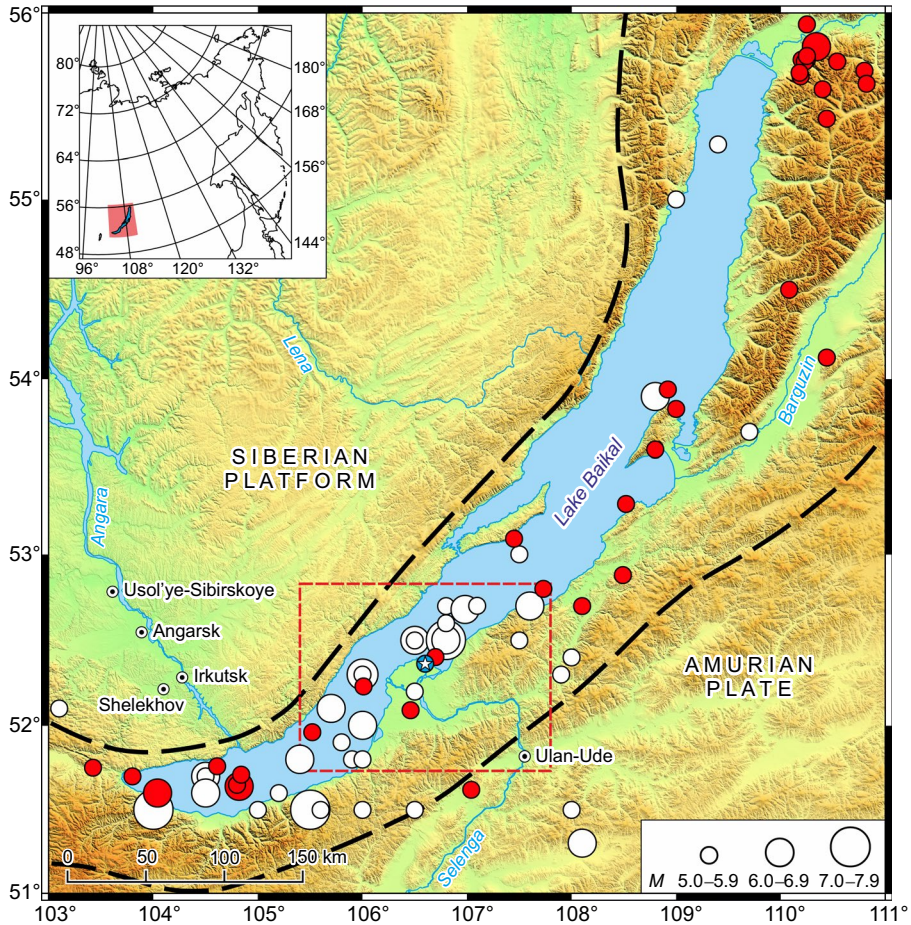
Fig. 1 Seismicity of the Lake Baikal basin and its mountainous framing according to historical (1742–1959, white circles) and instrumental (1960–2020, red circles) data. Epicenters of M ≥ 5 earthquakes are shown. White star in blue circle denotes the epicenter of the December 9, 2020 Kudara earthquake (M$_w$ 5.5). The black dashed lines represent boundary of the Baikal rift zone (Logatchev and Zorin 1987). The red dashed frame denotes the area shown in Fig. 2

a noticeably higher level of seismic activity in Middle Baikal if compared to the subsequent time. During the period of instrumental observations (from 1960 to 2020), not a single earthquake with M ≥ 6 was registered in the Middle Baikal area. The December 9, 2020 M$_w$ 5.5 Kudara earthquake considered in this article, is the strongest seismic event in 50 years since the earthquake of March 28, 1970 (M$_{LH}$ 5.5) (Golenetskii et al. 1973).
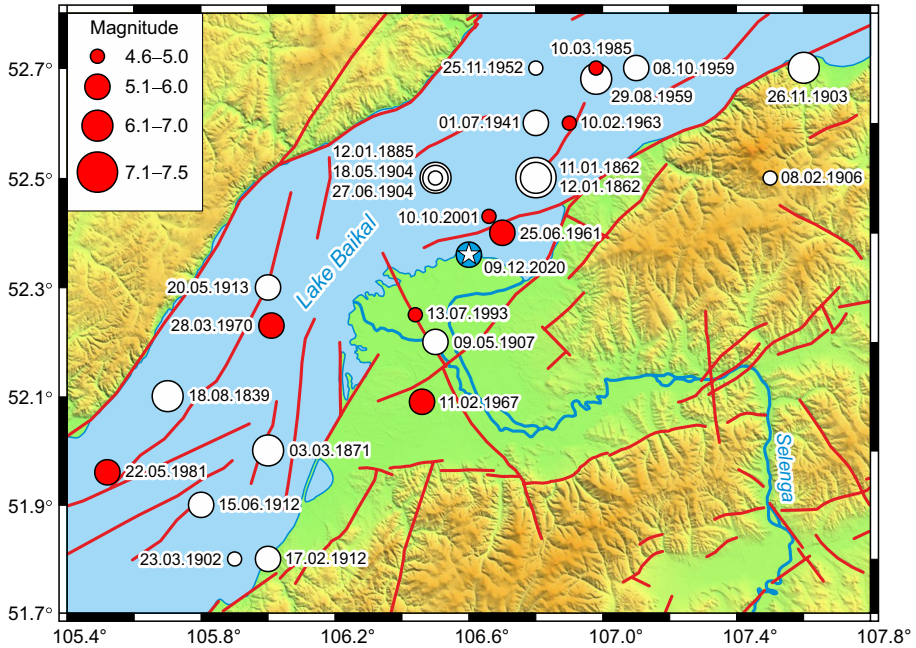
Fig. 2 Seismicity of Middle Baikal and the delta of the Selenga River according to historical (before 1960, white circles) and instrumental (from 1960, red circles) data. Epicenters of M > 4.5 earthquakes are shown. White star in blue circle denotes the epicenter of the December 9, 2020 Kudara earthquake (M_w 5.5). Red lines indicate active faults according to Lunina (2016)

3 Data and methods

The collection of macroseismic data was carried out mainly using an internet question-naire posted on the website of the Baikal Branch of the Geophysical Survey of the Russian Academy of Sciences (GS RAS) (http://seis-bykl.ru). The questionnaire was put into operation in September 2008 after the experience of studying of strong August 27, 2008, M_w 6.3 Kultuk earthquake in order to obtain a broader public response and significantly increase the amount of macroseismic data (Radziminovich et al. 2014).

The internet questionnaire consists of several blocks reflecting the observed diagnostic effects (Fig. 3): (1) location of observation (text field); (2) date and time of observation (pop-up menu and text fields); (3) humans behaviour (check-box for each behaviour type); (4) household items and buildings reaction (check-box for each diagnostic effect); (5) effects in the natural environment (check-box for each effect); (6) additional earthquake information (duration of oscillations, earthquake manifestation characteristic, the presence or absence of underground hum, unusual animals behaviour, felt aftershocks) (text fields). In addition, eyewitnesses can describe their personal impressions, as well as the observations of their relatives, friends or acquaintances, in the two memo-fields. As it follows from our experience, such text descriptions are often more informative if compared to the check-boxes marked in the internet questionnaire due to the more detailed characteristic of one or another diagnostic effect. It should be noted that currently, an automatic mode is not applied for both the processing of macroseismic data and the assessment of intensity.

Fig. 3 The screenshot of the internet questionnaire on the Baikal Branch of the GS RAS website (http://seis-bykl.ru)

Originally, the website of the Baikal Branch of the GS RAS and, respectively, the internet questionnaire were designed for desktops. However, our respondents currently do not experience any difficulty in visiting the website from mobile devices, which significantly expands the potential for using the internet questionnaire, including the geographical aspect.

Only questionnaires containing geographical position of an observer (at least at settlement level) and at least one diagnostic effect are selected for processing. Specifying the exact post address is preferred, but currently it is optional, since not all eyewitnesses are ready to disclose their personal data. All responses were grouped according to the place (populated area) from where they were received. The intensity assessment in each settlement is made on the basis of all questionnaires received from the same place, taking into account the number of observation of certain diagnostic effect. Each settlement where the intensity has been assessed is considered an intensity data point (IDP).

The MSK-64 macroseismic scale (Medvedev et al. 1965) was used to assess the intensity. Despite the fact that the MSK-64 was developed almost 60 years ago, it is still in practice in Russia and is widely known to the international seismological community. Moreover, since the introduction of MSK-64 into practice, a large amount of macroseismic data as well as intensity assessments made with this scale, has been collected in Russia and, in particular, in Eastern Siberia. Thus, the choice of the MSK-64 for assessing macroseismic data is primarily due to the need to ensure the compatibility of the intensity estimates for recent earthquakes with older data sets. Nevertheless, the entire set of macroseismic data obtained was also analyzed with the modern European macroseismic scale EMS-98 (Grünthal 1998), which is in many respects similar to the MSK-64 (Musson et al. 2010), but allows in some cases to reduce uncertainties in intensity assessments.

Along with the use of the internet questionnaire, the field survey was carried out within the near-field (the Selenga River delta) during the first three days after the earthquake. A direct survey of the eyewitnesses was undertaken; eyewitness responses were recorded on a paper questionnaires. Damage to buildings was documented through photography. Unfortunately, due to restrictions on movement between regions, as well as on contact between people associated with the COVID-19 pandemic, the field survey was rather limited. Nevertheless, the field survey made it possible the intensity assessment in some places within the near-field by the indoors diagnostic effects and, in some cases, by damage to buildings. Since both the paper and internet questionnaires contain very similar questions, there were no any difficulties with the merging of the field and internet survey data. However, in case of intensity assessment on the basis of both field and internet questionnaire data, preference was given to the data obtained during the field survey as more reliable and informative.

Strong ground motions at the Irkutsk seismic station (IRK) were recorded using a Guralp CMG-5 T broadband accelerometer. At the Ulan-Ude seismic station (UUDB), strong ground motions were recorded using a Nanometrics TS-120 velocimeter; then the velocigram was converted into an accelerogram using a differentiation procedure. The instrumental intensity assessment using recorded PGA values was carried out with the instrumental section of the MMSK-92 scale (Shebalin and Aptikaev 2003). The MMSK-92 is among the seismic scales of the Mercalli family (Aptikaev et al. 2008; Aptikaev and Erteleva 2017) and has been used in Russia since the early 1990s along with MSK-64, mostly for instrumental intensity assessment. For comparison, we also used the equation relating intensity and PGA proposed by Caprio et al. (2015).

