Operational Procedures of Agencies Contributing to the ISC

Seismological Monitoring in Latvia

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Latvia

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6.2 Seismological Monitoring in Latvia

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The development of modern seismological monitoring in Latvia was set up after the Kaliningrad earthquake on September 21, 2004 where the magnitude of the main shock reached $M_W = 5.2$ (*Gregersen et al.*, 2007) and the intensity of shaking at the epicentre was 6.5 points according to the MSK-64 scale (*Nikonov et al.*, 2005). In the south of Latvia (village of Kalni and town of Saldus), the intensity of shaking reached 5 points on the EMS-98 scale (*Nikulin*, 2005). In October 2006, the Slītere station was created in the north-west of Latvia, which became part of the GEOFON international seismic network of GFZ Potsdam, Germany. Thanks to the cooperation agreement between the Latvian Environment, Geology and Meteorology Center (LEGMC) and GFZ Potsdam, it became possible not only to create a seismological station with modern instruments and equipment, but also to use other stations of the GEOFON network as well as some stations of national networks in the Baltic region to localise seismic events in the East Baltic Region (EBR), which covers Estonia, Latvia, Lithuania, the Kaliningrad region of Russia and the adjacent part of the Baltic Sea (Lat: 53.9° – 59.7° N; Lon: 19,4°E – 29.6°E, see box in Figure 6.8). This article describes the history of seismological monitoring in Latvia, presents the characteristics of the data acquisition (since 2006) and processing, gives some review of the natural and technogenic seismicity of the East Baltic region and briefly discusses the problems of monitoring tectonic earthquakes and man-made seismic phenomena. Prospects for optimizing the seismological monitoring are outlined as well.

6.2.1 Regional Seismicity and History of Seismological Monitoring in Latvia

Latvia is located in the west of the East European Platform (EEP) with a very low level of natural seismic activity (*Nikulins*, 2011). Its territory is more than 1800 km away from the divergent border in the North Atlantic and the convergent border in the Mediterranean Sea. However, there is intraplate, natural seismicity.

In Latvia, historical earthquakes occurred in 1616 in the Bauska region, in 1821 in the Koknese region, in 1857 in the Irben Strait and in 1896 in the Jelgava region (*Doss*, 1909; *Avotinja et al.*, 1988). In Estonia, historical earthquakes occurred in 1670 in the Pärnu region, in 1823 in the Kuigatsi region, in 1827 in the Haapsalu region, and in 1881 in the Narva region. Modern EBR earthquakes occurred in

1976 on the island of Osmussaare, in the shelf zone of Estonia (M = 4.7) (*Kondorskaya et al.*, 1988), and in 2004 in the Kaliningrad region of Russia (M_W = 5.0 and 5.2) (*Gregersen et al.*, 2007).

Since the Kaliningrad earthquakes caused damage in the territory of Latvia, the need arose to monitor the seismic regime throughout the territory of the EBR to assess the seismic hazard of the territory of Latvia. This chapter provides an overview of the development of seismological observations in Latvia.

The Early History of Seismological Observations in Latvia

The beginning of seismological observations in Latvia dates back to the 1960s when, with the help of the Department of Earth Physics of Moscow State University, the seismic station "Baldone" operated in the territory of the Radio-Astrophysical Observatory of the Academy of Sciences of Latvia until 1991. A long-period seismograph SD-1 was installed at the station. Teleseismic and strong earthquakes were recorded together with other stations in Minsk, Moscow and Pulkovo, and the deep structure of the Earth's crust and mantle was estimated based on the analysis of converted phases and the determination of dispersion curves of phase and group velocities of surface waves (*Hot'ko*, 1974).

The second stage of seismological observations dates back to 1994, when the State Geological Survey of Latvia created the short-period, analogue seismic station Skujas in the Valmiera region in the north-east of Latvia. In addition, a three-component seismic recorder (GBV-316) was installed at the station in 2000. Skujas station operated until 2013 and was then closed. The station recorded over 2,900 seismic events, including over 1,400 teleseismic and 550 regional seismic events. 600 seismic events could not be identified as man-made seismic events or tectonic earthquakes because only one analogue seismic station was used.

