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# Seismic activity and earthquake catalogue of the East Baltic region

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The unified seismological catalogue of the East Baltic region has been compiled. It provides an important base for the further seismic hazard assessment of the region. It is essentially required in view of the prospects of establishing new nuclear power plants in the region (Kaliningrad District, Belarus, East Lithuania). The catalogue covers the time period since 1375. The catalogue unravelled quite an uneven distribution of seismic events both in the latter and the temporal terms. The periods of seismic activity, like the one in 1908–1909, are followed by periods of seismic quiescence (e. g., 1912–1972). It is rather difficult to explain such a variability of seismic activity. The latter differentiation of seismic activity may be explained by a different degree of faulting of the earth's crust in the Baltic sedimentary basin, as well as by the residual glacioisostatic processes. The earthquake catalogue shows that only strong earthquakes were registered in the region until 1844. Since that year, the reporting has become much more precise. However, using Stepp's method allowed to assess the catalogue as complete since 1780. Some oldest reports of earthquakes in Prussia (1303) and Lithuania (1328) should be still discussed in detail to identify the consistency of these annals.

**Key words:** Baltic, earthquake catalogue, seismic activity, fault

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## INTRODUCTION

The Baltic region is situated within the East European Craton, also referred to as the East European Platform. This tectonic setting is notable for a low seismic activity. The crystalline basement that was formed as early as about 1.8 Ga is overlain by the Baltic sedimentary basin which was established in the latest Vendian–Cambrian times. The basin is only slightly tectonised. It is cut by a number of faults formed at different phases of tectonic activity. The main faulting was related to Caledonian orogeny processes along the platform margin during the latest Silurian–earliest Devonian (Stripeika, 1999). The most dense fault system was established in Latvia. The amplitude of the largest faults is in the range 300–600 m.

The recent geodetic measurements of the GPS network have shown that the earth's crust of the Baltic region is subject to horizontal forces that vary from extension to compression in different parts of the region (Zakarevičius et al., 2011). This explains the occurrence of earthquakes, which are related to the reactivation of the old system of faulted structures.

## OVERVIEW OF REGIONAL SEISMICITY

The seismic activity in the East Baltic region is lower as compared with that in the Fennoscandian Shield. On the other hand, the East Baltic region is more seismically active than the rest territories of the East European Platform due to the peripheral position of the region and residual glacioisostatic processes. Seismological data are very important for judging about the seismic activity of the Baltic region, because it is part of the vast East European Craton (Platform) which provides a large data base on the earthquake activity in a region with similar geological conditions. The available evidences indicate that the largest earthquakes in the East European Platform do not exceed M 5.0–5.5. These data put the consistent limit of the maximum magnitude of the largest possible earthquake in the region.

The East Baltic region is classified as a territory of a low or very low seismic activity (Jimenez et al., 2003). In the historical sources, there are noted a few dozens of weak or moderate seismic events. The net of local seismic stations in the East Baltic region is sparse; moreover, some stations experienced technical problems and did not operate properly and continuously all the time; therefore, the instrumental seismological information is rather poor. Usually, data of the seismological centres and seismic stations of Fennoscandia are used to analyse the seismic activity of the region. It should be noted that the seismic stations of Fennoscandian countries are able to detect only the seismic events of the magnitude $M > 2.5$, and the errors of location may vary from ~50 km up to hundreds of km (Pačėsa, unpublished report).

The oldest known seismic event in the East Baltic region was reported in the chronicles of Peter from Duisburg, who described an earthquake in Prussia in 1303: "...the land was shaking in all Prussia. Three times the ground was shaken altogether with buildings and only a few of them remained non-destroyed..." This report cannot be accepted without doubts, however. The author mentions a large amount of ruined buildings, but gives no details and says nothing about the amount of casualties. One of the strongest earthquakes known in the Mediterranean region (the maximum intensity $I_{max}$ = XI, and the magnitude about $M \sim 8.0$; Guidoboni, Comastri, 1997) happened on the same day. It is possible that it resulted in the ground shaking felt in Prussia. Alternatively, the chronicler could have "transposed" the images of ruins from the Mediterranean region to the South-East Baltic region.

In the beginning of the 20th century, Professor B. Doss from Riga University collected information about 18 moderate earthquakes (intensity of the order V–VII on the MSK-64 scale), which took place in Latvia and Estonia. The catalogue covered the period from 1616 to 1911.

In 1988, systematic studies in Belarus and the Baltic States provided new evidence about the seismic activity to increase the list of earthquakes to more than forty events (Avotinia et al., 1988). After a couple of years, the catalogue was reviewed and the magnitudes of some events were re-evaluated (Boborikin et al., 1993). One can notice an increase of seismic activity in Baltic region in 1908–1909. This period coincides with the strong ($M = 7.5$) Messina earthquake in Italy on the 28th December 1908.

One of the strongest instrumentally recorded earthquakes took place in Osmussaare (Estonia) in 1976; its magnitude reached $M = 4.75$. Earthquakes of the magnitudes $M_w = 5.0$ and $M_w = 5.2$ (following other interpretations their $M_w$ is evaluated, respectively, as 4.3 and 5.0) in the Kaliningrad District of Russia on September 21, 2004 were unexpected in a low-seismicity area. A recorded aftershock was weaker, reaching $M_L = 3.0$ (Aronov et al., 2005).

The earthquakes caused moderate building damages in the Kaliningrad District and smaller damages in North Poland and in South and West Lithuania. The largest earthquake was the strongest ever recorded instrumentally in the region, and it was felt at a distance of up to 800 km (Gregersen et al., 2007). In the west and south directions, the perceptibility area is abruptly cut off by the Tornquist–Teisseyre Zone representing the southwestern margin of the East European Craton. Due to the fact that the area was covered by a sparse network of seismic stations and a number of stations were located rather far away, different seismic agencies provided quite different locations of the two seismic events (Gregersen et al., 2007). The earthquakes were instrumentally localised at a depth of 16–20 km under the central-northern part of the Sambia Peninsula in the Kaliningrad enclave. For these events, it has been noted that the macroseismic calculations 10–19 km deep are in reasonable agreement. The source mechanism of the largest earthquake was determined to be the right lateral strike slip of WNW–ESE trending near-vertical fault parallel to the northern coast of the Sambia Peninsula (Fig. 1). Based on available tectonic stress information it was interpreted that the underlying cause of the earthquakes is the absolute plate motion (Gregersen et al., 2007).

The seismic events in the Kaliningrad area urged reviewing the perception of seismicity of the East Baltic region. Before these earthquakes, the possible maximum earthquake magnitude was evaluated to be $M = 4.8$, while the magnitude of the Kaliningrad earthquake was as high as $Mw = 5.2$, and, taking into consideration the commonly accepted safety margin of 0.5, the maximum magnitude should be evaluated at $M = 5.7$.

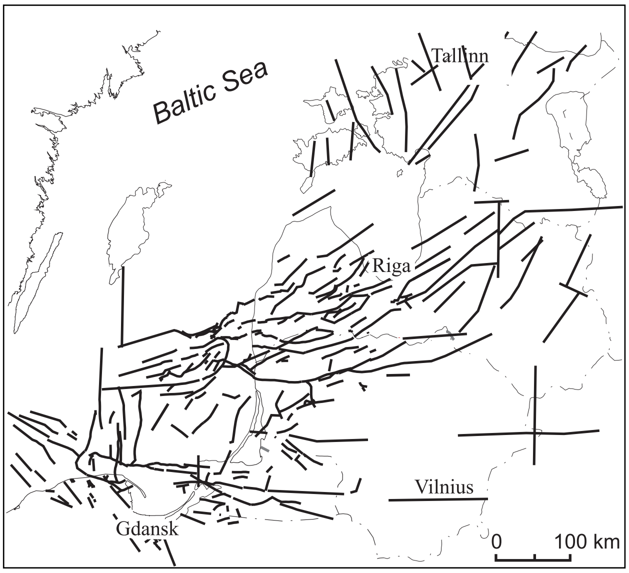

**Fig. 1.** Major faults defined in the sedimentary cover of the Baltic sedimentary basin

**1 pav.** Pagrindiniai lūžiai, išskirti Baltijos sedimentacinio baseino nuosėdinėje dangoje

No single earthquake was registered reliably in Lithuania. It is known that in 1909 there was some ground shaking in the Bezdonys village located several tens of kilometres away from Vilnius, but the primary reports must be reexamined. The above-mentioned Peter from Duisburg reported about the shaking Skirsnemunė castle in 1328; after the event, the castle was abandoned. However, this report also causes some doubts. A. Nikonov (personal communication) includes the seismic events of years 1303 and 1328 into the newly revised seismological catalogue of the South-Eastern Baltic region, while Grunthal and Riedel (2007) deny the existence of such past events. A passive seismic project, called PASSEQ, was implemented in East Europe, including Lithuania, in 2006–2007. The preliminary results (I. Janutytė, personal communication) show some events in Middle Lithuania, the Curonian Lagoon area and in the Baltic Sea near the Kaliningrad area; the seismic records resemble those related to tectonic events.

## THE IGNALINA NNP SEISMIC MONITORING SYSTEM

In 1988, the Governmental Expert Group came to the conclusion that the evaluation of seismicity in the site of the Ignalina NPP has not been properly done. The Seismic Alarm System (SAS) and the Seismic Monitoring System (SMS) were established in the Ignalina NPP area in 1999. According to the initial design, the system consisted of six seismic stations located around the Ignalina NPP within the radius of about 30 km. The data collection centre was located at the Ignalina NPP. However, only four out of six seismic stations were established in Lithuania (Fig. 2).

The SAS supposed to generate an alarm signal if a strong seismic wave was approaching the Ignalina NPP. Until 2008, the SAS did not operate properly and had some imperfections. The main goal of the SMS was to monitor the local seismicity. The SMS consists of four short-period (T = 1 s) vertical seismometers placed in boreholes 30 m deep. The sensitivity of each seismometer is 3000 V/(m/s) and the damping ratio 0.7. The Guralp LTD hardware producer and 24 bit digitizers were used to convert an analogue signal to a digital signal (hardware producer GeoSIG).