4 Results

The macroseismic data of the Kudara earthquake in the near-field (the Selenga River delta) were obtained by a field survey that covered 27 settlements. The highest observed intensity VI–VII MSK-64 or VI EMS-98 was recorded in the Kudara village at an epicentral distance of 16 km. In this village, as well as in other settlements located within the range of up to 50 km, minor damage in some buildings was documented: cracks in the plaster, fallen pieces of plaster (Fig. 4), and also cracks in brick ovens and chimneys.

The bulk of the macroseismic data was collected using the internet questionnaire. It is worth noting that since 2008 earthquakes in the Baikal region were not characterized by a high
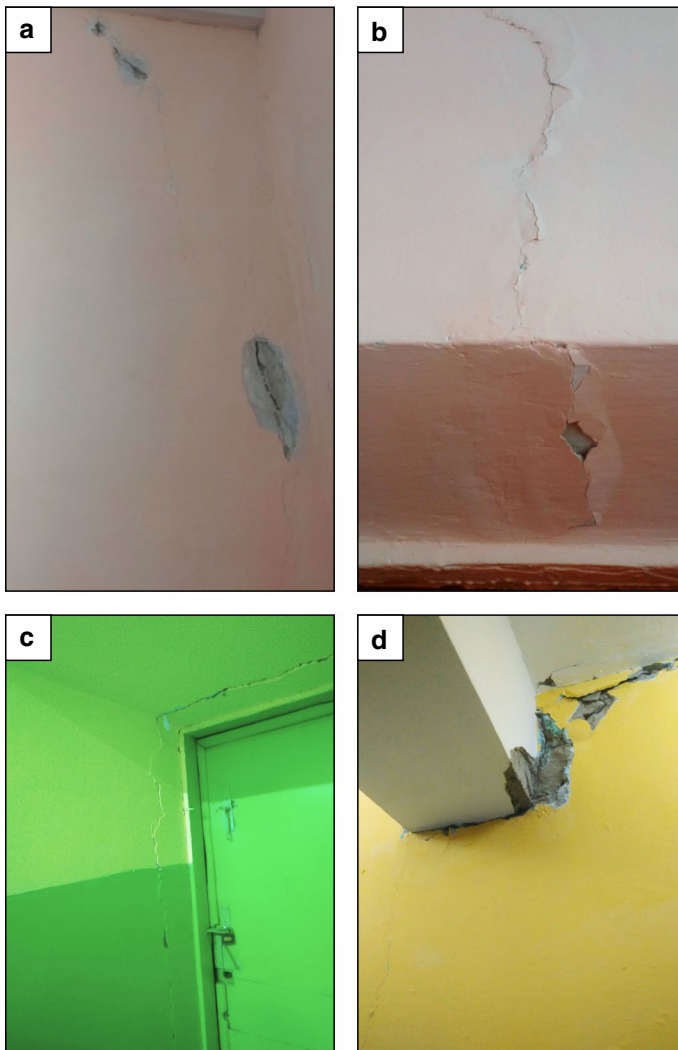
Fig. 4 Examples of damage to buildings caused by the Kudara earthquake. **a**, **b** secondary school in the settlement of Kamensk; **c**, **d** secondary school in the village of Kudara

magnitude and the number of eyewitness responses, as a rule, did not exceed several hundred (Radziminovich et al. 2014, 2020); nevertheless, in the case of the Mw 5.5 Kudara earthquake 1433 responses were received from 120 settlements in Eastern Siberia. The majority of these places are located in the far-field, only seven are located in the near-field and are among those covered by the field survey. Out of a total of 1433 responses, 1334 contain at least minimal information about diagnostic effects and are suitable for analysis and preparation of the IDPs map. If only single response was received from a settlement, these data were also included in the analysis, since in the conditions of a low population density in Eastern Siberia, any macroseismic data is of significant value. Thus, we consider each settlement from which at least one response was received as an intensity data point. As a result, 113 IDPs were derived from internet questionnaire, 7 IDPs—from both internet and field data, and 20 IDPs—only from field survey.

More than half of the responses total number (53%) was received during the first 4 h after the earthquake (Fig. 5); we can consider this period the most productive. It should be noted that there was an interruption in data receiving process caused by a temporary failure in the server's operation due to a heavy overload with requests. The failure occurred on December 10 at 06:04 local time (20 min after the earthquake) and lasted for 13 min until 06:17. After the server operations were restored, the data collection continued but its rate decreased slightly.

In the following hours, the receipt of responses gradually slowed down and practically stopped by the end of the first day after the earthquake. The dependence of the number of responses versus time is described by Eq. (1), calculated with the least squares method:

$$N = 237.13(\pm0.94)Ln(T) - 444.76(\pm4.62), \tag{1}$$

Fig. 5 The number of responses versus time during a period of 24 h. The red line is the approximating curve. The magenta dashed lines denote 13-min gap in data caused by server temporary failure due to heavy overload
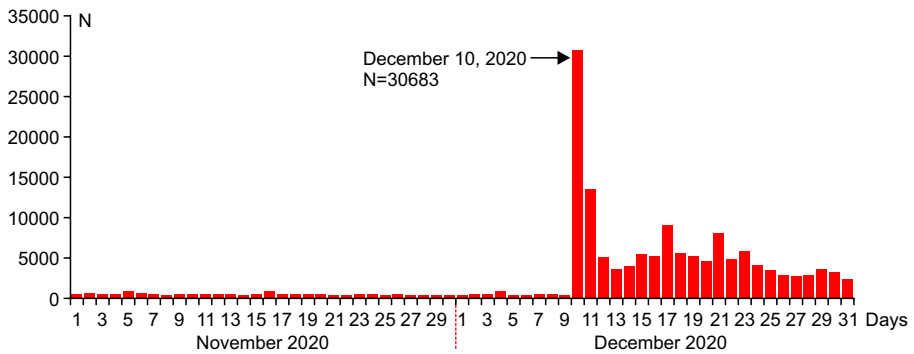
Fig. 6 The number of daily visits to the Baikal Branch of the GS RAS website (http://seis-bykl.ru) during November–December 2020

where N is the number of responses received, T is the time since the earthquake occurrence, minutes; correlation coefficient r = 0.99. As follows from Eq. (1), the reaction of society to an earthquake, expressed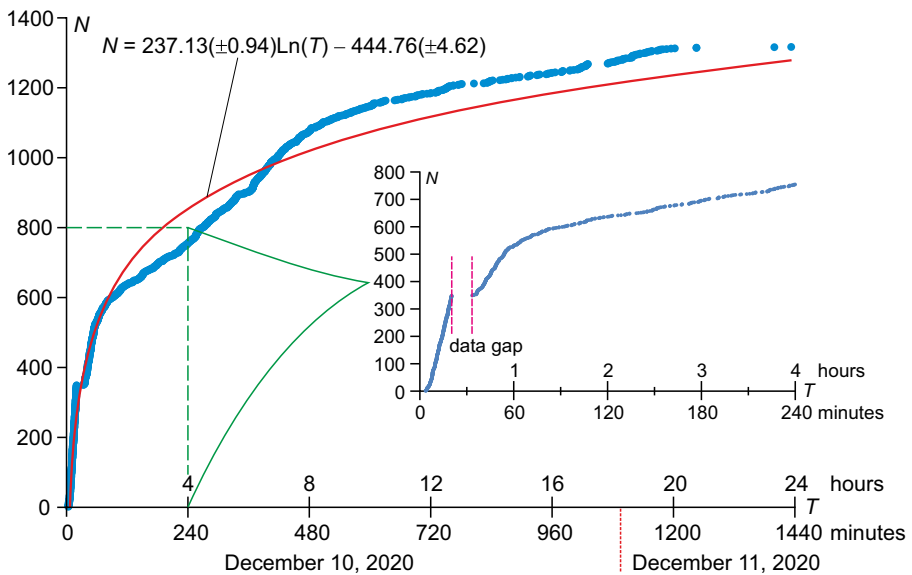 in the number of responses vs time, is very well described by a logarithmic law. An equally good correspondence of the eyewitnesses reaction to the logarithmic law was also noted during the March 29, 2019, M_w 4.8 Khoitogol-II earthquake, which was felt with a lower intensity in large cities of the Baikal region (Radziminovich et al. 2020).

The high level of interest of Eastern Siberia inhabitants in the actual information on Kudara earthquake is confirmed by the number of visits to the BB GS RAS website. During the month preceding the Kudara earthquake (November–early December 2020), the average number of daily visits to the website did not exceed 500, however, on the day of the earthquake the number of visits increased drastically and exceeded 30,000. Moreover, public attention to the actual seismological information remained at high level during at least three weeks after the earthquake until the end of 2020, with the average number of site visits about 5000 per day (Fig. 6).

Table 2 lists the brief description of the most typical diagnostic effects observed during the Kudara earthquake and used for the intensity assessments with the MSK-64 and EMS-98 scales. The full list of IDPs is presented in Table 3. Based on Table 3, we have prepared the IDPs map of the Kudara earthquake, presented on Fig. 7. As we can see, the populated areas covered by the internet questionnaire are unevenly distributed over the territory. Most of the responses came from areas adjacent to major rivers and transport routes. Many rural settlements, remote from regional administrative centers and often located in hard-to-reach areas, practically "dropped out" from the internet-survey.

Intensity V MSK-64/EMS-98 was observed at distances up to 253 km. Usually, such intensity does not lead to buildings damage; nevertheless, the earthquake caused a wide public resonance among the population of Baikal region, especially among residents of large cities. The intensity III–IV MSK-64/EMS-98 was observed at distances of up to 570 km.