The Modern Stage of Seismological Observations

The third stage of instrumental observations in Latvia began after the Kaliningrad earthquakes in 2004, when the Latvian Environment, Geology and Meteorology Center, together with GFZ Potsdam, created the Slitere seismic station in northwestern Latvia. Participation in the GEOFON network allowed access to seismic stations in the Baltic region and the creation of the Baltic Virtual Seismic Network (BAVSEN). BAVSEN includes its own Slitere station (SLIT), a number of stations of the GEOFON network (PABE, PBUR, VSU, PUL), as well as some stations of national networks of countries in the Baltic region (Fig. 6.8), in particular stations of Finland (MEF, RAF), Estonia (MTSE, ARBE), Denmark (BSD) and Poland (SUW). To localise regional EBR seismic events, 6 stations were mainly used (SLIT, VSU, MTSE, ARBE, MEF, RAF).

The Finnish stations (MEF and RAF) play an important role in the localization of regional seismic events in EBR, since they are located on the crystalline basement of the Fennoscandian shield in very favourable seismic and geological conditions. Often, the first P-wave can be confidently identified on the records of these stations. However, in 2019, data availability from the RAF station was sometimes limited. Lithuanian stations (PABE, PBUR) were used much less frequently for localization of seismic events in EBR. Almost no stations were used in Poland (SUW) and Denmark (BSD) for localization of regional seismic events in EBR. In addition, some stations stopped registering (SRPE - Estonia),