In 1999, the Lithuanian Geological Survey (LGT) started a project of seismological monitoring in Lithuania. The main goal of the project was to collect, analyse, process and store data of the Ignalina NPP SMS. An agreement between authorities of the LGT and the Ignalina NPP was signed to ensure the exchange of seismic data and the main results of analysis. Specialists of the Ignalina NPP were responsible for the maintenance of the system, while the data were processed in the LGT.

From the beginning, some flaws in the SMS were noted, because of which the seismic stations did not work about 30% of time during the warm seasons. The system was upgraded after two earthquakes of the average magnitude, which shook the Kaliningrad District (Russia) in 2004. The system upgrade was started in spring 2007 and ended in summer 2008. Analogue / digital converters, data transfer equipment and software for data registering have been changed and short-period tree-component seismometers have been installed at each seismic station additionally.

Until 2008, the SMS had recorded only a few local seismic events, but after the system upgrading the number of registered local seismic events increased significantly. During 2008–2009, there were registered 48 local seismic events, mostly from quarries in Lithuania, Latvia, Estonia and Belarus, and some explosions in the Baltic Sea because of military unmining operations (Fig. 2). The magnitude of local events ranged from M = 1.6 to M = 2.9. After the upgrade, the number of recorder teleseismic and regional events increased. For example, 731 seismic events were registered in 2008, while only 125 events had been recordd in 2006, i.e. before the SMS upgrade. The majority of the recorded teleseismic events were related to seismic events reported in the seismic bulletins of the United States Geological Survey (USGS) and the European-Mediterranian Seismological Centre. It was realised that the Ignalina NPP SMS was capable to detect almost all M ≥ 5 seismic events from all over the world.

The SMS recorded just a few local tectonic events in more that 10 years of operation. An earthquake in the middle of the Baltic Sea was recorded in 2001 and two Kaliningrad earthquakes were recorded in 2004 (Figs. 4, 5), along with other seismic stations in the region, the Suwalki station lo-

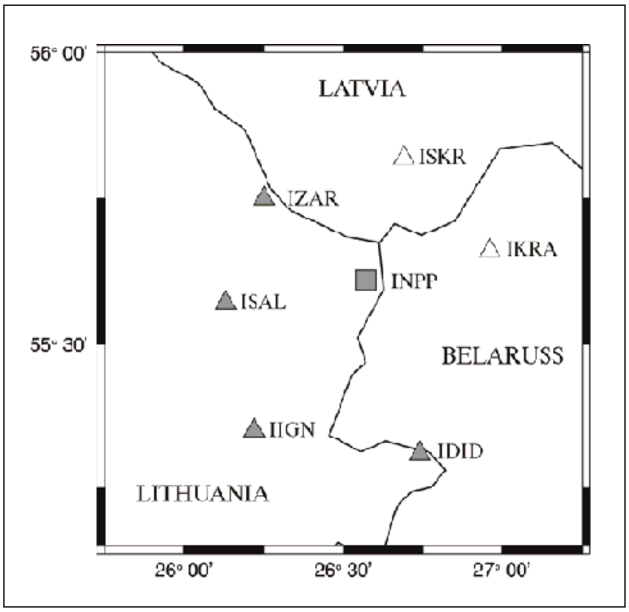

**Fig. 2.** Seismic stations of the Ignalina NPP. Grey square corresponds to the Ignalina NPP site, grey triangles to the operating seismic stations, and open triangles to designed but not built seismic stations

**2 pav.** Ignalinos AE seisminės stotys. Pilkas kvadratas – Ignalinos AE, pilki trikampiai – įrengtos seisminės stotys, balti trikampiai – planuotos stotys

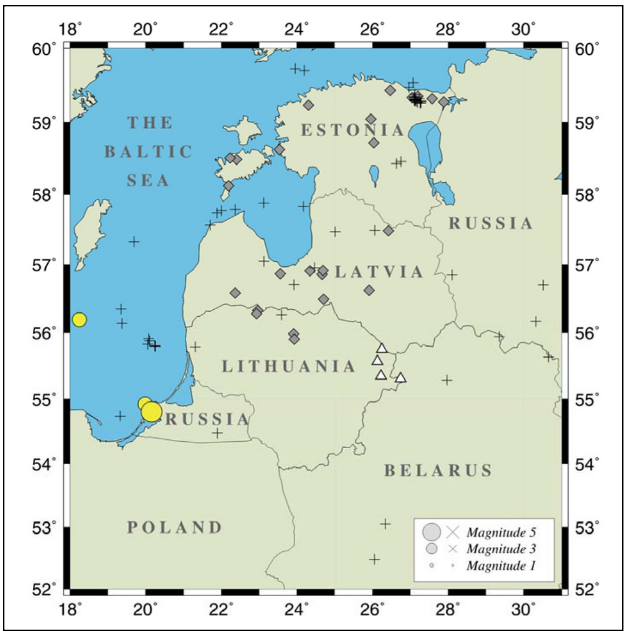

**Fig. 3.** Local seismic events recorded by the SMS of the Ignalina NPP during 1999–2009. Triangles correspond to seismic stations of the Ignalina NPP, grey diamonds to explosions in queries, circles to earthquakes, and crosses to explosion events

**3 pav.** Lokalūs seisminiai įvykiai, užfiksuoti Ignalinos AE seismologiniame tinkle 1999–2009 metais. Trikampiai – seisminės stotys, pilki rombai – sprogdinimai karjere, apskritimai – Žemės drebėjimai, kryžiai – sprogdinimai Baltijos jūroje

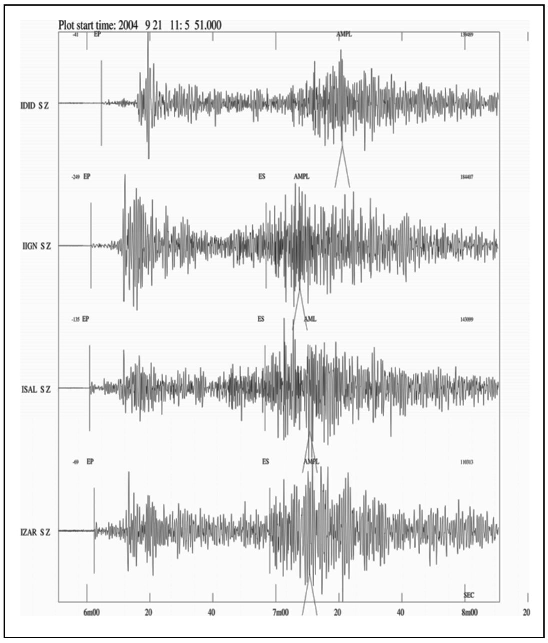

**Fig. 4.** Seismograms of the first Kaliningrad event on 21 September 2004, 11:05 (GMT) recorded at the IZAR, IIGN, ISAL and IDID seismic stations of the Ignalina NPP network

**4 pav.** Pirmojo Žemės drebėjimo Kaliningrade 2004 09 21 11:05 (GTM) seismogramos, užrašytos Ignalinos AE seisminėse stotyse

cated closest to the epicentres (Fig. 6). All other local seismic events were quarry blasts or explosions of un-mining operations in the Baltic Sea.

## SEISMIC CATALOGUE OF EASTERN BALTIC REGION

### Compilation of regional seismic catalogue

The territory as large as 700 × 850 km has been evaluated (Table 1, Fig. 7).

First of all, there was determined the area of investigation – a rectangular limited by longitudes 17–31 and latitudes 52–60. Furthermore, the study area in the southwest was truncated by the Teisseyre–Tornquist zone, and in the northwest it follows the boundary of the sedimentary basin.

The seismic catalogue of the Eastern Baltic region was compiled using three main sources: the seismic database of the Northern Europe (FENCAT), provided and supported by the Seismological Institute of Helsinki University (HU; http://www.seismo.helsinki.fi), the Joint Catalogue of the Eastern European platform, covering the time-span from ancient times to 2006 (Sharov et al., 2007), and the catalogue of Belarus and the Baltic countries (Aronov, Aronova, 2007).

Probably FENCAT is the most consistent seismic catalogue of Northern Europe. The historical part of the catalogue starts from the year 1375, and the catalogue of the last

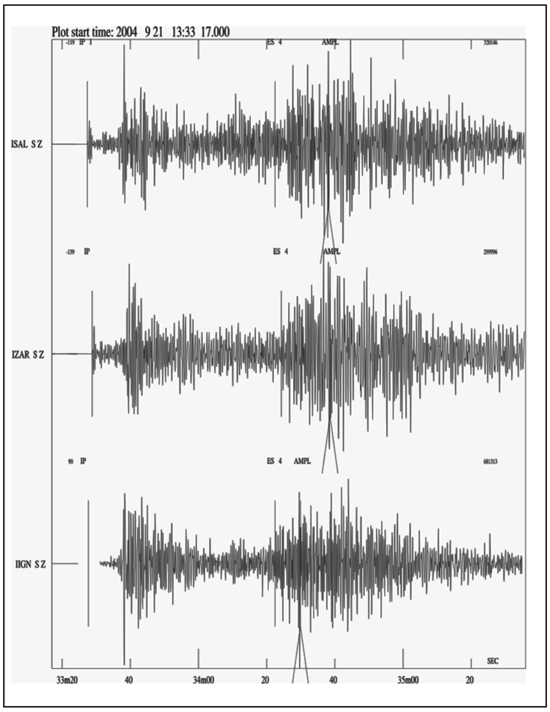

**Fig. 5.** Seismograms of the second Kaliningrad event on 21 September 2004, 13:32 (GMT) recorded at the IZAR, IIGN, ISAL and IDID seismic stations of the Ignalina NPP network

**5 pav.** Antrojo Žemės drebėjimo Kaliningrade 2004 09 21 13:23 (GTM) seismogramos, užrašytos Ignalinos AE seisminėse stotyse