The lowest intensity II MSK-64/EMS-98 was noticed at the distance of up to 980 km (city of Krasnoyarsk). On the one hand, the felt effects of the M 5.5 earthquake at such a significant distance may raise doubts. We received only one response from Krasnoyarsk via the internet questionnaire, although the fact that the earthquake was felt in this city is also confirmed by publications in mass-media containing eyewitness testimonies. Taking into

Table 2 Typical diagnostic effects observed during the December 9, 2020, Kudara Earthquake

Intensity, MSK-64/ EMS-98	Diagnostic effects in case of Kudara earthquake	
	Effects on humans	Effects on objects / Damage to building
II	The earthquake was felt indoors (very few). People were not frightened and stayed on place	No effect
III	The earthquake was felt indoors (few). People were not frightened and stayed on place	Glasses and windows slightly rattled (few)
IV	People were not frightened (many). People were frightened (most). People stay on place (most). People left their houses (few). People run outside in panic (very few)	Glasses and windows rattled (many). Furniture rattled (many). Doors swung, opened or shut (few). Small objects shifted or fell (very few). The building structure creaked (many)
V	People were not frightened (few). People were frightened (most). People stay on place (many). People left their houses (few). People ran outside in panic (very few)	Glasses and windows rattled (many). Furniture swayed or shifted (many). Doors swung, opened or shut (few). Small objects shift or fall (many). Building structure creak (many). Whitewash flakes fell (few). Cracks in plaster (few)
VI	People were awakened (most). People were frightened (most). People left their houses (many)	Small objects shift or fall (most). Whitewash flakes fell (many). Cracks in plaster (many). Fallen pieces of plaster (many). Cracks in chimneys (few)

Table 3 Intensity data points derived from macroseismic data on December 9, 2020, Kudara earthquake

No	IDP	Latitude, N	Longitude, E	Distance, km	I, MSK-64	I, EMS-98
1	Kudara	52.22	106.66	16	VI–VII	VI
2	Dubinino	52.30	106.76	13	VI	VI
3	Bolshoye Kolesovo	52.11	106.54	28	VI	VI
4	Posolskoye	52.02	106.19	47	VI	VI
5	Korsakovo	52.25	106.62	12	V–VI	V
6	Oymur	52.33	106.84	16	V–VI	V
7	Dulan	52.38	106.88	19	V–VI	V
8	Kamensk	51.98	106.58	42	V–VI	V
9	Shigayevo	52.18	106.47	22	V	V
10	Tvorogovo	52.17	106.48	22	V	V
11	Handala	52.11	106.71	28	V	V
12	Kargino	52.09	106.60	30	V	V
13	Kabansk	52.05	106.65	35	V	V
14	Sukhaya	52.54	107.11	40	V	V
15	Yelan'	51.98	106.68	42	V	V
16	Selenginsk	52.01	106.86	43	V	V
17	Tyrgan	52.76	106.34	47	V	V
18	Yelantsy	52.80	106.41	51	V	V
19	Il'inka	52.12	107.27	53	V	V
20	Bolshoye Goloustnoye	52.04	105.41	88	V	V
21	Kuitun	51.53	107.75	121	V	V
22	Angarskiye Khutora	51.93	104.78	133	V	V
23	Tankhoy	51.55	105.12	135	V	V
24	Zelenyy Sad	52.27	104.57	138	V	V
25	Pervomaisky	52.26	104.47	145	V	V
26	Milovidy	52.28	104.42	148	V	V
27	Khomutovo	52.47	104.40	149	V	V
28	Dzerzhinsk	52.28	104.39	150	V	IV
29	Irkutsk	52.27	104.33	154	V	V
30	Markova	52.22	104.21	163	V	V
31	Ust'-Kuda	52.43	104.14	167	V	V
32	Shelekhov	52.21	104.10	171	V	V
33	Angarsk	52.54	103.89	185	V	V
34	Usol'ye-Sibirskoye	52.75	103.65	204	V	V
35	Belorechenskiy	52.81	103.53	213	V	V
36	Seredkina	53.44	103.40	245	V	V
37	Cheremkhovo	53.16	103.07	253	V	V
38	Inkino	52.28	106.73	12	IV–V	IV
39	Novaya Derevnya	52.16	106.61	22	IV–V	IV
40	Zarechiye	52.55	107.15	43	IV–V	V
41	Tataurovo	52.14	107.44	62	IV–V	IV
42	Turuntayevo	52.20	107.64	73	IV–V	IV
43	Ulan-Ude	51.83	107.62	91	IV–V	IV–V
44	Nizhniy Sayantuy	51.74	107.52	93	IV–V	IV–V

Table 3 (continued)

No	IDP	Latitude, N	Longitude, E	Distance, km	I, MSK-64	I, EMS-98
45	Gusinoozersk	51.28	106.50	120	IV–V	IV–V
46	Dobrolet	52.25	104.83	121	IV–V	IV
47	Zaigrayevo	51.83	108.27	128	IV–V	IV–V
48	Revyakina	52.59	104.63	136	IV–V	IV
49	Khudyakova	52.27	104.58	137	IV–V	IV
50	Khimik	52.28	104.54	140	IV–V	IV–V
51	Sosnovyy Bor	52.66	104.50	145	IV–V	IV–V
52	Kalinovka	51.28	107.79	145	IV–V	IV–V
53	Pivovarikha	52.27	104.45	146	IV–V	IV–V
54	Oyok	52.59	104.46	147	IV–V	IV–V
55	Malaya Topka	52.35	104.32	155	IV–V	IV–V
56	Karluk	52.42	104.30	156	IV–V	IV
57	Granovshchina	52.46	104.29	157	IV–V	V
58	Urik	52.46	104.25	160	IV–V	IV
59	Shiryayeva	52.55	104.22	162	IV–V	IV–V
60	Mamony	52.31	104.18	164	IV–V	IV–V
61	Smolenshchina	52.26	104.13	168	IV–V	IV–V
62	Mukhorshibir	51.05	107.83	168	IV–V	IV–V
63	Maksimovshchina	52.27	104.11	169	IV–V	IV–V
64	Sagan-Nur	51.34	108.44	170	IV–V	IV–V
65	Zuy	52.46	104.05	173	IV–V	IV
66	Baklashi	52.23	104.05	174	IV–V	IV–V
67	Vvedenshchina	52.21	103.95	181	IV–V	IV
68	Chistyye Klyuchi	52.18	103.95	181	IV–V	IV
69	Kachug	53.96	105.88	184	IV–V	IV–V
70	Zvezdnyy	52.44	103.74	194	IV–V	IV
71	Bokhan	53.16	103.77	210	IV–V	IV
72	Sredniy	52.89	103.49	217	IV–V	IV–V
73	Usol'ye-7	52.90	103.29	231	IV–V	IV–V
74	Svirsk	53.09	103.33	234	IV–V	IV–V
75	Zabituy	53.28	102.83	273	IV–V	IV–V
76	Sherashovo	52.26	106.70	13	IV	IV
77	Shergino	52.11	106.74	29	IV	IV
78	Fofonovo	52.05	106.75	36	IV	IV
79	Talovka	52.11	107.07	42	IV	IV
80	Troitskoye	52.12	107.18	47	IV	IV
81	Yelovka	52.06	107.47	68	IV	IV
82	Sukhoy Ruchey	51.81	106.02	73	IV	IV
83	Gurulba	51.82	107.41	81	IV	IV
84	Sarma	53.10	106.83	84	IV	IV
85	Babushkin	51.71	105.86	88	IV	IV
86	Kharantsy	53.22	107.42	110	IV	IV
87	Nikolayevskiy	51.65	107.80	114	IV	IV
88	Listvyanka	51.86	104.86	131	IV	IV

Table 3 (continued)

No	IDP	Latitude, N	Longitude, E	Distance, km	I, MSK-64	I, EMS-98
89	Bozoy	52.93	104.85	134	IV	IV
90	Baikal	51.87	104.81	134	IV	IV
91	Ust-Ordynskiy	52.80	104.75	134	IV	IV
92	Bolshaya Rechka	51.95	104.74	135	IV	IV
93	Metallurg	52.16	104.58	139	IV	IV
94	Novolisikha	52.24	104.45	146	IV	IV
95	Zhavoronki	52.18	104.47	146	IV	IV
96	Molodezhnyy	52.24	104.42	149	IV	IV
97	Kuda	52.44	104.40	149	IV	IV
98	Pad' Melnichnaya	52.16	104.38	152	IV	IV
99	Onguren	53.64	107.59	156	IV	IV
100	Potentsial	52.14	104.32	157	IV	IV
101	Biryusinka	52.17	104.31	157	IV	IV
102	Nadezhda	52.19	104.30	157	IV	IV
103	Lavrentievo	52.15	104.30	158	IV	IV
104	Novoye	52.20	104.28	158	IV	IV
105	Ekspress	52.17	104.28	159	IV	IV
106	Prometey	52.19	104.26	160	IV	IV
107	Izumrud	52.17	104.26	160	IV	IV
108	Olkha	52.16	104.11	170	IV	IV
109	Meget	52.42	104.05	173	IV	IV
110	Golubyye Yeli	52.14	104.07	174	IV	IV
111	Baikalsk	51.51	104.15	193	IV	IV
112	Petrovsk-Zabaykalskiy	51.28	108.83	194	IV	IV
113	Utulik	51.54	104.06	196	IV	IV
114	Telma	52.70	103.71	199	IV	IV
115	Kultuk	51.72	103.70	211	IV	IV
116	Slyudyanka	51.66	103.71	212	IV	IV
117	Novomaltinsk	52.87	103.55	213	IV	IV
118	Ozernyy	52.71	103.45	216	IV	IV
119	Mikhaylovka	52.96	103.28	233	IV	IV
120	Ulekchin	50.47	104.30	263	IV	IV
121	Tabarsuk	53.43	102.91	274	IV	IV
122	Kutulik	53.35	102.78	278	IV	IV
123	Zhigalovo	54.81	105.16	288	IV	IV
124	Bagantuy	53.59	102.64	298	IV	IV
125	Zalari	53.56	102.51	304	IV	IV
126	Zakamensk	50.37	103.29	318	IV	IV
127	Zima	53.93	102.04	350	IV	IV
128	Burinskaya Dacha	54.07	102.14	352	IV	IV
129	Sayansk	54.11	102.18	352	IV	IV
130	Nizhneudinsk	54.90	99.03	572	III–IV	III–IV
131	Barguzin	53.62	109.63	246	III–IV	III–IV
132	Uro	53.55	109.84	254	III–IV	III–IV

Table 3 (continued)

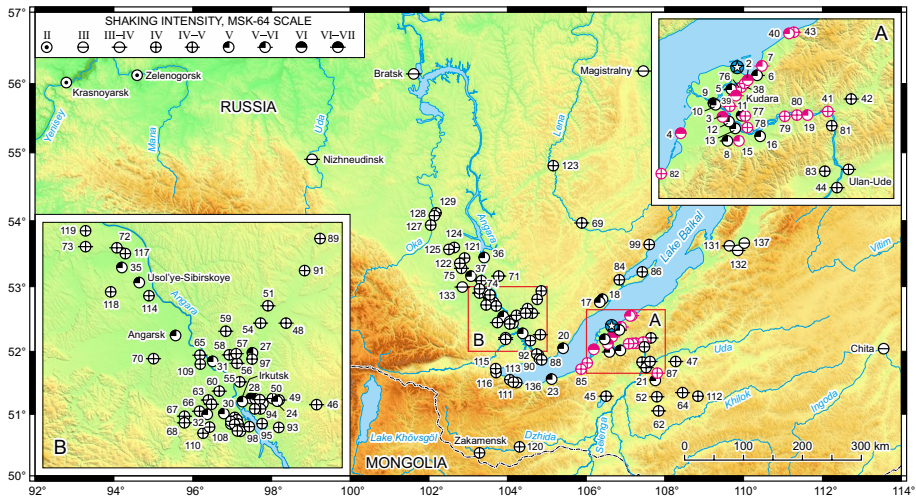| No	IDP	Latitude, N	Longitude, E	Distance, km	I, MSK-64	I, EMS-98
133	Parfenovo	52.99	102.85	262	III–IV	III–IV
134	Magistralnyy	56.17	107.45	427	III–IV	III–IV
135	Bratsk	56.13	101.61	529	III–IV	III
136	Solzan	51.50	104.23	188	III	III
137	Suvo	53.66	110.01	269	III	III
138	Chita	52.03	113.55	474	III	II
139	Zelenogorsk	56.11	94.59	882	II	II
140	Krasnoyarsk	56.01	92.79	982	II	II