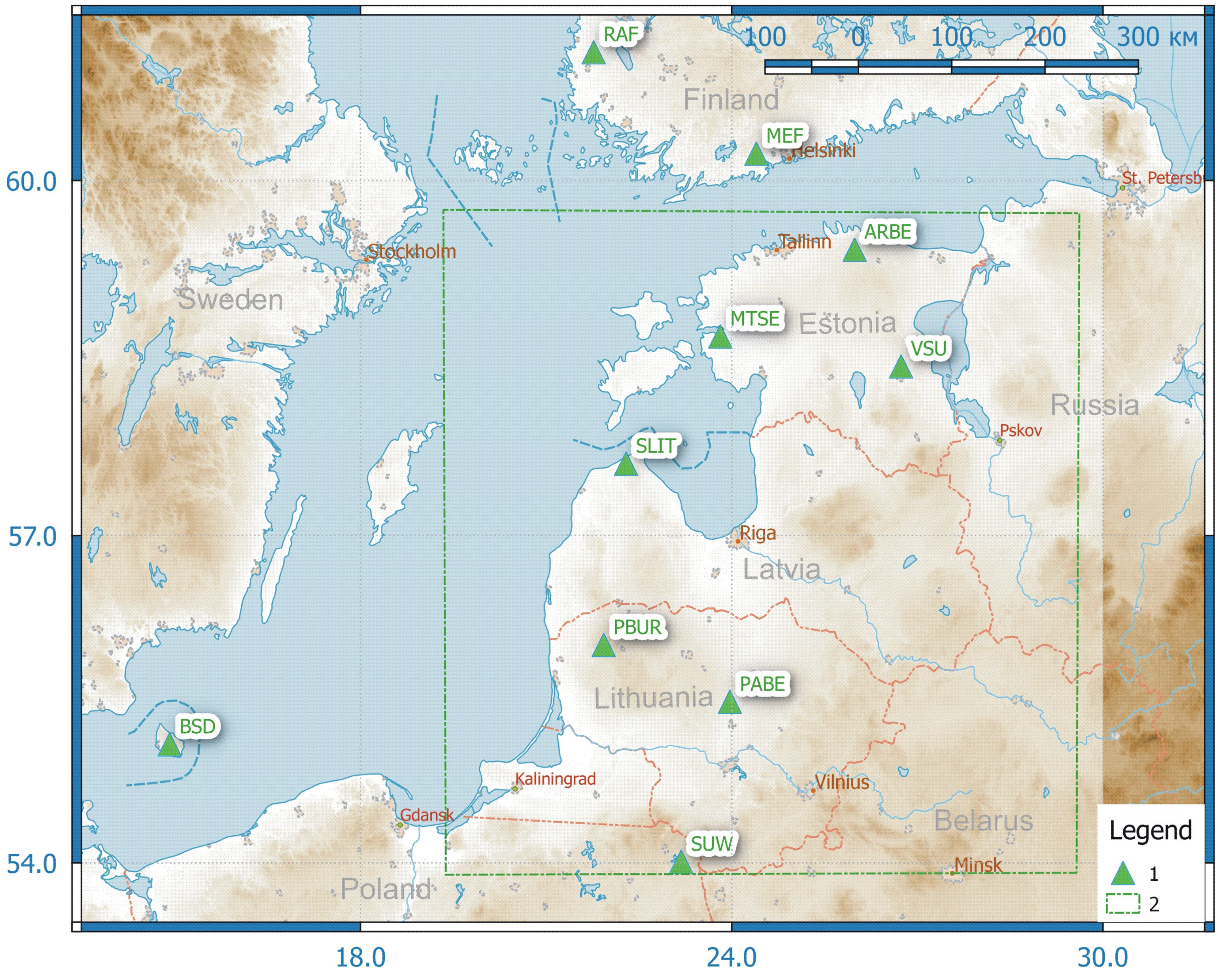

Figure 6.8: *Baltic virtual seismic network BAVSEN. Labels: 1 - seismic stations; 2 - border of the East Baltic region (Estonia, Latvia, Lithuania, Kaliningrad region of Russia, western part of the Pskov region of Russia, northwestern Belarus, part of north-east Poland, adjacent waters of the Baltic Sea.*

or access to the data of these stations from the GFZ Potsdam server (PUL - Russia) was terminated. Therefore, from 2015 it was necessary to switch to high-frequency HH* channels, although from 2008 to 2015 broadband BH* channels were used for localisation.

For the localization of teleseismic events with magnitudes greater than 5.5, a larger number of stations were used, including PABE, PBUR, SUW and BSD. However, the quality of hypocentre localization of remote seismic events was low because of the large azimuthal gap for BAVSEN network stations. The Latvian seismic station Slitere is located in the north-west of Latvia in the Kurzeme region. The station is located 5.5 km from the coast of the Baltic Sea in the territory of the Slitere lighthouse (Fig. 6.9). The sensor is located at a depth of 6.5 m from the surface of the ground in moraine deposits.

6.2.2 Data Aquisition

The Slitere station, like other stations of the GEOFON network, is equipped with typical seismological equipment, which consists of the following main elements (Fig. 6.10): STS-2 sensors, PS6 Earth Data 24 analogue-to-digital converter, SeisComp software and communications unit, GPS antenna. SeisComp is seismological software for the collection, processing, dissemination and interactive analysis of data,

Figure 6.9: *Seismic station Slitere (Latvia). 1 - lighthouse "Slitere"; 2 - entrance to the instrumental bunker; 3 - tool house; 4 - SeisComp unit and analogue-to-digital converter PS6 Earth Data 24; 5 - a view of the STS-2 sensor from the height of the upper compartment; 6 - a view of the STS-2 sensor from the height of the middle compartment.*

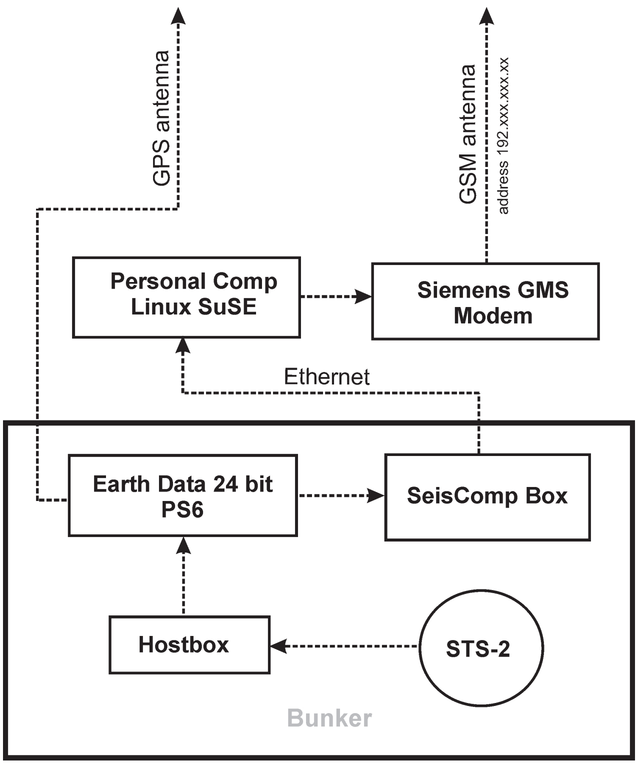

Figure 6.10: *Scheme of typical equipment of a GEOFON seismic network station.*

developed at Potsdam by the German Geoscience Research Center GFZ and gempa GmbH. A schematic diagram of a typical GEOFON station is presented in Figure 6.10.