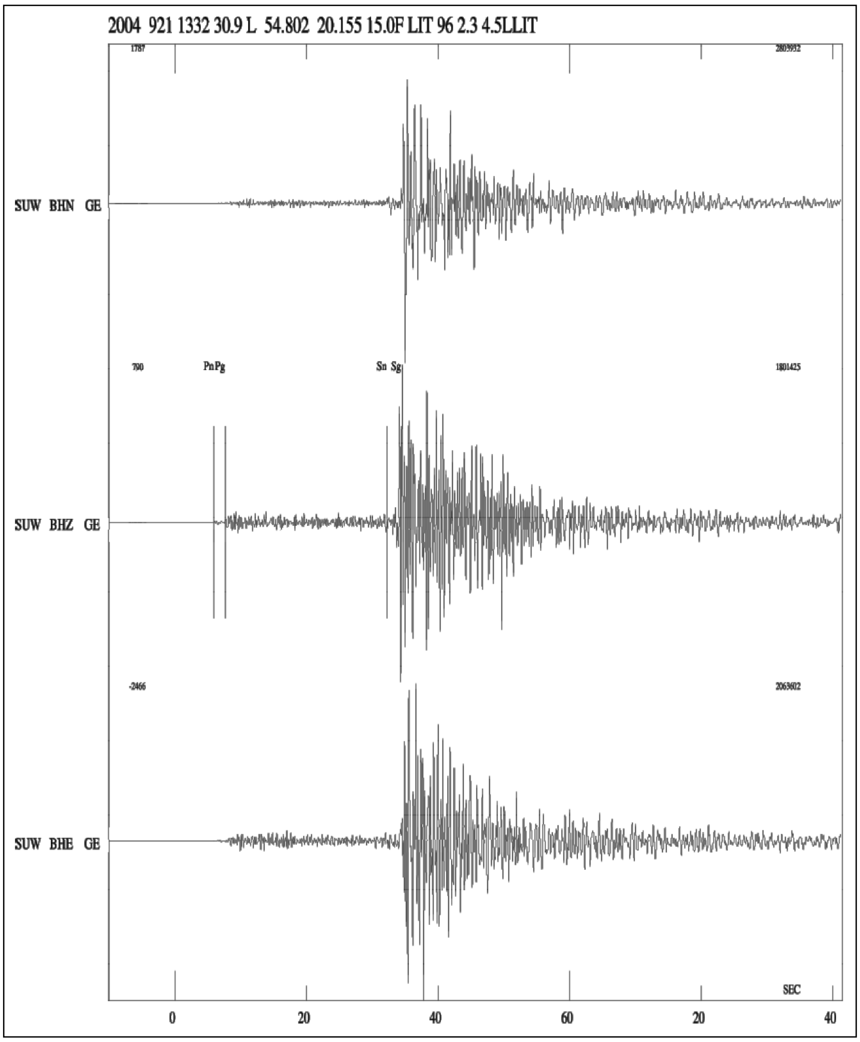

**Fig. 6.** Seismograms of the second Kaliningrad event on 21 September 2004, 13:32 (GMT) recorded at the SUW seismic station

**6 pav.** Antrojo Žemės drebėjimo Kaliningrade 2004 09 21 13:23 (GTM) seismogramos, užrašytos Suvalkų seisminėje stotyje

Table 1. **Joint catalogue of seismic events of the Eastern Baltic region (foreshocks and aftershocks are shown). The catalogue is presented in short NORDIC format. Magnitude types: m – macroseismic magnitude, W – moment magnitude, I – intensity magnitude, L – local magnitude, B – body-wave magnitude, i – epicentral intensity. Siesmological centres and data sources: KJW – Wahlström, referring to Kjellen, 1990; DSI – Nikonov and Sildvee, according to Doss, 1988; DOS – Doss, 1910; PAN – Panasenko, 1977, 1979; SIL – Nikonov ir Sildvee, 1988; KON – Kondorskaya et al., 1988; ANA – Ananin and Panasenko, 1982; BLR – Aronov and Aronova, 2007; LGS – values calculated by the Lithuanian Geological Survey; BER – Bergen University, Seismological Observatory; HEL – Seismological Institute, HU; EEP – joint catalogue of the Eastern European platform (Earthquakes and microseismicity ...; 2007. A character next to the identificator of an event: "F" marks foreshock, "A" – aftershock, "?" – less credible event. Coordinates of epicentres are provided in the geographical system of coordinates, degrees and decimal degrees**

1 lentelė. **Jungtinis Rytų Baltijos regiono seisminis katalogas. Nurodyti pagrindiniai parametrai (magnitudė, gylis, koordinatės, laikas), informacijos šaltiniai**

| Year | Month | Day | Hour | Min | Sec | RI | Latit., deg. | Long., deg. | Depth, km | Agency | MAG | MAG | MAG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1375 | | | | | | L | 57.5 | 18.5 | 10 | KJW | 4.0 MKJW | | |
| 1540 | | | | | | L | 57.7 | 18.7 | 5 | KJW | 4.3 MKJW | | |
| 1572 | 1 | 6 | 8 | | | L | 53 | 18.5 | 5 | POL | 4.9 WPOL | 3.0 S | |
| 1602 | | | | | | L | 59.5 | 24.7 | 5 | BLR | 3.8 LBLR | 6.0 iBLR | |
| 1607 | | | | | | L | 59.7 | 24.7 | 5 | BLR | 3.8 LBLR | 6.0 iBLR | |
| 1616 | 6 | 30 | 5 | 30 | | L | 56.4 | 24.2 | 5 | EEP | 4.1 LEEP | 6.5 iBLR | 4.0 IDOS |
| 1670 | 2 | 1 | 22 | | | L | 58.4 | 24.5 | 8 | DSI | 3.9 LBLR | 3.9 MDSI | 6.0 iBLR |
| 1783 | 3 | | | | | L | 56.9 | 23.4 | | DOS | 4.0 LBLR | 4.0 IBLR | |
| 1785 | 10 | 11 | | | | L | 57.4 | 21.6 | | DOS | 3.5 LBLR | 3.5 IDOS | 5.0 iBLR |
| 1803 | 1 | 8 | 23 | 15 | | L | 53.1 | 23.1 | 5 | BLR | 3.6 LEEP | 6.0 iBLR | 3.6 LBLR |
| 1807 | 2 | 23 | 3 | | | LF | 56.9 | 24 | 5 | DOS | 3.0 LBLR | 3.0 IDOS | 3.5 iBLR |