Fig. 7 The IDPs map of the December 9, 2020 Kudara earthquake. Insets show the epicentral area (1) and the area adjacent to the city of Irkutsk (2) on a larger scale. The settlements for which macroseismic data were collected only through field survey are highlighted in magenta. White star in blue circle denotes the epicenter of the December 9, 2020 Kudara earthquake. The IDPs are numbered in accordance with Table 3

account the limited initial macroseismic data, the intensity assessment (II MSK-64/EMS-98) in Krasnoyarsk might be considered as uncertain. On the other hand, the felt effects is confidently confirmed in settlement of Magistralny (425 km), town of Bratsk (530 km), and town of Nizhneudinsk (570 km). Three reports were received from each locality with a detailed description of felt effects, which allows us to assign the intensity III–IV MSK-64/EMS-98.

Despite the fact that the internet-survey covered 120 populated areas within the earthquake perceptibility zone, most of the responses (about 82%) came from large cities of Eastern Siberia, namely, from Ulan-Ude, Irkutsk, Angarsk, Shelekhov and Usol'ye-Sibirskoye. On the one hand, this is quite understandable, since urban areas in Eastern Siberia are characterized by the high concentration of the population: approximately 44% of the population of the Republic of Buryatia lives in Ulan-Ude, while up to 41% of the population of the Irkutsk Region is concentrated in the cities of Irkutsk, Angarsk, Shelekhov and Usol'ye-Sibirskoye. In addition, the high urban population density, combined

with the widespread distribution and availability of the Internet, initially implies a greater number of responses received through the internet questionnaire. On the other hand, earthquake effects in large cities are of particular interest. First, the intensity assessments within urban areas are characterized by much more complete information background and therefore more reliable. Secondly, the high population density, as well as the presence of multi-storey buildings, make the urbanized environment more vulnerable to seismic impact compared to rural areas. Accordingly, a detailed study of all aspects of a relatively strong earthquake in the urban environment is of priority importance.

The most typical diagnostic effects noticed in the mentioned cities as a percentage of the total number of observations are shown in Fig. 8. The earthquake was felt by the absolute majority of residents; from 50 to 80% of respondents experiencing severe fright, but a panic reaction was observed only in very few cases. Most of the eyewitnesses stayed where they were, however, up to 20% of the respondents left their homes. Among the diagnostic effects reflecting the reaction of household objects inside the premises, eyewitnesses most often (up to 60%) mention the rattling of dishes, glass and doors, as well as the shaking and swaying of furniture and strong vibrations of TVs and PC monitors. The mentions of such effects as the displacement and falling of light loose objects, the rocking of wall mirrors, photo frames and paintings reach 40%. The spontaneous slamming of doors and sashes (20%), as well as the moving of doors of wardrobes, swinging of hanging objects, splashing liquid from receptacles and aquariums, is mentioned much less frequently. Some eyewitnesses mention wave-like vibrations of stretch ceilings. The reaction of buildings was expressed mainly in the creak and crackle of the building structure (~40%), as well as in relatively rare cases of shedding of whitewash flakes (~3–15%). The occurrence of cracks in the wall, according to eyewitness reports, are sporadic and rather imply cracking of the plaster.

In 35% of the responses received from Irkutsk, the earthquake is characterized as a strong short shock; 30% of respondents report wave-like vibrations; trembling is mentioned in 20% of responses (Fig. 9). Apparently, long-term and relatively weak wave-like vibrations and trembling are caused by the passing of P-waves; shaking intensity of these weak vibrations may be estimated as degree II–III. The ensuing strong shock (or a series of shocks) corresponds to the arrival and passage of S-waves, which caused the main part of the macroseismic effect. On the contrary, 48% of the respondents in Ulan-Ude define the character of the earthquake as wave-like vibrations; a sharp jolt or shock was mentioned in only 2% of the responses.

Taking into account the percentage of observations of diagnostic effects mentioned above, the intensity in the cities of Irkutsk, Angarsk, Shelekhov and Usol'ye-Sibirskoye can be estimated as V MSK-64/EMS-98. At the same time, in the city of Ulan-Ude the percentage of observation of almost all diagnostic effects is lower than in other cities. In particular, in Ulan-Ude people reacted to the earthquake noticeably more calmly and, despite the fright experienced, did not leave the premises or did it much more rarely than residents of other large cities. The only exception is shaking and swaying of furniture, although lower threshold of this diagnostic effect corresponds to the intensity IV, as follows from MSK-64 and EMS-98 scales. Thus, we can estimate the intensity in Ulan-Ude as IV–V MSK-64/EMS-98.

The use of internet questionnaire made it possible to obtain reliable macroseismic data for five large cities of Eastern Siberia. Seismic stations are located only in two of these cities—Irkutsk and Ulan-Ude, which allows us to compare instrumental and macroseismic estimates of the intensity. Such a comparison makes practical sense, since macroseismic data on strong earthquakes still play an important role in the work on the seismic zoning of
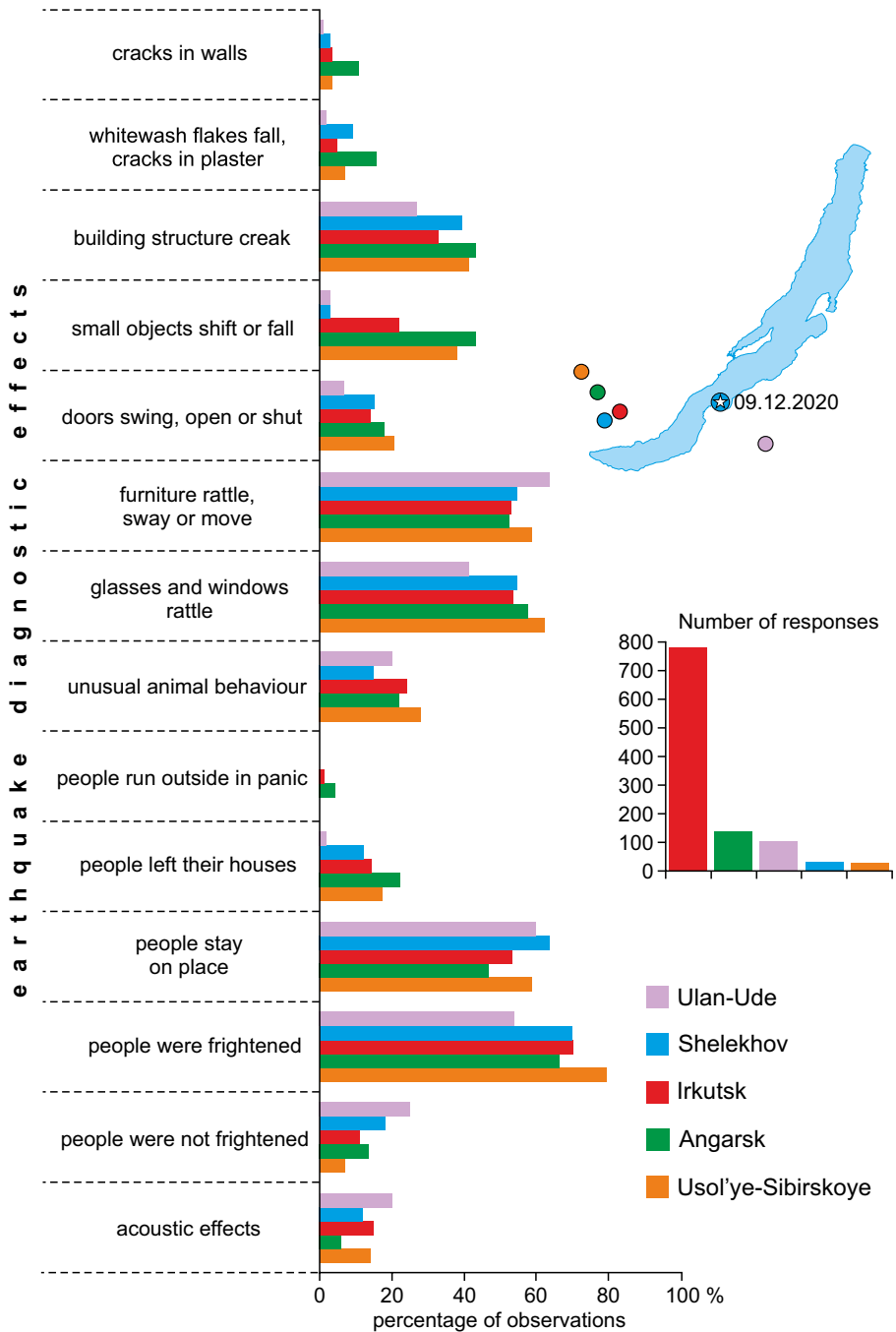
Fig. 8 The most typical diagnostic effects observed in large cities of the Southern Baikal region. White star in blue circle denotes the epicenter of the December 9, 2020 Kudara earthquake
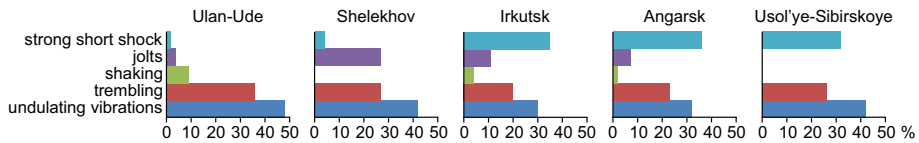
Fig. 9 Perceptible effects of the Kudara earthquake as described by eyewitnesses in large cities of the Southern Baikal region

the territory of the Baikal region. Accordingly, the seismic hazard of the Baikal region is assessed in degrees of the seismic intensity scale (Ulomov 2014), and a conversion (at least approximate) of macroseismic intensity into parameters of strong ground motion requires reliable correlation dependences. Moreover, number of seismic stations in the Baikal region is relatively small, while their spatial distribution is rather uneven. Seismic stations are concentrated mainly in the immediate vicinity of the rift zone. Thus, there are no direct measurements of peak ground velocities (PGV) and peak ground accelerations (PGA) in areas remote from the main seismically active zones. Thus, there is a clear lack of strong ground motion data. Meanwhile, the development of correlation equations requires a large number of data pairs "ground motion—macroseismic intensity". For this reason, any reliable estimates of the macroseismic intensity for locations where instrumental records of strong ground motion are also available are considered a valuable addition to the existing data set.