The Streckeisen STS-2 Broadband Sensor has three inertial pendulums with angular geometry. In the vertical plane, the axis of the pendulums are oriented at an angle of 54.7° relative to the vertical axis. In the horizontal plane, the axis of the pendulums are oriented approximately at an angle of 120° from each other. The generator constant has a value of 1500 ± 15 V $\cdot$ s/m. The frequency range covers the band from 0.00833 to more than 50 Hz. Many stations in the GEOFON network use high-frequency HH*, broadband BH*, low-frequency LH*, and ultra-low-frequency VH* channels.

The seismological data is sent as MiniSeed from the stations to the servers at GFZ Potsdam via internet, and from Slitere to the LEGMC processing center (Fig. 6.11).

The download for the several stations required for the localisation of events takes place automatically from the GFZ Potsdam server in accordance with the SeedLink data transfer protocol.

6.2.3 Analysis

At the next stage, seismic events are sampled in GSE1.0 format using SeismicHandler (*Stammler*, 1993). Further, initial information is processed in the environment of Seisan (*Havskov and Ottemöller*, 1999), a seismic analysis system consisting of a set of programs and a database.

For hypocentre location, a modified version of the Hypocenter program is used (*Lienert et al.*, 1986; *Lienert and Havskov*, 1995). The main modification is the ability to use more phases of seismic waves, localise teleseismic events and use the Nordic format directly from the database. Four seismic velocity

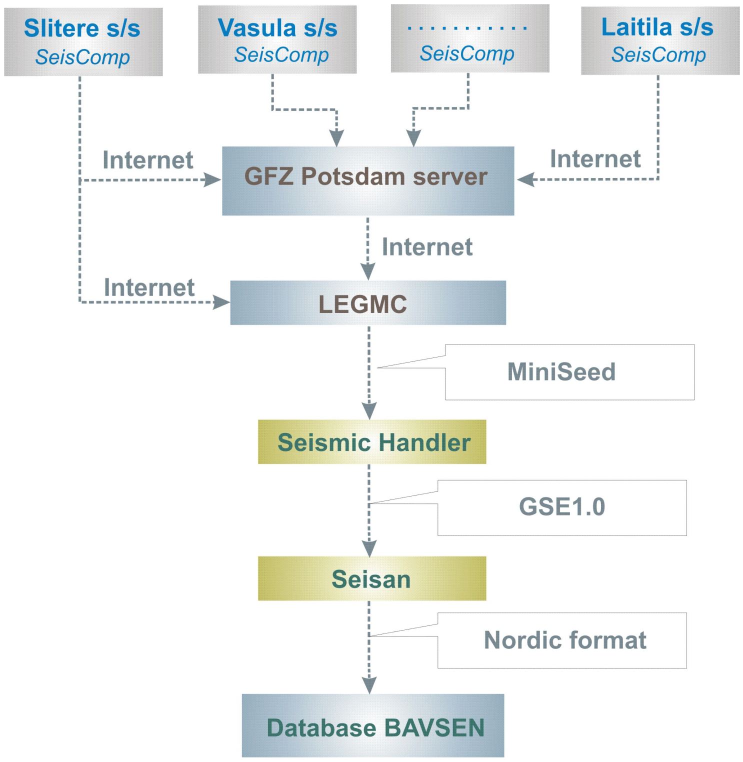

Figure 6.11: *Flow chart of transmission of seismological information from the stations to the servers, data formats, software and processing steps.*

models are used for locating regional seismic events: iasp91 (*Kennett and Engdahl*, 1991), Helsinki model – hel (Institute of Seismology, University of Helsinki), Fennoscandian model (fen) and proprietary model baltic08.