Table 1. **Continued**

| Year | Month | Day | Hour | Min | Sec | RI | Latit., deg. | Long., deg. | Depth, km | Agency | MAG | MAG | MAG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1821 | 2 | 20 | 8 | | | LF | 56.6 | 25.3 | | BLR | 2.5 LBLR | 2.5 iBLR | |
| 1821 | 2 | 21 | 3 | 30 | | LF | 56.6 | 25.3 | 3 | BLR | 4.0 LBLR | 6.5 iBLR | |
| 1821 | 2 | 22 | 4 | | | LF | 56.6 | 25.3 | | BLR | 2.5 LBLR | 2.5 iBLR | |
| 1821 | 2 | 22 | 7 | | | LF | 56.6 | 25.3 | | BLR | 2.5 LBLR | 2.5 iBLR | |
| 1821 | 2 | 22 | 7 | 30 | | L | 56.6 | 25.3 | 13 | EEP | 4.5 LEEP | 7.0 iBLR | 4.5 LBLR |
| 1821 | 2 | 23 | | | | LA | 56.6 | 25.3 | | BLR | 2.5 LBLR | 2.5 iBLR | |
| 1823 | 2 | 6 | 0 | | | L | 58 | 26.2 | 7 | DSI | 3.9 LBLR | 7.0 iBLR | 3.9 MDSI |
| 1827 | 9 | 28 | 12 | | | L | 59 | 23.5 | 14 | DSI | 4.0 LEEP | 4.0 MDSI | 5.0 iBLR |
| 1844 | 1 | 12 | 22 | | | L | 58.6 | 23.7 | 6 | DSI | 2.5 LBLR | 2.5 MDSI | 4.0 iBLR |
| 1853 | 2 | 5 | 1 | 45 | | LF | 56.8 | 25.7 | | DOS | 2.9 LBLR | 5.0 iBLR | 3.5 IDOS |
| 1853 | 2 | 5 | 2 | | | L | 56.7 | 25.6 | | DOS | 3.5 LBLR | 6.0 iBLR | 2.9 IDOS |
| 1853 | 3 | 26 | 1 | 30 | | L | 59.5 | 24.7 | 5 | DSI | 1.2 LBLR | 1.2 MDSI | 2.5 iBLR |
| 1853 | 12 | 29 | 23 | 45 | | L | 56.96 | 24.13 | | DOS | 3.5 LBLR | 3.5 IDOS | 6.0 iBLR |
| 1854 | 1 | 5 | 4 | | | LA | 56.96 | 24.13 | | DOS | 2.9 LBLR | 2.9 IDOS | 4.0 iBLR |
| 1857 | 5 | 18 | 9 | | | L | 57.8 | 22.2 | 10 | DOS | 4.5 LEEP | 3.0 MDOS | 7.0 iBLR |
| 1858 | 1 | 15 | 14 | 10 | | L | 59.3 | 22.6 | 8 | DSI | 3.0 LBLR | 3.0 MDSI | 5.0 iBLR |
| 1869 | 2 | 15 | 3 | | | L | 59.5 | 24.7 | 6 | DSI | 2.5 LBLR | 2.5 MDSI | 5.0 iRBS |
| 1870 | 2 | 6 | 4 | 45 | | L | 56.96 | 24.13 | | DOS | 3.5 LBLR | 3.5 IDOS | 5.0 iBLR |
| 1870 | 2 | 6 | 5 | 20 | | LA | 56.96 | 24.13 | | DOS | 2.9 LBLR | 2.9 IDOS | 4.0 iBLR |
| 1870 | 2 | 11 | | | | LA | 56.96 | 24.13 | | BLR | 2.5 LBLR | 4.0 iBLR | |
| 1877 | 10 | 16 | 5 | 25 | | L | 59 | 23.5 | 10 | DSI | 4.2 LEEP | 3.5 MDSI | 6.0 iBLR |
| 1881 | 1 | 28 | 14 | 15 | | L | 59.4 | 28.2 | 4 | DSI | 3.2 LBLR | 3.0 MDSI | 5.5 iBLR |
| 1887 | 12 | 10 | | | | L | 54.2 | 28.5 | 10 | EEP | 3.7 LEEP | 3.7 PPAN | 6.0 iBLR |
| 1893 | 8 | 29 | 5 | 50 | | L | 53.89 | 30.34 | 7 | BLR | 3.5 LBLR | 5.0 iBLR | |
| 1896 | 9 | 20 | 15 | | | L | 56.7 | 23.7 | 5 | DOS | 3.5 LEEP | 3.5 IDOS | 5.0 iBLR |
| 1896 | 11 | 12 | 8 | 30 | | L | 53.89 | 30.34 | 7 | BLR | 4.0 LBLR | 6.0 iBLR | |
| 1907 | 1 | 22 | 2 | | | L | 56.9 | 24.07 | 7 | BLR | 3.5 LBLR | 5.0 iBLR | |
| 1908 | 12 | 15 | 3 | | | L? | 54.8 | 25.8 | | LGS | 4.0 LLGS | 5.5 iBLR | |
| 1908 | 12 | 28 | 5 | | | L | 54.6 | 25.8 | 9 | BLR | 4.5 LBLR | 7.0 iBLR | |
| 1908 | 12 | 28 | 20 | | | LF | 56.9 | 24.14 | | BLR | 2.9 LBLR | 4.0 iBLR | |
| 1908 | 12 | 28 | 22 | 45 | | LF | 57 | 24.15 | | BLR | 2.9 LBLR | 4.0 iBLR | |
| 1908 | 12 | 29 | 1 | | | L | 56.8 | 26.3 | 10 | BLR | 4.5 LBLR | 7.0 iBLR | |
| 1908 | 12 | 29 | 3 | 30 | | L | 56.94 | 24.07 | 10 | BLR | 3.5 LBLR | 5.5 iBLR | |
| 1908 | 12 | 29 | 22 | | | L | 55.8 | 26.7 | 11 | EEP | 4.5 LEEP | 6.5 iBLR | 4.5 LBLR |
| 1908 | 12 | 29 | | | | L | 57.5 | 25.7 | | BLR | 3.5 LBLR | 6.0 iBLR | |
| 1908 | 12 | 30 | | | | L | 54.308 | 22.3 | | POL | 2.9 LBLR | 3.5 IPOL | |
| 1908 | 12 | 30 | 5 | | | LA | 56.94 | 24.07 | 10 | BLR | 2.9 LBLR | 5.0 iBLR | |
| 1908 | 12 | 31 | 4 | | | LA | 56.95 | 24 | | BLR | 3.5 LBLR | 6.0 iBLR | |
| 1909 | 1 | 31 | 7 | 15 | | LA | 56.9 | 24.1 | 6 | EEP | 3.5 LEEP | 5.0 iBLR | 3.5 LBLR |
| 1909 | 2 | 12 | 1 | | | L | 56.6 | 20.2 | | BLR | 3.5 LBLR | 3.0 iBLR | |
| 1909 | 6 | 2 | 8 | 30 | | L | 58.4 | 25.6 | 7 | SIL | 1.8 LBLR | 1.8 MSIL | 3.0 iBLR |
| 1910 | 5 | 21 | 3 | | | L | 56.95 | 24.05 | 10 | BLR | 4.0 LBLR | 6.0 iBLR | 4.0 LEEP |
| 1912 | 4 | 8 | 16 | 30 | | LF | 59.7 | 25 | 5 | DSI | 2.0 LBLR | 2.0 MDSI | 3.0 iBLR |
| 1912 | 4 | 8 | 23 | 15 | | LF | 59.7 | 25 | 5 | DSI | 1.6 LBLR | 1.6 WDSI | 2.0 iBLR |
| 1912 | 6 | 15 | | | | L | 59.7 | 25 | 6 | DSI | 2.0 LBLR | 2.0 MDSI | 3.5 iBLR |
| 1931 | 7 | 12 | 22 | | | L | 59.4 | 25.3 | 5 | KSI | 3.0 LBLR | 4.5 iBLR | 2.5 MKSI |
| 1932 | 2 | 24 | 19 | | | L | 52.6 | 20.03 | | POL | 4.5 LPOL | | |
| 1972 | 9 | 4 | 0 | 26 | 33 | L | 57.1 | 18.4 | | WAH | 2.4 LWAH | | |
| 1976 | 10 | 25 | 8 | 39 | 45 | L | 59.26 | 23.39 | 14 | KON | 4.7 LBLR | 4.7 BKON | 6.5 iBLR |
| 1976 | 10 | 25 | 8 | 49 | | LA | 59.3 | 23.5 | 12 | SIL | 3.5 LBLR | 3.5 SIL | 4.5 iBLR |
| 1976 | 10 | 25 | 9 | 7 | | LA | 59.3 | 23.5 | 12 | SIL | 3.0 LBLR | 3.0 SIL | 3.5 iBLR |
| 1976 | 11 | 8 | 10 | 17 | 7 | LA | 59.32 | 23.46 | | ANA | 3.5 LBLR | 3.5 ANA | 4.5 iBLR |
| 1976 | 11 | 22 | 12 | 14 | 42.5 | LA | 59.32 | 23.42 | 13 | BLR | 3.0 LBLR | 2.5 ?SIL | 3.0 iBLR |
| 1978 | 5 | 10 | 9 | 5 | | LI | 52.8 | 27.7 | 10 | BLR | 3.5 LEEP | 3.5 LBLR | 4.5 iBLR |
| 1979 | 7 | 24 | 16 | 2 | 46.4 | L | 55.45 | 19.7 | | HEL | 2.7 LHEL | | |
| 1980 | 1 | 9 | 1 | 24 | 52.4 | L | 58.91 | 22.99 | | HEL | 2.4 LHEL | | |
| 1981 | 6 | 22 | 19 | 27 | 37.7 | L | 59.45 | 22.66 | 7 | HEL | 2.6 LHEL | | |
| 1982 | 6 | 2 | 7 | 58 | 17.7 | L | 57.04 | 21.94 | | HEL | 2.3 LHEL | | |
| 1983 | 12 | 1 | 22 | 26 | 34 | L | 52.95 | 27.81 | 7 | BLR | 2.8 LBLR | 4.5 iBLR | |
| 1985 | 10 | 17 | 1 | 32 | 24 | L | 52.9 | 28.4 | 7 | EEP | 3.1 LEEP | 4.0 iBLR | 3.1 LBLR |
| 1987 | 4 | 7 | 23 | 1 | 28 | LF | 58.3 | 26.1 | 10 | BLR | 2.7 LBLR | 3.5 iBLR | |
| 1987 | 4 | 8 | 23 | 2 | 22 | L | 58.4 | 26.1 | 14 | BLR | 3.5 LBLR | 3.5 SIL | 5.0 iBLR |
| 1987 | 7 | 5 | 2 | 42 | 11.7 | LA | 58.3 | 26 | 8 | BLR | 2.9 LBLR | 3.5 iBLR | |
| 1987 | 9 | 22 | 18 | 25 | | L | 58.7 | 26.4 | 9 | BLR | 3.0 LBLR | 4.5 iBLR | |
| 1988 | 4 | 29 | 15 | 36 | 52 | L | 56.97 | 19.53 | 1 | BER | 3.3 CBER | | |
| 1988 | 4 | 29 | 15 | 41 | 22.7 | L | 56.32 | 21.4 | 7 | BER | 3.2 CBER | 3.1 LBER | |
| 1988 | 9 | 2 | 19 | 17 | | L | 58.8 | 26.4 | 7 | BLR | 2.9 LBLR | 5.0 iBLR | |
| 1994 | 3 | 12 | 7 | 56 | 58.6 | L | 55.2 | 17.91 | 0 | BER | 2.4 LBER | | |
| 1995 | 3 | 6 | 10 | 24 | 24.3 | L | 55.04 | 30.82 | 18 | BER | 2.2 LBER | | |
| 1998 | 3 | 16 | 4 | 9 | 5.6 | LI | 52.87 | 27.6 | | BLR | 1.9 LBLR | 4.5 iBLR | |
| 2002 | 12 | 18 | 21 | 14 | 21.9 | L | 56.115 | 17.991 | 2.2 | HEL | 3.5 LHEL | 4.2 BUSG | 3.5 LBER |
| 2003 | 1 | 12 | 11 | 43 | 47.8 | L | 59.402 | 23.415 | 10 | HEL | 1.2 LHEL | | |
| 2004 | 1 | 28 | 15 | 40 | 0.2 | L | 58.792 | 23.851 | 10 | HEL | 1.6 LHEL | | |
| 2004 | 9 | 21 | 11 | 5 | 4.8 | LF | 54.774 | 20.04 | 10 | HEL | 4.6 WLGS | 4.5 WBER | 4.8 LHEL |
| 2004 | 9 | 21 | 13 | 32 | 31.9 | L | 54.834 | 20.025 | 10 | HEL | 4.8 WLGS | 4.7 WHRV | 5.2 LUPP |
| 2004 | 9 | 21 | 13 | 36 | 33.8 | LA | 54.87 | 19.99 | 3 | BLR | 3.0 LBLR | 3.0 iBLR | |
| 2006 | 11 | 6 | 1 | 11 | 40.3 | L | 59.677 | 24.857 | 2.7 | HEL | 1.1 LHEL | | |