The peak ground acceleration recorded at the IRK seismic station was 34.5 cm/s^2 (NS horizontal component) (Fig. 10). This value, according to the instrumental part of the MMSK-92 intensity scale (Shebalin and Aptikaev 2003), corresponds to the instrumental intensity 6. At the same time, the maximum PGA has a very short duration, as it is clearly seen on the waveform. A waveform fragment with PGA corresponding to the instrumental intensity 5 MMSK-92 is characterized by a significantly longer duration (up to 4.5 s). So, we can see a good accordance between the intensity assessment from both instrumental and macroseismic data in Irkutsk (V MSK-64/EMS-98).

The correlation between instrumental and macroseismic data in the city of Ulan-Ude is not quite so good as in city of Irkutsk. According to the accelerogram of the UUDB station, the maximum PGA registered on EW horizontal component is only 1.97 cm/s^2. This PGA corresponds to the instrumental intensity 3 MMSK-92, while the duration of oscillations with a maximum amplitude is extremely short. Based on the recorded PGA values, the expected instrumental intensity in Ulan-Ude would be 2–3 MMSK-92, while the macroseismic data allow intensity assessment as IV–V MSK-64/EMS-98.

It is also very interesting to test the applicability of the global relations linking the macroseismic intensity and the peak ground motions for the Southern Baikal region. We use, in particular, the equation by Caprio et al. (2015):

$$I = 2.270 + 1.647 Lg(\text{PGA}), \quad \text{if } Lg(\text{PGA}) \leq 1.6 \tag{2}$$

where I is intensity, PGA is peak ground acceleration.

The Fig. 10 shows that the observed intensity both in Irkutsk and Ulan-Ude is significantly higher (by degree I–II) than can be expected from the Eq. (2) (Caprio et al. 2015) and the recorded PGA values. It should be noted that Caprio et al. (2015) used only those points with both macroseismic and instrumental data, the distance between which did not exceed two kilometers. The UUDB seismic station is located more than two kilometers from the
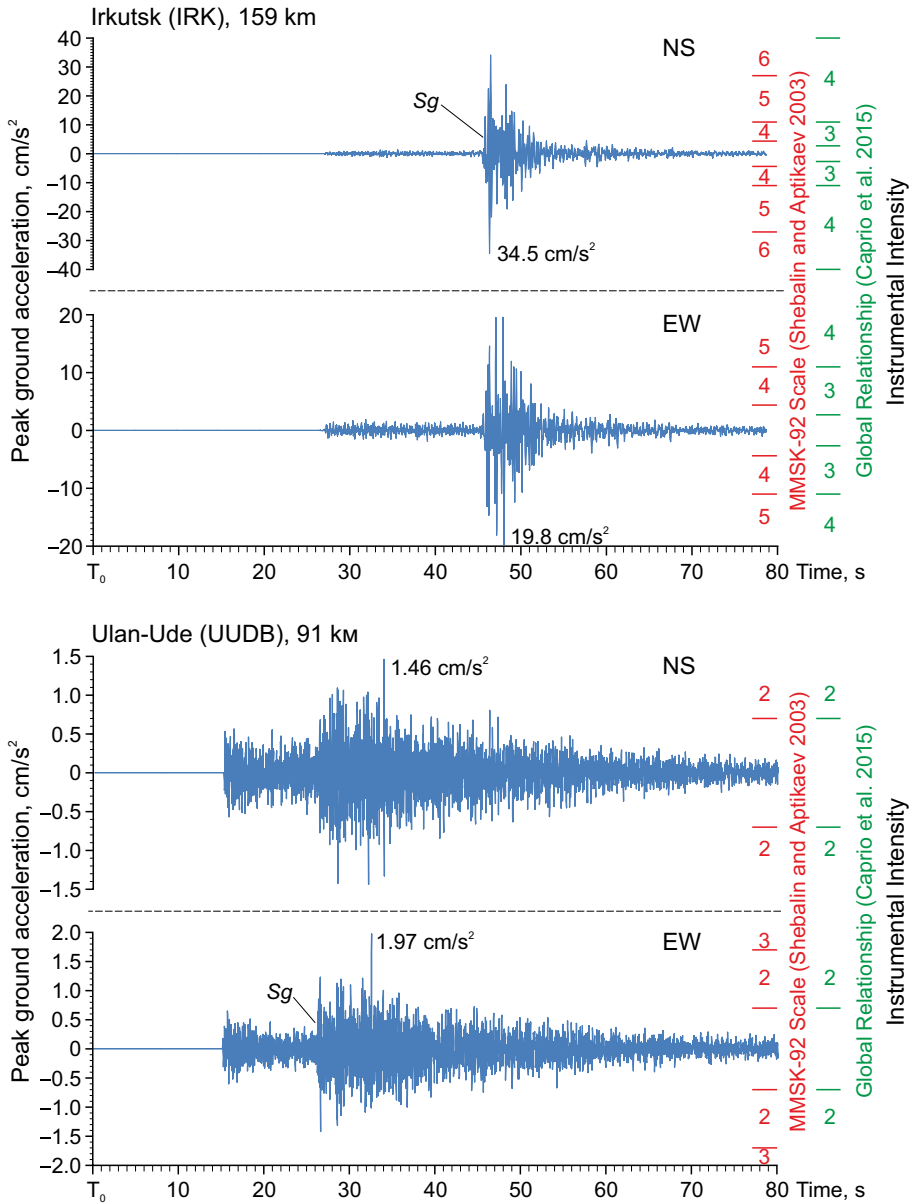
Fig. 10 The peak ground accelerations at the seismic stations Irkutsk (IRK) and Ulan-Ude (UUDB). The instrumental intensity according to the MMSK-92 scale (Shebalin and Aptikaev 2003) and global relation (Caprio et al. 2015) are shown in red and green, respectively

main part of the city of Ulan-Ude, where reliable macroseismic data were obtained. Perhaps for this reason, the equation by Caprio et al. (2015) is not entirely applicable in this case. The sharp discrepancy between macroseismic and instrumental intensity estimates in Ulan-Ude can also be explained by significant differences in the ground conditions of the main part of the city and the location of the UUDB seismic station (Dzhurik et al. 2015).

The IRK seismic station is located directly within the densely populated residential area of city of Irkutsk form where a fairly large amount of macroseismic data was obtained within a radius of 2 km. The intensity in city of Irkutsk as a whole is assessed as V MSK-64/EMS-98; this assessment fully applies to the area where the IRK seismic station is located. According to Eq. (2) (Caprio et al. 2015), the PGA value of 34.5 cm/s^2 corresponds to a shaking intensity of degree 4. Thus, the assessment of the instrumental intensity using the global relation (2) in the conditions of the Southern Baikal region may lead to a somewhat underestimated value. Obviously, the development of a reliable regional equation requires further accumulation of both strong ground motions records and reliable macroseismic data to statistically significant volumes.

5 Discussion

The IDPs map of the December 9, 2020 Kudara earthquake (see Fig. 7) demonstrates the predominant propagation of moderate intensity mainly to the northwest of the epicenter. However, such intensity distribution pattern poorly corresponds to the regional macroseismic equation linking the intensity, magnitude, and hypocentral distance. Currently, the equation suggested by Shebalin (1972) is used for the territory of the Baikal region:

$$I = bM - vLg\sqrt{\Delta^2 + h^2} + c \tag{3}$$

 where I is the intensity; M is the magnitude; Δ is the epicentral distance; h is the hypocenter depth; b, v and c are regional coefficients equal to 1.5, 4.0 and 4.0, respectively (Kondorskaya and Shebalin 1982). Taking into account the parameters of the earthquake (M_w 5.5, $h = 20$ km) and using the Eq. (3), we can expect the intensity V at distances of no more than 60 km. At the same time, the intensity V was observed at distances of up to four times larger than expected (Fig. 11). The same could be said about the spatial distribution of IDPs where intensity were assessed as IV.