The baltic08 regional velocity model was created based on the results of deep seismic sounding using the Sovetsk – Riga – Kohtla-Järve 563.4 km long geo-traverse (*Sadov and Penzina*, 1986). According to these studies, the deep geological structure of the East Baltic region has the following features: (1) the Earth's crust is characterised by a depression; (2) the Mohorovičić discontinuity can be distinguished into three parts: northern (PK 600 - PK 420, PK = pickets, km along seismic profile), central (PK420 - PK170) and southern (PK170 - PK130); (3) the crust in the northern and southern parts is less thick (46 and 40 km) than in the central part, where it shows an anomalous deep base of the Earth's crust with 64 km; (4) five layers can be distinguished within the Earth's lithosphere: M1 - crust-mantle-boundary; M2 - intramantle border; IV, II' and II - intracrustal borders. The baltic08 model consists of 5 layers shown in Table 6.3.

Seismic Background Noise Characteristic

The characteristics of the seismic background noise gives an idea of the capabilities of the seismic stations of the BAVSEN network. Figure 6.12 shows the spectral power density of seismic noise in busy periods (daytime, during working hours (May 22, 2019 from 09:20 to 09:40 - red curve) and quiet periods (at night during the weekend (May 25, 2019 from 23:20 to 23:40 - blue curve) for stations of the BAVSEN network, mainly located in the EBR.