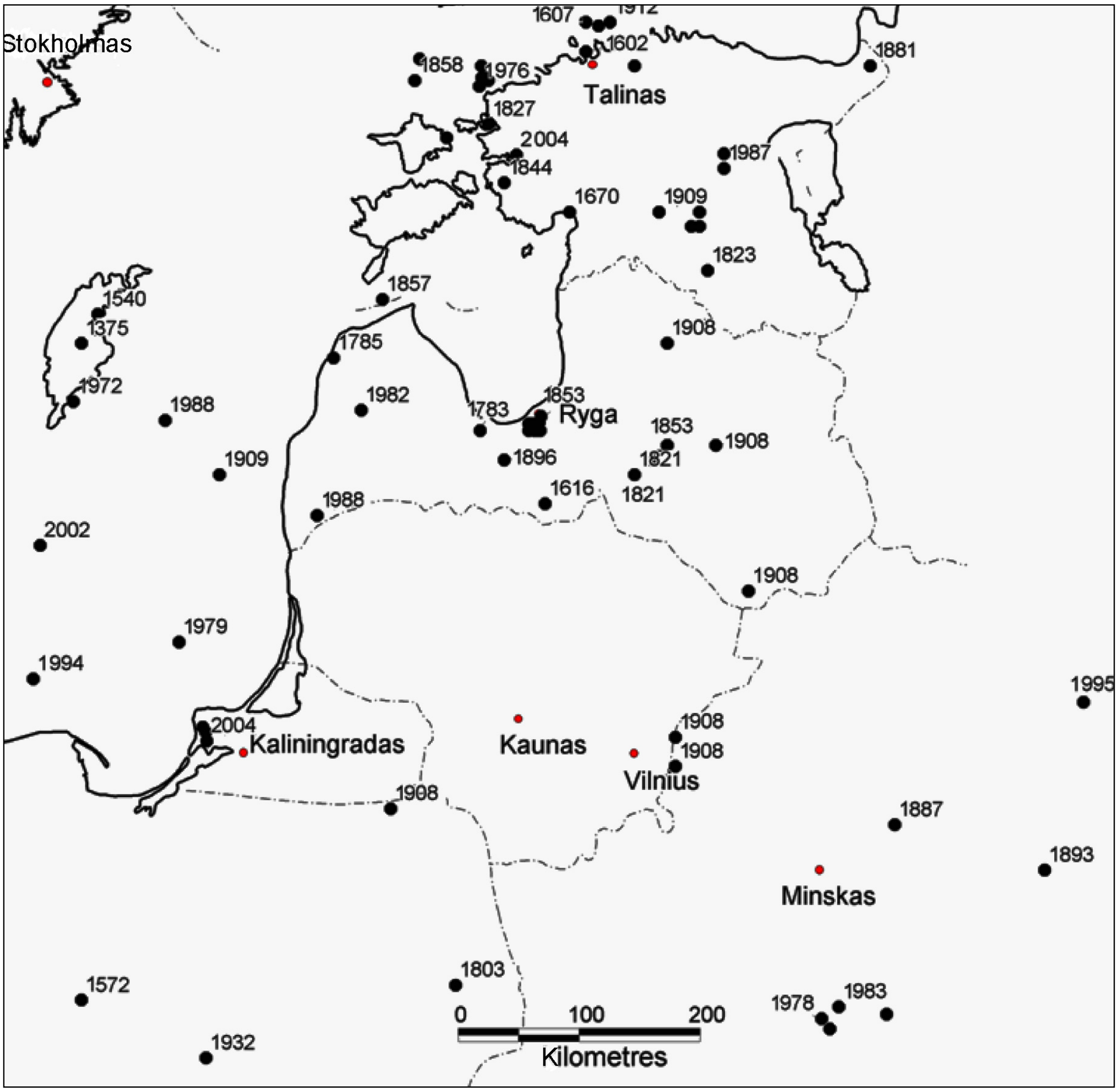

**Fig. 7.** Seismic events from the united catalogue of the Eastern Baltic. Years of events are indicated
**7 pav.** Seisminiai įvykiai, nurodyti bendrame seismologiniame kataloge (surašyti Žemės drebėjimų metai)

decades utilises data from all seismic networks of Fennoscandia and some neighbouring countries. Moreover, this catalogue discriminates between natural and man-made events, and it is quite easy to eliminate events of non-tectonic origin.

The Joint Catalogue of the Eastern European platform (Sharov et al., 2007) was compiled using the Specialized Earthquake Catalogue of Northern Eurasia (Special Earthquake Catalogue ...; 1996) covering the time span from the ancient times to 1995. The Specialized Earthquake Catalogue was compiled by a group of Russian researches headed by N. V. Kondorskaya and V. I. Ulomovov within the frames of the project concerning the seismic zoning of the Russian Federation territory. This catalogue covered the area of East Europe and some adjacent territories.

The catalogue of Belarus and the Baltic countries (Aronov, Aronova, 2007) contains historical events mainly. This catalogue lists some smaller magnitude events which have not been included into other catalogues. Furthermore, quite an explicit macroseismic information is provided for each event, and the initial sources of information are indicated.

Since the primary catalogues overlap both in space and time, the same event could be included in more than one data set. Hence, a great deal of effort has been made to analyse the records included in the source catalogues in the search for duplicates. The identification of duplicate events in the different data sets was based on a comparison of:

- the date of occurrence;
- epicentral coordinates;

- the magnitude of earthquakes;
- the reference of the seismic record.

Generally, standard methods define two events as duplicated when the relative differences of` dates of occurrence, epicentral coordinates, and magnitude values are below the predefined values. This approach was not deemed fully adequate for the joint catalogue, given the imprecise location of many earthquakes (e. g., the locations of two or more simultaneous entries show a significant difference, sometimes matched by a difference in magnitude). Thus, an accurate and thorough manual inspection was also made to identify duplicates and to select the proper entries to the catalogue. When analogous earthquakes were identified, only one entry was reported in the final catalogue applying a simple hierarchy scheme.

Regarding the historical events (before 1964), the catalogue of Belarus and the Baltic countries (Aronov, Aronova, 2007) was considered the most authoritative for the study area, followed in priority by the FENCAT and the Joint Catalogue of the Eastern European platform (Earthquakes and microseismicity ...; 2007).

The FENCAT database was considered most reliable for the description of recent seismicity.

The conventional probabilistic seismic hazard assessment (PSHA) approach is based on the assumption that earthquakes are random events occurring with a Poisson distribution in time. As seismicity rates for the analysis are estimated based on the earthquake catalogue, correlated or "dependent" events are removed from the record to maintain this assumption. The dependent events, such as foreshocks and aftershocks, must be identified and removed, and only the main shock is included into the catalogue.

Aftershocks and foreshocks were identified using the Gardner and Knopoff approach (1974). This technique identifies dependent events specifying the spatial and temporal extent of earthquake sequences as a function of the magnitude, Mm, of the main shock. Earthquakes are considered to belong to the same ith sequence if they are located within Di(Mm) km and occurred within a period of Ti (Mm) days from the main shock (Table 2). Only the largest shock from each cluster enters the final catalogue. The Gardner and Knopoff method was applied to the joint catalogue, and aftershocks (A), foreshocks (F) and induced events (I) have been identified (Table 1). Finally, all independent events and events of non-natural origin have been removed from the final catalogue of the Eastern Baltic (Table 3).

Table 2. **Time and distance limits for windows used to identify foreshocks and aftershocks**

2 lentelė. **Lydimųjų smūgių filtravimo lango laiko ir nuotolio ribos**

| Magnitude of main event | Window limits | |
|---|---|---|
| | Distance km | Time, days |
| 5 | 33.33 | 103.89 |
| 4 | 11.11 | 34.63 |
| 3 | 3.7 | 11.54 |

The same window was used for both foreshocks and aftershocks. The following relationships were applied for space-time windows:

$$L = 10^{(0.1238M + 0.983)}$$
$$T = 10^{(0.5409M-0.547)} / 365.$$

The obtained window parameters are presented in Table 3.

The application of the Garner and Knkopoff (1974) approach was preferred to fixed window methods (i. e. catalogues are deprived of the presence of aftershocks and foreshocks by using a non-dependent magnitude space-time window) as it avoids overestimating the aftershock and foreshock populations. The Gardner and Knopoff (1974) method was applied to the East Baltic catalogue, using the Di(Mm) and Ti(Mm) values proposed by authors for South California. Although both the seismicity and the seismotectonic setting of South California and the East Baltic region differ significantly, the application of such values was proven to be suitable for the identification of sequences in areas of low to moderate earthquakes.

### Magnitude unification

The joint seismic catalogue of the Eastern Baltic region was compiled using several different catalogues in which seismic events are presented in different magnitude types. Therefore, different magnitude types had to be unified, preferably to the moment magnitude, because the joint catalogue of the Eastern Baltic is intended to use for seismic hazard assessment.

Almost all events from the FENCAT catalogue are in local magnitudes (LHEL). Unfortunately, magnitudes of historical events have been taken from different catalogues and papers of different researchers, and the magnitude types and their evaluation methods were quite different. It was impossible to unify the magnitudes of historical events.

The joint catalogue of the Eastern European platform and the catalogue of Belarus and the Baltic states contain local magnitudes. Events in the FENCAT catalogue are characterised by magnitudes of different types and different agencies.

Using the complete FENCAT catalogue of the years 1980–2008 and the MAG program from the SEISAN 8.2 software package, a correlation between CBER (coda magnitude defined at Bergen University) and LHEL (local magnitude defined at Helsinki University) was established:

$$LHEL = 1.562 \times CBER - 1.664,$$

and a relation between LBER (local magnitude defined at Bergen University) and LHEL was found:

$$LHEL = 1.205 * LBER - 0.146.$$

The CBER and LBER magnitudes of the joint catalogue were converted to LHEL magnitudes using the presented relations.