Such a configuration of the macroseismic field may be partially caused by the peculiarities of the Eastern Siberia population distribution. Figure 12 shows the distribution of settlements in Eastern Siberia. These settlements differ noticeably in terms of population, but the vast majority of them are small villages and hamlets. Populated areas with the status of a city or town and a comparably large population (more than ten thousands) are relatively few. The highest concentration of the settlements and, accordingly, the population is typical for the areas adjacent to the main rivers and transport routes, which, in turn, have a direction similar to the prevailing direction of the perceptible shaking propagation. However, another explanation is also possible. The higher intensity observed in settlements north and northwest of the epicenter could be due to their location within the ancient, tectonically stable Siberian platform. This tectonic structure is characterized by a higher value of seismic quality factor (Q) and a significantly lower seismic waves attenuation if compared to the structures of the Baikal rift zone (Dobrynina et al. 2016). In turn, attenuation largely depends on the geological and geophysical characteristics of the lithosphere (Dobrynina et al. 2011, 2016). Thus, the geological structure and, accordingly, the differences in the parameters of attenuation of seismic waves can be reflected in the intensity distribution within an earthquake perceptibility zone. The Kudara earthquake macroseismic field allows us to consider the seismic waves attenuation in the study area significantly lower than expected from the Eq. (3). The intensity distribution pattern of earthquakes on March 28, 1970 (Golenetskii et al. 1973), May 22, 1981 (Golenetskii et al. 1984), and October
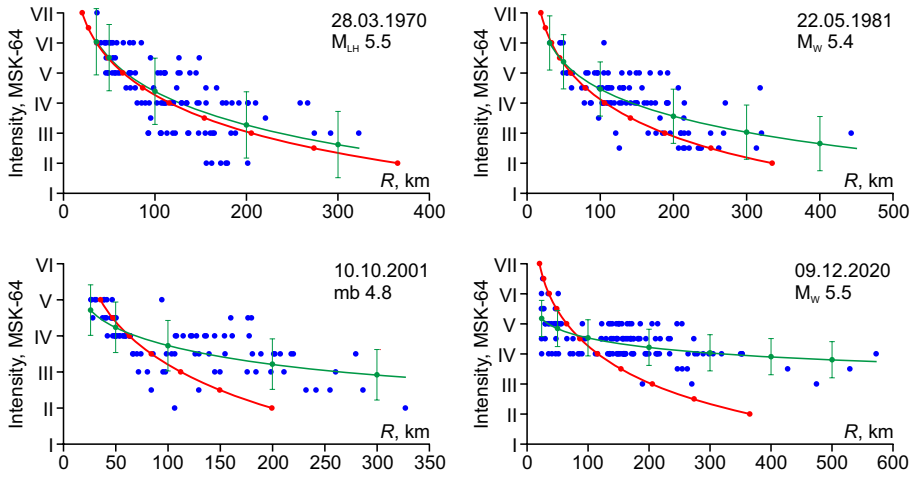
Fig. 11 The intensity attenuation for earthquakes of the Selenga River delta area. Blue dots represent the intensity data points. The red curve is the theoretical intensity attenuation according to Eq. (3). Green curve is the attenuation according to actual data determined by logarithmic approximation with Microsoft Excel software. Errors bars show the standard deviation
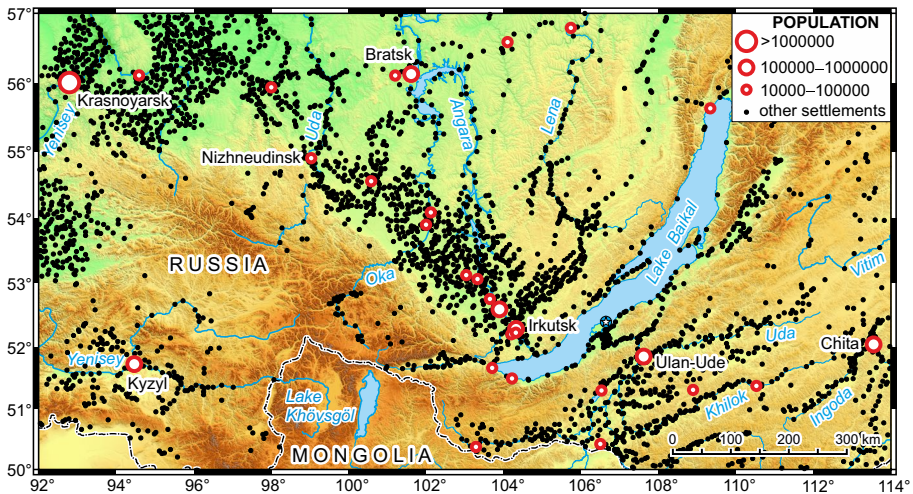

Fig. 12 Distribution of settlements in Eastern Siberia. White circles with red border denote cities or towns; black circles are small villages and hamlets

10, 2001 (Radziminovich et al. 2007) is also confirms this regularity, in no way taken into account in the regional macroseismic equation.

Intensity assessments based on the MSK-64 and EMS-98 scales show quite good agreement (see Table 3). Some differences are noted particularly for uncertain intensity (e.g. IV–V), while the intensities estimated with EMS-98 are slightly lower if compared to MSK-64. The uncertain assessments made using both the MSK-64 and EMS-98 scales are

likely due to insufficiently detailed initial macroseismic data. In such cases, it is extremely difficult to assign a certain intensity, regardless what particular scale is used. In general, a comparison of the intensity assessments performed with the MSK-64 and EMS-98 scales demonstrates the possibility of using the EMS-98 scale in the conditions of Eastern Siberia, and also confirms the previously drawn conclusions about the compatibility of these two scales (Musson et al. 2010; Aptikaev and Erteleva 2017). In turn, this allows us to expect a relatively easy re-evaluation of the previously collected macroseismic data on earthquakes in Eastern Siberia using modern intensity scales.

The effect of increased intensity is most clearly manifested in the city of Irkutsk and its immediate vicinity, as well as in points located in the Angara River valley. This is proved also with macroseismic data on historical seismic events. One of the most illustrative examples is the January 12, 1862, M 7.5 Tsagan earthquake that caused damage to buildings in Irkutsk at epicentral distance of ~170 km (Golenetskii 1996). According to modern point of view, the macroseismic intensity of the Tsagan earthquake in Irkutsk is estimated as VII–VIII MSK-64 (Golenetskii 1996), while the intensity expected from the regional macroseismic equation should not exceed VI–VII. The intensity in Irkutsk higher than one can expect was observed during strong earthquakes on November 26, 1903 (M 6.7) (Voznesenskii 1905), on August 29, 1959 (M 6.8) (Solonenko and Treskov 1960), as well as on July 13, 1993 (mb 4.8) (Golenetskii et al. 1995). The epicenters of all these events were also located in the Selenga River delta.

The increased intensity in Irkutsk can be explained, in particular, by the local site effects. Systematic local amplification within a relatively small area during strong earthquakes is largely believed to be related to the geological structure and the subsoil conditions (Celebi 1987; Bouckovalas and Kouretzis 2001; Sbarra et al. 2012; Burjánek et al. 2014; García-Pérez et al. 2021). The city of Irkutsk is located in the wide valley of the Angara River on its four terraces above the floodplain with Quaternary deposits, represented by alluvial, deluvial and eluvial complexes of more than 10 m thickness. A thick (from 420 to 900 m) stratum of Jurassic deposits (sandstones, mudstones, siltstones) is widespread within the city area (Solonenko 1962). Many parts of the city are characterized by significantly water-saturated ground (Shenkman et al. 2011). Loose Quaternary sediments in combination with water saturation can be considered as one of the possible factors affecting the amplification of macroseismic intensity within Irkutsk as compared to the expected ones according to regional macroseismic Eq. (3). The local amplification, apparently, is reflected in the instrumental data as well. This effect is evidenced by examples of at least two recent events: October 10, 2001, mb 4.8 Ust'-Selenga earthquake (Radziminovich et al. 2007) and December 9, 2020 M_w 5.5 Kudara earthquake (this study). The PGA recorded at the IRK seismic station (12.2 cm/s^2 in the first case and 34.5 cm/s^2 in the second) correspond to instrumental intensity 5 and 6 MMSK-92 (Shebalin and Aptikaev 2003), while the observed intensity is IV–V MSK-64 and V MSK-64/EMS-98, respectively. It should be noted that our knowledge of site effects within Irkutsk is far from sufficient for practical application in seismic hazard assessing. This issue requires further detailed research using a dense network of accelerometers installed in areas with different subsoil conditions and a well-studied geological structure.

The Kudara earthquake made it possible to test the internet questionnaire on an example of comparatively strong earthquake. Its use allowed us to get almost 1500 reports of earthquake perceive effects from 120 populated areas in Eastern Siberia in a quite short time. The internet questionnaire is as good as traditional methods, such as paper questionnaire posting or field survey, in terms of the number of settlements covered by the survey, and far exceeds them in terms of the number of responses received. We can consider the achieved

result as an evidence of the quite high efficiency of internet questionnaire, especially taking into account the fact that the number of responses previously did not exceed 500–600. Obviously, by the time of the Kudara earthquake, the interest of the Baikal region residents in the actual seismological information had significantly increased.

Along with the undoubted efficiency of the internet questionnaire, it is necessary to note some of its limitations. Proceeding from the fact that the Kudara earthquake was definitely felt at distances over 500 km, we could expect to obtain responses from a much larger number of settlements, including the small ones far from the epicenter. Actually, the bulk of the responses came from large cities and suburbs; settlements located in countryside account for less than 20% of all responses. Moreover, the epicentral area (Selenga River delta) is a relatively densely populated rural area with a large number of settlements. Taking into account the strong macroseismic effects, including light damage to buildings within the near-field (intensity VI–VII MSK-64/EMS-68), we could expect a wider public response, but as a result we received very few responses from single settlements.

There are may be several reasons for such apparent imbalance. The small number of responses may be partly due to the low population density in rural areas, but we can hardly consider this explanation as the only possible one. A more important role, in our opinion, is played by the differences between urban and rural residents in lifestyle and interests. In the urban environment, earthquakes are more perceptible due to the presence of multistory buildings; thus, more people get quite vivid impressions and begin to take an interest in what is happening, including the scientific side of the event. Boatwright and Phillips (2017) when analyzing the "Did You Feel It?" internet questionnaire system on the example of California, has suggested that the experience of a felt earthquake stimulates eyewitnesses to share their own observations with seismologists. This conclusion applies to comparatively prosperous regions, but in areas with sharp socioeconomic contrasts, the situation may look completely different. Hough and Martin (2021), using the example of India, have convincingly shown that the interest of earthquake eyewitnesses in providing information is influenced by many factors, mostly the incomes and educational level. Comparative analysis of "Did You Feel It?" efficiency in the United States and India showed a fairly even distribution of responses among different population groups in California, while in India there is a sharp prevalence of responses from urban residents (Hough and Martin 2021). In the case of the Kudara earthquake we can see approximately the same situation. Inhabitants of rural areas of Eastern Siberia often are not interested or do not find it necessary to provide any useful information about an earthquake to Geophysical Survey; official inquiries in many cases are also ignored. The rural population is more interested in the problems of everyday life; relatively rare felt earthquakes remain for many people in rural areas just an episode that is not given much importance. That means, the further the settlement is located from the regional administrative center, the less chances we have for obtaining representative macroseismic data. This is also confirmed by the low efficiency of sending out questionnaires via regular post practiced in the Baikal region up to the present: responses are received, as usual, for no more than 50% of official inquiries that have been sent to rural settlements administration.

The awareness of population about existence of specialized seismological web-sites, where people can get up-to-date information and share their own impressions is also play a certain role. Residents of large cities are much better informed through the coverage of seismic events in the city mass-media. It should be noted that access to the broadband Internet (up to 4G) is currently not a problem in Eastern Siberia due to widespread of mobile communications. As it follows from (Nagirnaya 2015), as of 2013, there are 71.6 mobile Internet users per 100 people in Eastern Siberia. Because of that, in theory, we could expect the

receive responses from almost any point in the Baikal region. In fact, however, we need further efforts to explain the importance of sharing of macroseismic data to population with the aim to significantly increase the number of responses in nearest future.

Another limitation of the internet questionnaire is lack of responses from populated areas where earthquake was not felt. As a rule, we can obtain eyewitness responses only from settlements where an earthquake was clearly noticeable and caused at least a small public interest. Places where the earthquake was not felt or was so weak that it have not cause a reaction from people, basically remain outside the web-survey. In the conditions of Eastern Siberia, this limitation is reinforced by the extremely unbalanced distribution of settlements over the territory. Most of the populated areas are along rivers and transport routes. Thus, vast areas remain sparsely populated and possibility of obtaining any macroseismic information from those places is very small.