Table 3. **Final (clean) joint catalogue of seismic events of the Eastern Baltic region. Abbreviations as in Table 1**

3 lentelė. **Galutinis bendras Rytų Baltijos regiono Žemės drebėjimų katalogas. Sutartinius ženklus žr. 1 lentelėje**

| Year | Month | Day | Hour | Min | Sec | RI | Lat. | Long. | Depth | Agency | MAG | MAG | MAG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1375 | | | | | | L | 57.5 | 18.5 | 10 | KJW | 4.0 MKJW | | |
| 1540 | | | | | | L | 57.7 | 18.7 | 5 | KJW | 4.3 MKJW | | |
| 1572 | 1 | 6 | 8 | | | L | 53 | 18.5 | 5 | POL | 4.9 WPOL | 3.0 S | |
| 1602 | | | | | | L | 59.5 | 24.7 | 5 | BLR | 3.8 LBLR | 6.0 iBLR | |
| 1607 | | | | | | L | 59.7 | 24.7 | 5 | BLR | 3.8 LBLR | 6.0 iBLR | |
| 1616 | 6 | 30 | 5 | 30 | | L | 56.4 | 24.2 | 5 | EEP | 4.1 LEEP | 6.5 iBLR | 4.0 IDOS |
| 1670 | 2 | 1 | 22 | | | L | 58.4 | 24.5 | 8 | DSI | 3.9 LBLR | 3.9 MDSI | 6.0 iBLR |
| 1785 | 10 | 11 | | | | L | 57.4 | 21.6 | | DOS | 3.5 LBLR | 3.5 IDOS | 5.0 iBLR |
| 1803 | 1 | 8 | 23 | 15 | | L | 53.1 | 23.1 | 5 | BLR | 3.6 LEEP | 6.0 iBLR | 3.6 LBLR |
| 1821 | 2 | 22 | 7 | 30 | | L | 56.6 | 25.3 | 13 | EEP | 4.5 LEEP | 7.0 iBLR | 4.5 LBLR |
| 1823 | 2 | 6 | 0 | | | L | 58 | 26.2 | 7 | DSI | 3.9 LBLR | 7.0 iBLR | 3.9 MDSI |
| 1827 | 9 | 28 | 12 | | | L | 59 | 23.5 | 14 | DSI | 4.0 LEEP | 4.0 MDSI | 5.0 iBLR |
| 1844 | 1 | 12 | 22 | | | L | 58.6 | 23.7 | 6 | DSI | 2.5 LBLR | 2.5 MDSI | 4.0 iBLR |
| 1853 | 2 | 5 | 2 | | | L | 56.7 | 25.6 | | DOS | 3.5 LBLR | 6.0 iBLR | 2.9 IDOS |
| 1853 | 3 | 26 | 1 | 30 | | L | 59.5 | 24.7 | 5 | DSI | 1.2 LBLR | 1.2 MDSI | 2.5 iBLR |
| 1853 | 12 | 29 | 23 | 45 | | L | 56.96 | 24.13 | | DOS | 3.5 LBLR | 3.5 IDOS | 6.0 iBLR |
| 1857 | 5 | 18 | 9 | | | L | 57.8 | 22.2 | 10 | DOS | 4.5 LEEP | 3.0 MDOS | 7.0 iBLR |
| 1858 | 1 | 15 | 14 | 10 | | L | 59.3 | 22.6 | 8 | DSI | 3.0 LBLR | 3.0 MDSI | 5.0 iBLR |
| 1869 | 2 | 15 | 3 | | | L | 59.5 | 24.7 | 6 | DSI | 2.5 LBLR | 2.5 MDSI | 5.0 iRBS |
| 1870 | 2 | 6 | 4 | 45 | | L | 56.96 | 24.13 | | DOS | 3.5 LBLR | 3.5 IDOS | 5.0 iBLR |
| 1877 | 10 | 16 | 5 | 25 | | L | 59 | 23.5 | 10 | DSI | 4.2 LEEP | 3.5 MDSI | 6.0 iBLR |
| 1881 | 1 | 28 | 14 | 15 | | L | 59.4 | 28.2 | 4 | DSI | 3.2 LBLR | 3.0 MDSI | 5.5 iBLR |
| 1887 | 12 | 10 | | | | L | 54.2 | 28.5 | 10 | EEP | 3.7 LEEP | 3.7 PPAN | 6.0 iBLR |
| 1893 | 8 | 29 | 5 | 50 | | L | 53.89 | 30.34 | 7 | BLR | 3.5 LBLR | 5.0 iBLR | |
| 1896 | 9 | 20 | 15 | | | L | 56.7 | 23.7 | 5 | DOS | 3.5 LEEP | 3.5 IDOS | 5.0 iBLR |
| 1896 | 11 | 12 | 8 | 30 | | L | 53.89 | 30.34 | 7 | BLR | 4.0 LBLR | 6.0 iBLR | |
| 1907 | 1 | 22 | 2 | | | L | 56.9 | 24.07 | 7 | BLR | 3.5 LBLR | 5.0 iBLR | |
| 1908 | 12 | 28 | 5 | | | L | 54.6 | 25.8 | 9 | BLR | 4.5 LBLR | 7.0 iBLR | |
| 1908 | 12 | 29 | 1 | | | L | 56.8 | 26.3 | 10 | BLR | 4.5 LBLR | 7.0 iBLR | |
| 1908 | 12 | 29 | 3 | 30 | | L | 56.94 | 24.07 | 10 | BLR | 3.5 LBLR | 5.5 iBLR | |
| 1908 | 12 | 29 | 22 | | | L | 55.8 | 26.7 | 11 | EEP | 4.5 LEEP | 6.5 iBLR | 4.5 LBLR |
| 1908 | 12 | 29 | | | | L | 57.5 | 25.7 | | BLR | 3.5 LBLR | 6.0 iBLR | |
| 1908 | 12 | 30 | | | | L | 54.308 | 22.3 | | POL | 2.9 LBLR | 3.5 IPOL | |
| 1909 | 2 | 12 | 1 | | | L | 56.6 | 20.2 | | BLR | 3.5 LBLR | 3.0 iBLR | |
| 1909 | 6 | 2 | 8 | 30 | | L | 58.4 | 25.6 | 7 | SIL | 1.8 LBLR | 1.8 MSIL | 3.0 iBLR |
| 1910 | 5 | 21 | 3 | | | L | 56.95 | 24.05 | 10 | BLR | 4.0 LBLR | 6.0 iBLR | 4.0 LEEP |
| 1912 | 6 | 15 | | | | L | 59.7 | 25 | 6 | DSI | 2.0 LBLR | 2.0 MDSI | 3.5 iBLR |
| 1931 | 7 | 12 | 22 | | | L | 59.4 | 25.3 | 5 | KSI | 3.0 LBLR | 4.5 iBLR | 2.5 MKSI |
| 1932 | 2 | 24 | 19 | | | L | 52.6 | 20.03 | | POL | 4.5 LPOL | | |
| 1972 | 9 | 4 | 0 | 26 | 33 | L | 57.1 | 18.4 | 0 | WAH | 2.4 LWAH | | |
| 1976 | 10 | 25 | 8 | 39 | 45 | L | 59.26 | 23.39 | 14 | KON | 4.7 LBLR | 4.7 BKON | 6.5 iBLR |
| 1978 | 5 | 10 | 9 | 5 | | L | 52.8 | 27.7 | 10 | BLR | 3.5 LEEP | 3.5 LBLR | 4.5 iBLR |
| 1979 | 7 | 24 | 16 | 2 | 46.4 | L | 55.45 | 19.7 | 0 | HEL | 2.7 LHEL | | |
| 1980 | 1 | 9 | 1 | 24 | 52.4 | L | 58.91 | 22.99 | 0 | HEL | 2.4 LHEL | | |
| 1981 | 6 | 22 | 19 | 27 | 37.7 | L | 59.45 | 22.66 | 7 | HEL | 2.6 LHEL | | |
| 1982 | 6 | 2 | 7 | 58 | 17.7 | L | 57.04 | 21.94 | 0 | HEL | 2.3 LHEL | | |
| 1983 | 12 | 1 | 22 | 26 | 34 | L | 52.95 | 27.81 | 7 | BLR | 2.8 LBLR | 4.5 iBLR | |
| 1985 | 10 | 17 | 1 | 32 | 24 | L | 52.9 | 28.4 | 7 | EEP | 3.1 LEEP | 4.0 iBLR | 3.1 LBLR |
| 1987 | 4 | 8 | 23 | 2 | 22 | L | 58.4 | 26.1 | 14 | BLR | 3.5 LBLR | 3.5 SIL | 5.0 iBLR |
| 1987 | 9 | 22 | 18 | 25 | | L | 58.7 | 26.4 | 9 | BLR | 3.0 LBLR | 4.5 iBLR | |
| 1988 | 4 | 29 | 15 | 36 | 52 | L | 56.97 | 19.53 | 1 | BER | 3.5 LHEL | 3.3 CBER | |
| 1988 | 4 | 29 | 15 | 41 | 22.7 | L | 56.32 | 21.4 | 7 | BER | 3.3 LHEL | 3.2 CBER | 3.1 LBER |
| 1988 | 9 | 2 | 19 | 17 | | L | 58.8 | 26.4 | 7 | BLR | 2.9 LBLR | 5.0 iBLR | |
| 1994 | 3 | 12 | 7 | 56 | 58.6 | L | 55.2 | 17.91 | 0 | BER | 2.4 LBER | | |
| 1995 | 3 | 6 | 10 | 24 | 24.3 | L | 55.04 | 30.82 | 18 | BER | 2.2 LBER | | |
| 1998 | 3 | 16 | 4 | 9 | 5.6 | L | 52.87 | 27.6 | 0 | BLR | 1.9 LBLR | 4.5 iBLR | |
| 2002 | 12 | 18 | 21 | 14 | 21.9 | L | 56.115 | 17.99 | 2.2 | HEL | 3.5 LHEL | 4.2 BUSG | 3.5 LBER |
| 2003 | 1 | 12 | 11 | 43 | 47.8 | L | 59.402 | 23.415 | 10 | HEL | 1.2 LHEL | | |
| 2004 | 1 | 28 | 15 | 40 | 0.2 | L | 58.792 | 23.851 | 10 | HEL | 1.6 LHEL | | |
| 2004 | 9 | 21 | 13 | 32 | 31.9 | L | 54.834 | 20.025 | 10 | HEL | 5.0 LHEL | 4.8 WLGS | 4.7 WHRV |
| 2006 | 11 | 6 | 1 | 11 | 40.3 | L | 59.677 | 24.857 | 2.7 | HEL | 1.1 LHEL | | |

The majority of events from the FENCAT and the Joint Catalogue of the Eastern European Platform, as well as from the catalogue of Belarus and the Baltic states have local magnitudes. Local magnitudes may have quite significant uncertainties (up to 1.0–1.5). However, it is quite a complicated and ambiguous problem to convert small local magnitudes to moment magnitudes, and this problem will be addressed in the further studies (Sharov, 2007). Therefore, a local magnitude type is presented in the joint seismic catalogue of the Eastern Baltic region.