The lack of information about the localities where the earthquake was either not felt or weak (intensity II–III) does not allow us to confidently assess the entire perceptibility zone. Boatwright and Phillips (2017), using the example of California, suggested to consider populated areas from where were no received any responses as those where earthquake was not felt. This approach is justified in case when the majority of citizens understand necessity and importance of providing their observations to seismologists. However, as mentioned above, in many parts of the world, interest of the population in "citizen science" remains very low (especially in rural areas).

6 Conclusions

The M_w 5.5 December 9, 2020 Kudara earthquake that occurred in Selenga River delta is being the strongest seismic event in study area for the last 50 years. The maximum observed intensity is assessed as VI–VII MSK-64 or VI EMS-98 scale; the earthquake caused minor damage to buildings in the near-field. The earthquake was clearly felt at epicentral distances over 500 km; very weak shakings were noted at a distance of up to 980 km.

The earthquake occurred early in the morning local time, caused strong fright to eyewitnesses, especially among residents of large cities, and provoked a wide response in the mass-media and social networks, which to some extent increased the fear in society. Acute reaction, as well as a long-term feeling of fear and uncertainty among eyewitnesses, allow us to make a conclusion that people in Southern Baikal region aren't ready to natural emergencies.

The seismic intensity recorded in city of Irkutsk and its vicinity (V MSK-64/EMS-98) was anomalously high if compared with the one expected from the regional macroseismic equation. A similar anomaly, revealed with macroseismic data, was repeatedly observed during strong earthquakes with epicenters in the Selenga River delta area. In the case of the Kudara earthquake, the presence of a local amplification effect in Irkutsk is independently confirmed by instrumental data.

The December 9, 2020 earthquake can be considered as one of the very few seismic events that allowed testing the internet questionnaire of Baikal Branch of GS RAS under stressful conditions. The results of using of the internet questionnaire mainly met our expectations and confirmed its rather high efficiency in the conditions of the Baikal region in comparison with traditional methods of macroseismic data collection. In particular, much more homogeneous macroseismic data were obtained, if compared with past times. At the same time, the analysis of the obtained data made it possible to reveal

some limitations of the internet questionnaire use, which can significantly affect the overall assessment of macroseismic field of strong earthquakes. The experience gained will be useful for further improving the online tool for macroseismic data collection as well as the data quality in the Baikal region.

Author contributions All authors contributed to the study conception. Material preparation, data collection and analysis were performed by YBR, NAG, TAT, OFL, AVN, and LRT. The first draft of the manuscript was written by YBR and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Availability of data and material The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

References

Ahmadzadeh S, Doloei GJ, Zafarani H (2020) Ground motion to intensity conversion equations for Iran. Pure Appl Geophys 177:5435–5449. https://doi.org/10.1007/s00024-020-02586-x

Aptikaev FF, Erteleva OO (2017) A new generation Russian seismic scale. Seismic Instruments 53:146–154. https://doi.org/10.3103/S0747923917020025

Aptikaev FF, Mokrushina NG, Erteleva OO (2008) The Mercalli family of seismic intensity scales. J Volcanol Seismol 2:210–213. https://doi.org/10.1134/S0742046308030081

Ardeleanu L, Neagoe C, Ionescu C (2020) Empirical relationships between macroseimic intensity and instrumental ground motion parameters for the intermediate-depth earthquakes of Vrancea region, Romania. Nat Hazards 103:2021–2043. https://doi.org/10.1007/s11069-020-04070-0

Atkinson GM, Wald DJ (2007) "Did You Feel It?" intensity data: a surprisingly good measure of earthquake ground motion. Seismol Res Lett 78:362–368. https://doi.org/10.1785/gssrl.78.3.362

Boatwright J, Phillips E (2017) Exploiting the demographics of "Did You Feel It?" responses to estimate the felt area of moderate earthquakes in California. Seismol Res Lett 88:335–341. https://doi.org/10.1785/0220160041

Bossu R, Laurin M, Mazet-Roux G, Roussel F, Steed R (2015) The importance of smartphones as public earthquake-information tools and tools for the rapid engagement with eyewitnesses: a case study of the 2015 Nepal earthquake sequence. Seismol Res Lett 86:1587–1592. https://doi.org/10.1785/0220150147

Bossu R, Landès M, Roussel F, Steed R, Mazet-Roux G, Martin SS, Hough S (2017) Thumbnail-based questionnaires for the rapid and efficient collection of macroseismic data from global earthquakes. Seismol Res Lett 88:72–81. https://doi.org/10.1785/0220160120

Bouckovalas GD, Kouretzis GP (2001) Stiff soil amplification effects in the 7 September 1999 Athens (Greece) earthquake. Soil Dyn Earthq Eng 21:671–687. https://doi.org/10.1016/S0267-7261(01)00045-8

Burjánek J, Edwards B, Fäh D (2014) Empirical evidence of local seismic effects at sites with pronounced topography: a systematic approach. Geophys J Int 197:608–619. https://doi.org/10.1093/gji/ggu014

Buslov MM (2012) Geodynamic nature of the Baikal Rift Zone and its sedimentary filling in the Cretaceous–Cenozoic: the effect of the far-range impact of the Mongolo-Okhotsk and Indo-Eurasian collisions. Russ Geol Geophys 53:955–962. https://doi.org/10.1016/j.rgg.2012.07.010

Calais E, Vergnolle M, San'kov V, Lukhnev A, Miroshnitchenko A, Amarjargal S, Déverchère J, (2003) GPS measurements of crustal deformation in the Baikal-Mongolia area (1994–2002): implications for current kinematics of Asia. J Geophys Res Solid Earth 108:2501. https://doi.org/10.1029/2002JB002373

Caprio M, Tarigan B, Worden CB, Wiemer S, Wald DJ (2015) Ground motion to intensity conversion equations (GMICEs): a global relationship and evaluation of regional dependency. Bull Seismol Soc Am 105:1476–1490. https://doi.org/10.1785/0120140286

Celebi M (1987) Topographical and geological amplifications determined from strong-motion and aftershock records of the 3 March 1985 Chile earthquake. Bull Seismol Soc Am 77:1147–1167. https://doi.org/10.1785/BSSA0770041147

Dobrynina AA, Chechel'nitskii VV, San'kov VA (2011) Seismic quality factor of the lithosphere of the southwestern flank of the Baikal rift system. Russ Geol Geophys 52:555–564. https://doi.org/10.1016/j.rgg.2011.04.008

Dobrynina AA, Sankov VA, Chechelnitsky VV, Déverchère J (2016) Spatial changes of seismic attenuation and multiscale geological heterogeneity in the Baikal Rift and surroundings from analysis of coda waves. Tectonophysics 675:50–68. https://doi.org/10.1016/j.tecto.2016.03.010

Du K, Ding B, Luo H, Sun J (2019) Relationship between peak ground acceleration, peak ground velocity, and macroseismic intensity in Western China. Bull Seismol Soc Am 109:284–297. https://doi.org/10.1785/0120180216

Dzhurik VI, TsA T, Serebrennikov SP, Drennov AF, Bryzhak EV, Eskin AY (2015) An overview of the technique for seismicity microzonation mapping of the Ulan-Ude city territory. Geodyn Tectonophys 6:365–386. https://doi.org/10.5800/GT-2015-6-3-0186

García-Pérez T, Ferreira AM, Yáñez G, Iturrieta P, Cembrano J (2021) Effects of topography and basins on seismic wave amplification: the Northern Chile coastal cliff and intramountainous basins. Geophys J Int 227:1143–1167. https://doi.org/10.1093/gji/ggab259

Golenetskii SI (1996) Macroseismic effects of the catastrophic Tsagan, Baikal Earthquake of 1862. Izv Phys Solid Earth 32:849–858

Golenetskii SI, Dem'yanovich MG, Fomina EV, Chipizubov AV, Avdeev VA, Kochetkov VM (1984) The May 22 and 27, 1981 earthquakes at Lake Baikal. In: Kondorskaya NV (ed) Earthquakes in the USSR in 1981. Nauka Publishing House, Moscow, pp 66–74 (in Russian)

Golenetskii SI, Bukina KI, Novomeiskaya FV, Fomina EV, Perevalova GI, Anisimova LV, Mylnikova GL, Tretyak EA, Khromovskikh VS, Kurushin RA, Demyanovich MG, Nikolaev VV (1973) Earthquakes of the Baikal Region. In: Vvedenskaya NA, Kondorskaya NV, Shebalin NV (eds) Earthquakes in the USSR in 1970. Nauka Publishing House, Moscow, pp 124–146 (in Russian)

Golenetskii SI, Ruzhich VV, Drennova GF, Emelyanova IA (1995) Felt and strong earthquakes within the Selenga River delta and the shock of July 13, 1993. Volcanol Seismol (vulkanologiya i Seismologiya) 4–5:215–223 (in Russian)

Goltz JD, Park H, Nakano G, Yamori K (2020) Earthquake ground motion and human behavior: Using DYFI data to assess behavioral response to earthquakes. Earthq Spectra 36:1231–1253. https://doi.org/10.1177/8755293019899958

Gomez-Capera AA, D'Amico M, Lanzano G, Locati M, Santulin M (2020) Relationships between ground motion parameters and macroseismic intensity for Italy. Bull Earthq Eng 18:5143–5164. https://doi.org/10.1007/s10518-020-00905-0

Grünthal G (1998) European macroseismic scale 1998 (EMS-98). Cahiers Du Centre Européen De Géodynamique Et De Séismologie Luxembourg 15:1–99

Hough SE (2012) Initial assessment of the intensity distribution of the 2011 Mw 5.8 Mineral, Virginia, earthquake. Seismol Res Lett 83:649–657. https://doi.org/10.1785/0220110140

Hough SE, Martin SS (2021) Which earthquake accounts matter? Seismol Res Lett 92:1069–1084. https://doi.org/10.1785/0220200366

Kuz'mina EA, Novopashina AV (2018) Groundwater outflows and fault density spatial relation in the Baikal rift system (Russia). Acque Sotterranee Italian J Groundwater 7:19–27. https://doi.org/10.7343/as-2018-317

Lesueur C, Cara M, Scotti O, Schlupp A, Sira C (2013) Linking ground motion measurements and macroseismic observations in France: a case study based on accelerometric and macroseismic databases. J Seismol 17:313–333. https://doi.org/10.1007/s1095001293192

Levi KG, Miroshnichenko AI, San'kov VA, Babushkin SM, Larkin GV, Badardinov AA, Wong HK, Colman S, Delvaux D (1997) Active faults of the Baikal depression. Bull Cent Rech Explor Prod Elf-Aquitaine 21:399–434