The seismic events of the joint catalogue of the Eastern Baltic region were revised to identify aftershocks (A), foreshocks (F) and induced events (I). Also, events of non-natural origin were removed from the final catalogue of the Eastern Baltic (Table 3).

## COMPLETENESS OF SEISMIC CATALOGUE

The magnitude distribution in the joint catalogue versus time was drawn to analyse the completeness of the catalogue. A natural tendency was noted: if the events were older, the number of events having smaller magnitudes was less, and this number was increasing with time.

The joint catalogue includes both the onshore and offshore parts of the Eastern Baltic region. In the continental part, the catalogue included historical events reported by written sources and instrumental events recorded by seismic stations. The marine part of the catalogue was based on instrumentally recorded events only as there were no earthquakes which would have been reported in historical sources in the sea.

It is evident from the plot of seismic events (Figs. 8, 9) that the number of registered earthquakes significantly increased since 1844. This year could be assumed as the lower cut-off for the "full" catalogue. The distribution of seismic events in time is rather uneven since 1844; this fact may can be explained in terms of the natural geological phenomena or, alternatively, by social processes. For example, only one seismic event was reported in 1912–1972; this, in a way, might be related to social perturbations (two world wars). On the other hand, such an explanation does not look consistent enough because a number of seismic stations have been installed in the region and nearby after World War II.

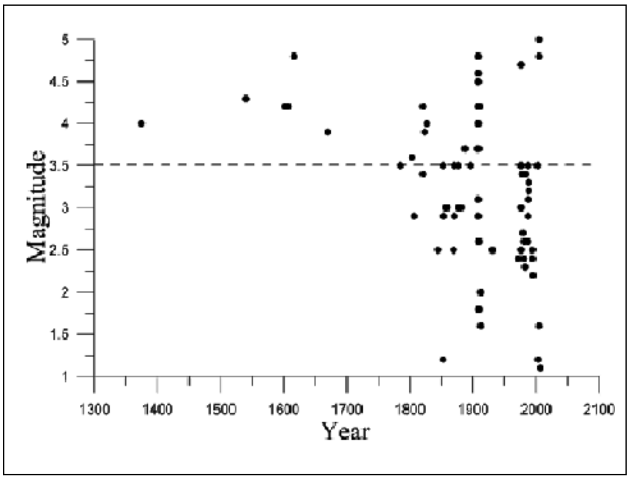

**Fig. 8.** Time distribution of earthquake magnitudes in the united catalogue
**8 pav.** Užregistruotų skirtingos magnitudės Žemės drebėjimų pasiskirstymas laike

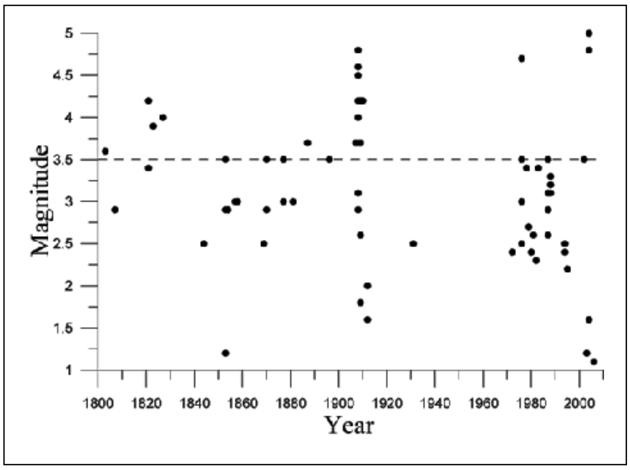

**Fig. 9.** Time distribution of earthquake magnitudes in the united catalogue for years 1800–2010. Note earthquake activity in 1908–1909
**9 pav.** Užregistruotų skirtingos magnitudės Žemės drebėjimų pasiskirstymas laike 1800–2010 m.

A quantitative approach by Stepp (1972) is widely used. This technique seeks to determine, for each magnitude, the time interval over which the mean rate of occurrence (λ) is stable. Given these stable occurrence rates, the completeness of the catalogue can be analysed.

According to Stepp's theory, λ is constant, the standard deviation (σ) varies as 1/SQRT(T), where T is the time interval of the sample. Figure 10 plots decade increments of σ versus T. It indicates the data of the catalogue to be quite poor. With some reservation, one can state that the catalogue is stable for magnitudes $4.1 \le M \le 5$ from 1990 back to 1770 and for magnitudes $3.5 \le M \le 4$ from 1900 back to 1770. It was assumed that the joint catalogue is "full" from 1780. However, these results contradict the natural logic as a number of new seismic stations have been installed in Scandinavian countries starting from 1980, which were capable to detect seismic events of $M \ge 2.5$ magnitudes (unpublished report of the Lithuanian Geological Survey), and the seismic catalogue of the Helsinki University was started in 1990. Therefore, it is almost impossible that seismic events with the magnitudes $M \ge 2.5$ could be not recorded since 1990. Probably the absence of seismic events of lower magnitudes during the last decades is related to natural phenomena, as is also the absence of seismic events in the middle of the 20th century, although the factor of natural perturbations cannot be ruled out, either.

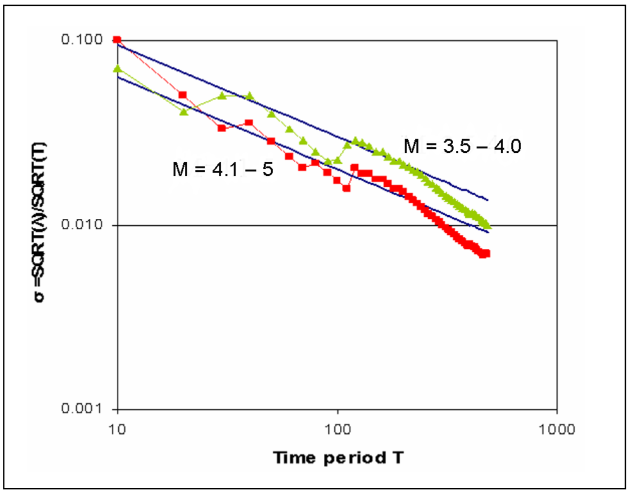

**Fig. 10.** Standard deviation (σ) of estimate of the mean rate of earthquake occurrence (λ), noted in the final catalogue of the Eastern Baltic region
**10 pav.** Žemės drebėjimų pasikartojimo dažnio (λ) standartinis nuokrypis (σ) pagal bendrą Rytų Baltijos regiono seismologinį katalogą

## MAGNITUDE FREQUENCY DISTRIBUTION IN THE BALTIC REGION

For assessing the seismic hazard, the B-value is an important parameter which defines the distribution of seismic events of different magnitude. There are not so many events in the Eastern Baltic region seismic catalogue, and the amount of events in each single seismogenic zone is even smaller. Thus, due to the lack of information it is difficult to find the reliable value of the parameter B for a certain zone. The geological features and tectonic stresses are quite homogeneous in all study area; thus, it was assumed that the parameter B has the same value for all the region and for each separate zone. The parameter B was calculated using the complete catalogue. It was found to be as high as 0.66 (standard deviation 0.12). The BVALUE program from SEISAN 8.2 software suite was used to calculate the B value (Fig. 11). For the sake of comparison, it may be noted that for Finland the B value is 0.59, i. e. quite similar to that estimated for the East Baltic region. It is somewhat lower than that defined for stable continental cratons (0.8) (e. g., Sharov et al., 2007).