Locati M, Capera AA, Puglia R, Santulin M (2017) Rosetta, a tool for linking accelerometric recordings and macroseismic observations: description and applications. Bull Earthq Eng 15:2429–2443. https://doi.org/10.1007/s10518-016-9955-y

Logachev NA (2001) Historic core of the Baikal rift zone. Dokl Earth Sci 376:43–46

Logachev NA (2003) History and geodynamic of the Baikal rift. Russ Geol Geophys 44:391–406

Logatchev NA, Zorin YA (1987) Evidence and causes of the two-stage development of the Baikal rift. Tectonophysics 143:225–234. https://doi.org/10.1016/0040-1951(87)90092

Logatchev NA, Zorin YA (1992) Baikal rift zone: structure and geodynamics. Tectonophysics 208:273–286. https://doi.org/10.1016/0040-1951(92)90349-B

Lukhnev AV, San'kov VA, Miroshnichenko AI, Ashurkov SV, Byzov LM, San'kov AV, Bashkuev YuB, Dembelov MG, Calais E (2013) GPS-measurements of recent crustal deformation in the junction zone of the rift segments in the central Baikal rift system. Russ Geol Geophys 54:1417–1426. https://doi.org/10.1016/j.rgg.2013.10.010

Lukhnev AV, San'kov VA, Miroshnichenko AI, Ashurkov SV, Calais E (2010) GPS rotation and strain rates in the Baikal-Mongolia region. Russ Geol Geophys 51:785–793. https://doi.org/10.1016/j.rgg.2010.06.006

Lukhnev AV, Sankov VA, Miroshnichenko AI, Sankov AV, Byzov LM (2021) Tectonic deformations and subsequent seismic events in the southwestern flank of the Baikal rift system based on GPS data. Dokl Earth Sci 500:756–760. https://doi.org/10.1134/S1028334X21090130

Lunina OV (2016) The digital map of the Pliocene-Quaternary crustal faults in the southern East Siberia and the adjacent Northern Mongolia. Geodyn Tectonophys 7:407–434. https://doi.org/10.5800/GT-2016-7-3-0215

Mats VD (2012) The sedimentary fill of the Baikal Basin: Implications for rifting age and geodynamics. Russ Geol Geophys 53:936–954. https://doi.org/10.1016/j.rgg.2012.07.009

Medvedev SV, Sponheuer W, Karnik V (1965) Seismic intensity scale version MSK 1964. Academy of Sciences of the USSR, Soviet Geophysical Committee, Moscow

Mel'nikova VI, Gileva NA, Radziminovich NA, Masal'skii OK, Chechel'nitskii VV (2010) Seismicity of the Baikal rift zone for the digital recording period of earthquake observation (2001–2006). Seismic Instruments 46:193–206. https://doi.org/10.3103/S0747923910020076

Mel'nikova VI, Radziminovich NA (2007) Parameters of seismotectonic deformations of the Earth's crust in the Baikal rift zone based on seismological data. Dokl Earth Sci 416:1137–1139. https://doi.org/10.1134/S1028334X07070355

Mordvinova VV, Kobelev MM, Treussov AV, Khritova MA, Trynkova DS, Kobeleva EA, Lukhneva OF (2016) Deep structure of the Siberian platform – Central Asian mobile belt transition zone from teleseismic data. Geodyn Tectonophys 7:85–103 (in Russian). https://doi.org/10.5800/GT-2016-7-1-0198

Musson RMW, Grünthal G, Stucchi M (2010) The comparison of macroseismic intensity scales. J Seismol 14:413–428. https://doi.org/10.1007/s10950-009-9172-0

Nagirnaya AV (2015) The Development of the Internet in Russian Regions. Izv Akad Nauk Geogr (2):41–52 (in Russian). https://doi.org/10.15356/0373-2444-2015-2-41-51

Novopashina AV, Lukhneva OF (2020) Methodical approach to isolation of seismic activity migration episodes of the northeastern Baikal rift system (Russia). Episodes 43:947–959. https://doi.org/10.18814/epiiugs/2020/020058

Novopashina AV, Lukhneva OF (2021) The propagation velocity of seismic activity migrating along the directions of the geodynamic forces prevailing in the northeastern Baikal rift system, Russia. Ann Geophys 64:SE436. https://doi.org/10.4401/ag-8654

Kondorskaya NV, Shebalin NV (eds) (1982) New Catalog of Strong Earthquakes in the USSR from Ancient Times through 1977. World Data Center A, Boulder, USA

Petit C, Déverchère J (2006) Structure and evolution of the Baikal rift: a synthesis. Geochem Geophys Geosyst 7:Q11016. https://doi.org/10.1029/2006GC001265

Quitoriano V, Wald DJ (2020) USGS "Did You Feel It?"—Science and Lessons From 20 Years of Citizen Science-Based Macroseismology. Front Earth Sci 8:120. https://doi.org/10.3389/feart.2020.00120

Radziminovich NA, Gileva NA, Melnikova VI, Ochkovskaya MG (2013) Seismicity of the Baikal rift system from regional network observations. J Asian Earth Sci 62:146–161. https://doi.org/10.1016/j.jseaes.2012.10.029

Radziminovich YB, Khritova MA, Gileva NA (2014) Modern methods for acquisition of macroseismic data and their possible uses for Eastern Siberia. J Volcanol Seismol 8:375–389. https://doi.org/10.1134/S0742046314060062

Radziminovich YB, Seredkina AI, Melnikova VI, Gileva NA (2020) The March 29, 2019 Earthquake in the Western Part of the Tunka Rift Basin System: source parameters and Macroseismic effects. Seismic Instruments 56:648–661. https://doi.org/10.3103/S0747923920060067

Radziminovich YB, Masalsky OK, Ruzhich VV, Tatkov GI, Kustova MG (2007) The October 10, 2001, mb=4.8 Ust-Selenga earthquake (Baikal Region). In: Starovoit OE (ed) Earthquakes of Northern Eurasia in 2001. Geophysical Survey RAS, Obninsk, pp. 345–359 (in Russian)

San'kov VA, Parfeevets AV, Lukhnev AV, Miroshnichenko AI, Ashurkov SV (2011) Late Cenozoic geodynamics and mechanical coupling of crustal and upper mantle deformations in the Mongolia-Siberia mobile area. Geotectonics 45:378–393. https://doi.org/10.1134/S0016852111050049

Sbarra P, Tosi P, De Rubeis V (2010) Web-based macroseismic survey in Italy: Method validation and results. Nat Hazards 54:563–581. https://doi.org/10.1007/s11069-009-9488-7

Sbarra P, De Rubeis V, Di Luzio E, Mancini M, Moscatelli M, Stigliano F, Tosi P, Vallone R (2012) Macroseismic effects highlight site response in Rome and its geological signature. Nat Hazards 62:425–443. https://doi.org/10.1007/s11069-012-0085-9

Sbarra P, Tosi P, De Rubeis V, Sorrentino D (2020) Quantification of earthquake diagnostic effects to assess low macroseismic intensities. Nat Hazards 104:1957–1973. https://doi.org/10.1007/s11069-020-04256-6

Shchetnikov AA, Radziminovich YB, Vologina EG, Ufimtsev GF (2012) The formation of Proval Bay as an episode in the development of the Baikal rift basin: A case study. Geomorphology 177:1–16. https://doi.org/10.1016/j.geomorph.2012.07.023

Shebalin NV (1972) Macroseismic data as information on source parameters of large earthquakes. Phys Earth Planet Int 6:316–323. https://doi.org/10.1016/0031-9201(72)90016-7

Shebalin NV, Aptikaev FF (2003) Development of scales of the MSK type. In: Earth's Magnetic Field. Mathematical Methods of Description. Macroseismics Problems. Computational Seismology, vol. 34. Moscow, GEOS, pp. 210–253 (in Russian)

Shenkman BM, Sholokhov PA, Shenkman IB (2011) Underflooding of Irkutsk by groundwater. Geogr Nat Resour 2:54–61 **(in Russian)**

Solonenko VP (1962) Some tasks of modern seismic microzoning. Geol Geofiz 9:69–82 (in Russian)

Solonenko VP, Treskov AA (1960) The August 29, 1959 Middle Baikal earthquake. Irkutsk Book Publishing House, Irkutsk (in Russian)

Steed RJ, Fuenzalida A, Bossu R, Bondár I, Heinloo A, Dupont A, Saul J, Strollo A (2019) Crowdsourcing triggers rapid, reliable earthquake locations. Sci Adv 5:eaau9824. https://doi.org/10.1126/sciadv.aau9824

Suvorov VD, Tubanov TsA (2008) Distribution of local earthquakes in the crust beneath central Lake Baikal. Russ Geol Geophys 49:611–620. https://doi.org/10.1016/j.rgg.2007.09.019

Tapponnier P, Molnar P (1979) Active faulting and Cenozoic tectonics of the Tien Shan, Mongolia, and Baykal regions. J Geophys Res: Solid Earth 84:3425–3459. https://doi.org/10.1029/JB084iB07p03425

Ten Brink US, Taylor MH (2002) Crustal structure of central Lake Baikal: Insights into intracontinental rifting. J Geophys Res: Solid Earth 107:2132. https://doi.org/10.1029/2001JB000300

Ulomov VI (2014) General seismic zoning of the territory of Russian Federation: GSZ-2012. Seismic Instruments 50:290–304. https://doi.org/10.3103/S0747923914040070

Voznesenskii AV (1905) Baikal Earthquake on November 13(26), 1903. In: News of the Permanent Central Seismic Commission, Vol. 2. Issue 1. Printing House of the Imperial Academy of Sciences, Saint-Petersburg, pp. 1–51 (in Russian)

Wald DJ, Quitoriano V, Worden CB, Hopper M, Dewey JW (2011) USGS "Did You Feel It?" internet-based macroseismic intensity maps. Ann Geophys 54:688–707. https://doi.org/10.4401/ag5354

Zanini MA, Hofer L, Faleschini F (2019) Reversible ground motion-to-intensity conversion equations based on the EMS-98 scale. Eng Struct 180:310–320. https://doi.org/10.1016/j.engstruct.2018.11.032

Zhao D, Lei J, Inoue T, Yamada A, Gao SS (2006) Deep structure and origin of the Baikal rift zone. Earth Planet Sci Lett 243(3–4):681–691. https://doi.org/10.1016/j.epsl.2006.01.033

Zorin YA, Turutanov EK, Mordvinova VV, Kozhevnikov VM, Yanovskaya TB, Treussov AV (2003) The Baikal rift zone: the effect of mantle plumes on older structure. Tectonophysics 371:153–173. https://doi.org/10.1016/S0040-1951(03)00214-2