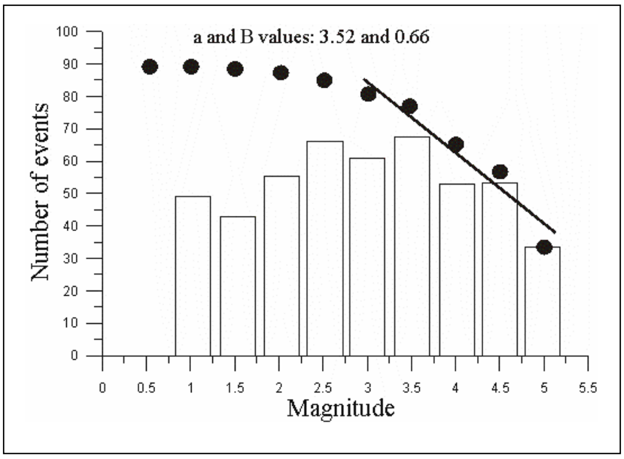

**Fig. 11.** Distribution of earthquake magnitudes within different magnitude limits. Columns show the distribution of different magnitudes. Circles show the total distribution of number of events of different magnitudes and the straight line shows the parameter B value
**11 pav.** Žemės drebėjimų magnitudžių pasikartojimas. Kolonėlės žymi skirtingos magnitudės Žemės drebėjimų skaičių, linija – B parametro liniją

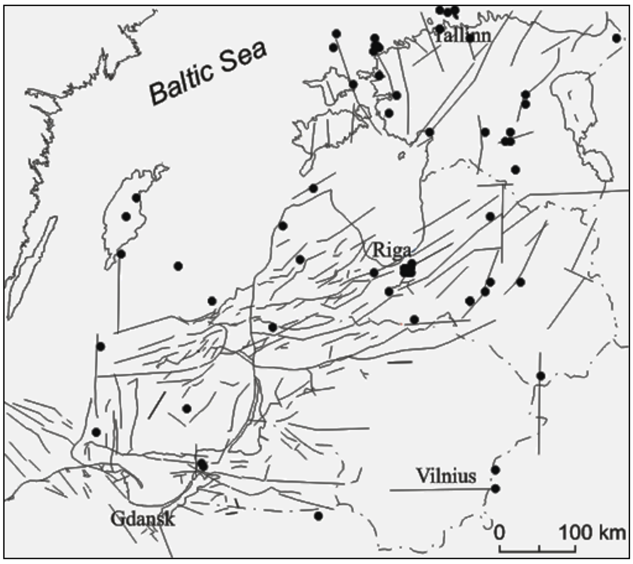

**Fig. 12.** Major faults defined in the sedimentary cover of the Baltic sedimentary basin, and earthquake epicentres
**12 pav.** Pagrindiniai Baltijos sedimentacinio baseino nuosėdinės dangos lūžiai ir Žemės drebėjimų epicentrai

## DISCUSSION

The new unified seismic catalogue unravels a very uneven distribution of seismic activity in the East Baltic region. It is attributed to several factors. The glacioisostatic processes are still active in Estonia and possibly in Latvia, as indicated by the distribution of the recent vertical ground movements defined by precise levelling, and by changes of the gravity field (Klaus, 2004; Oja, 2008; Saarse et al., 2003; Trim, 1998; Vallner et al., 1988; Torim, 1998). These processes ceased in the Lithuanian territory several thousand years ago (Šliaupa et al., 2005). Furthermore, the earth's crust of the region was subject to different faulting in various parts of the Baltic sedimentary basin. The Latvian territory hosts the most abundant network of faults. In Lithuania, the western part of the country is more tectonised, while only small-scale faults predominate in the east.

Most of the registered earthquakes are associated with known faults and fault zones. For instance, the Daugavpils earthquake of 1908 (east Latvia) was related to a block shift along the north-south trending Anisimovitshi fault zone. Some parts of the fault zone were initiated as early as the

Vendian–Lower Cambrian time and were most active during the Late Devonian–Carboniferous. The amplitude of the fault zone reaches 50 m. The Kaliningrad earthquakes of 2004 took place along the Prieglius fault zone trending WNW–ESE (Pačėsa et al., 2006). The amplitude of the fault zone is about 50 m. Several earthquakes were registered in the Baltic Sea. In the Polish offshore area they are related to the large-scale Leba ridge which hosts a number of oil and gas fields. Its amplitude reaches 600 m. The cluster of earthquakes in Latvia is associated with the largest-scale Liepaja–Saldus ridge formed during the latest Silurian–earliest Devonian and active throughout the Devonian. The amplitude of the zone is up to 600 m. Particular earthquakes are related to known individual faults, e. g., the Bauske fault (Bauske earthquake).

Such a close lateral association of faulted structures and earthquakes allows the identification and inventory of seismically active faults in the Baltic region, which should be performed in future.

## CONCLUSIONS

The unified seismological catalogue of the East Baltic region provides an important base for seismic hazard assessment. It is essentially required in view of the prospects of establishing new nuclear power plants in the region (Kaliningrad District, Belarus, east Lithuania) (Varpusuo et al., 2001; Šliaupa et al., 2006). The catalogue covers the time period since 1375. The catalogue has unravelled quite an uneven distribution of seismic events both in the latter and the temporal terms. The periods of seismic activity, like the one in 1908–1909, are followed by periods of seismic quiescence (e. g., 1912–1972). It is rather difficult to explain such a variability of seismic activity. In terms of the lateral variability, it is explained by a different degree of faulting of the earth's crust in the Baltic sedimentary basin and by the remaining glacioisostatic activity.

The catalogue shows that only strong earthquakes were registered until 1844. Since this year, the reporting has become much more precise. Therefore, the catalogue is considered complete only after this time. Some oldest reports of earthquakes of 1303 and 1324 in Prussia and Lithuania, respectively, should be still discussed in detail to identify the consistency of their annals.

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## RYTINĖS BALTIJOS REGIONO SEISMINGUMAS IR ŽEMĖS DREBĖJIMŲ KATALOGAS

*Santrauka*

Baltijos regionas pasižymi nedideliu seisminiu aktyvumu. Regiono teritorija yra Rytų Europos kratono vakarinėje dalyje. Kratono terminas nusako santykinai stabilią žemyno teritoriją, pasižyminčią mažu tektoniniu aktyvumu. Lietuvoje ir gretimose valstybėse praeityje ir dabar vykstantys tektoniniai bei su jais susiję procesai yra neintensyvūs ir neretai sudaro įspūdį, kad čia nevyksta jokie geodinaminiai procesai. Vis dėlto turimi geologiniai, geofizikiniai, geodeziniai ir kiti tyrimai rodo, kad Baltijos regionas yra veikiamas tektoninių jėgų. Žemės pluta yra suskaldyta įvairaus dydžio tektoninių lūžių, kurie formavosi skirtingais geologiniais periodais ir ne kartą buvo aktyvizuoti. Visa tai lemia horizontalius ir vertikalius tektoninių blokų judesius. Kartais šie judėjimai pasireiškia pakankamai stipriais Žemės drebėjimais, kurie Baltijos regione jau aprašyti istoriniuose analuose nuo XIV a. pradžios.

Žemės drebėjimų rizika priklauso ne tik nuo seisminio potencialo (t. y. kokio stiprumo gali būti Žemės drebėjimas viename ar kitame regione), bet ir nuo to, kaip pasirengta tokiems įvykiams (reikalavimai statinių konstrukcijai, visuomenės pasiruošimas gamtos nelaimėms). Todėl būtina detaliai ištirti teritorijos seisminio pavojaus galimybes, nustatyti padidintos rizikos zonas, į kurias būtų atsižvelgiama planuojant teritorijas.

Seisminio pavojaus vertinimo tyrimai Baltijos regione, taip pat ir Lietuvoje, pradėti neseniai – tik 9-ajame dešimtmetyje. Sukaupta medžiaga patvirtino realią Žemės drebėjimų grėsmę regione. Pastaraisiais metais naujausių tektoninių procesų pažinimą gerokai pakeitė atsiradę nauji tyrimų metodai (pvz., kosminė geodezija, giluminis seisminis zondavimas). Planuojami nauji didesnės ekologinės rizikos objektai Lietuvoje ir šalia jos (pvz., Visagino atominė elektrinė, netoli Lietuvos sienos planuojamos atominės elektrinės Baltarusijoje ir Kaliningrado srityje, plečiami chemijos pramonės objektai ir pan.) verčia išsamiai įvertinti seisminį pavojų.

Regioniniai seisminiai stebėjimai ir istoriniai duomenys rodo, kad Rytų Europos platformos periferijai, palyginti su jos vidine dalimi, būdingas didesnis seisminis aktyvumas, sietinas su didesniu tektoninių jėgų, kurios kyla už platformos ribų, poveikiu. Tad nenuostabu, kad Baltijos regionas, esantis vakariniame platformos pakraštyje, taip pat pasižymi santykinai didesniu seisminiu aktyvumu. Be to, šiaurinę regiono dalį veikia ir liekaniniai glacialiniai izostazijos procesai. Žemės drebėjimų, fiksuojamų Baltijos regione (ir apskritai platformoje), stiprumas yra gana tipiškas kratoniniams regionams – iki šiol užregistruotų Žemės drebėjimų magnitudė neviršija M = 5,5. Vis dėlto ši reikšmė pakankamai ženkli: tokie intensyvūs Žemės drebėjimai gali sukelti riboto dydžio infrastruktūrinius pažeidimus, ypač išplėtotuose industriniuose regionuose, kur nemažai ekologijai pavojingų objektų.

Pirmieji liudijimai apie Žemės drebėjimus pateikti jau XIV a. pradžioje (Prūsijos 1303 m. ir Skirsnemunės 1328 m. įvykiai) – taigi seismologinė informacija gana išraiškingai byloja apie pastarųjų 700 metų seisminį aktyvumą regione. Tiesa, reprezentatyvūs Žemės drebėjimų aprašymai pateikiami tik nuo XIX a. vidurio.

Vertinant regiono seisminį pavojingumą, labai svarbu sudaryti išsamų ir bendrą Žemės drebėjimų katalogą. Iki šiol skirtingi autoriai sudarė keletą tokių katalogų (pradedant Dosso darbais XX a. pradžioje). Šiame darbe buvo surinkta informacija apie 88 Žemės drebėjimus, įvykusius Baltarusijos teritorijoje ir Baltijos regione. Galima teigti, kad katalogas gerokai pasipildė 1844 m., kai labai padaugėjo fiksuojamų Žemės drebėjimų. Taip pat buvo parengtas atskiras seisminis katalogas be lydimųjų smūgių, kuris gali būti naudojamas tikimybinei teritorijos seisminio pavojingumo analizei. Stipriausias žinomas Žemės drebėjimas (M = 5,2) užfiksuotas Kaliningrado srityje 2004 metais. Sudarytas Žemės drebėjimų pasiskirstymo žemėlapis rodo labai netolygų seisminių įvykių pasiskirstymą, ir tai siejama su netolygiu teritorijos tektoniniu pažeidimu (lūžiai), taip pat netolygiu liekamuoju glacialinių izostazijos procesų poveikiu. Sudarytas seisminių įvykių katalogas yra svarbus pagrindas tolesniems teritorijos seisminio pavojingumo vertinimams.

**Raktažodžiai:** Baltijos regionas, Žemės drebėjimų katalogas, seismingumas, lūžis