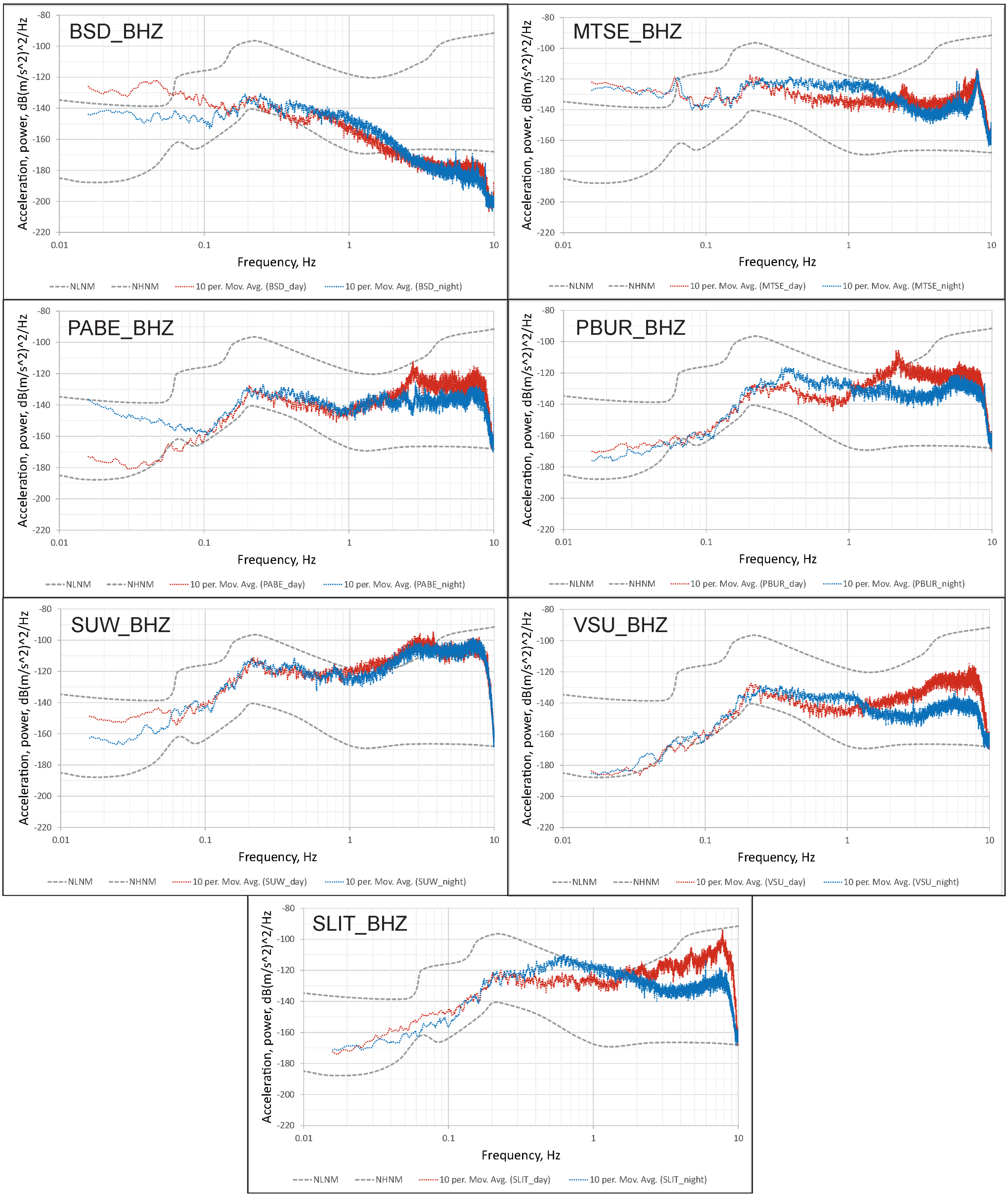

Figure 6.12: *Spectral power density of seismic background noise at BAVSEN stations during day time (red curve) and night time (blue curve). Dashed lines: Spectral power density of noise for NLNM (bottom) and NHNM (top) according to* Peterson *(1993).*

Layer	Depth of base km	Velocity km/s	Composition
h1	1.0	2.3	Sedimentary
h2	20.0	6.1	Metamorphic granite
h3	42.0	6.6	Diorite-granulite
h4	57.0	7.1	Granite-granulite
h5	70.0	8.2	Gabbro-peridotite-pyroxene
	>70.0	8.5	

Table 6.3: *baltic08 velocity model. The composition of the deeper layers are based on information about the geological structure of the Karelian-Kola region by V.V.Yakovleva (*Ankudinov and Dvoretskaya*, 1984;* Ankudinov et al.*, 1991).*

Only the BSD station is located on the Scandinavian shield. This station has a low noise level at high frequencies, starting from 2 Hz, but at low frequencies, less than 0.1 Hz, the noise level is quite high. BSD is located in the Baltic Sea, on the island of Bornholm. At stations located within the East Baltic region (SUW, SLIT, PABE, PBUR, MTSE and VSU), the noise level at high frequencies is significant and a technogenic impact in the daytime during working hours at SLIT, PABE, PBUR and VSU stations is obvious. Despite the fact that at many stations (SUW, VSU, PBUR, PABE, SLIT, PUL) in the EBR the sensors are located at depths from 2 to 10 m, this does not significantly reduce the background noise in the band above 1 Hz. In sedimentary cover and especially unconsolidated Quaternary sediments, there are adverse conditions that significantly reduce the effectiveness of seismological monitoring. The solution could be to install the sensors into deep pits and wells, which would increase the efficiency of seismic monitoring in the EBR.

EBR Regional Tectonic Earthquakes from 2008 to 2019

During the instrumental observation period from 2008 to 2019 in the EBR, low seismic activity caused by tectonic earthquakes was observed (Fig. 6.13).

During this period, only 8 tectonic earthquakes occurred in the indicated EBR territory, which were localised using the BAVSEN network. The magnitude range of earthquakes was 1.3 – 2.5. Mostly, the EBR earthquake centres were located along the western and northern coasts of Estonia, in the Gulf of Finland and in the area of Lake Võrtsjärv, in Estonia. The localization results according to BAVSEN data were compared with Institute of Seismology University of Helsinki (ISUH) data (for more information on the Finnish National Seismic Network see *Kortström, Uski and Oinonen*, (2018)). The results showed a satisfactory similarity. Thus, most of the modern tectonic earthquakes of the EBR, for the period from 2008 to 2019, are confined to the coastal and shelf zones of Estonia. In the past, historical earthquakes occurred in these areas, which is evidence of the preservation of a certain level of seismic activity.

Regional man-made Seismicity of the EBR from 2008 to 2019

Man-made seismicity is the predominant type of seismicity in EBR. It is due to the action of a large number of industrial quarries, as well as seismic sources located in the Baltic Sea. About 50 industrial

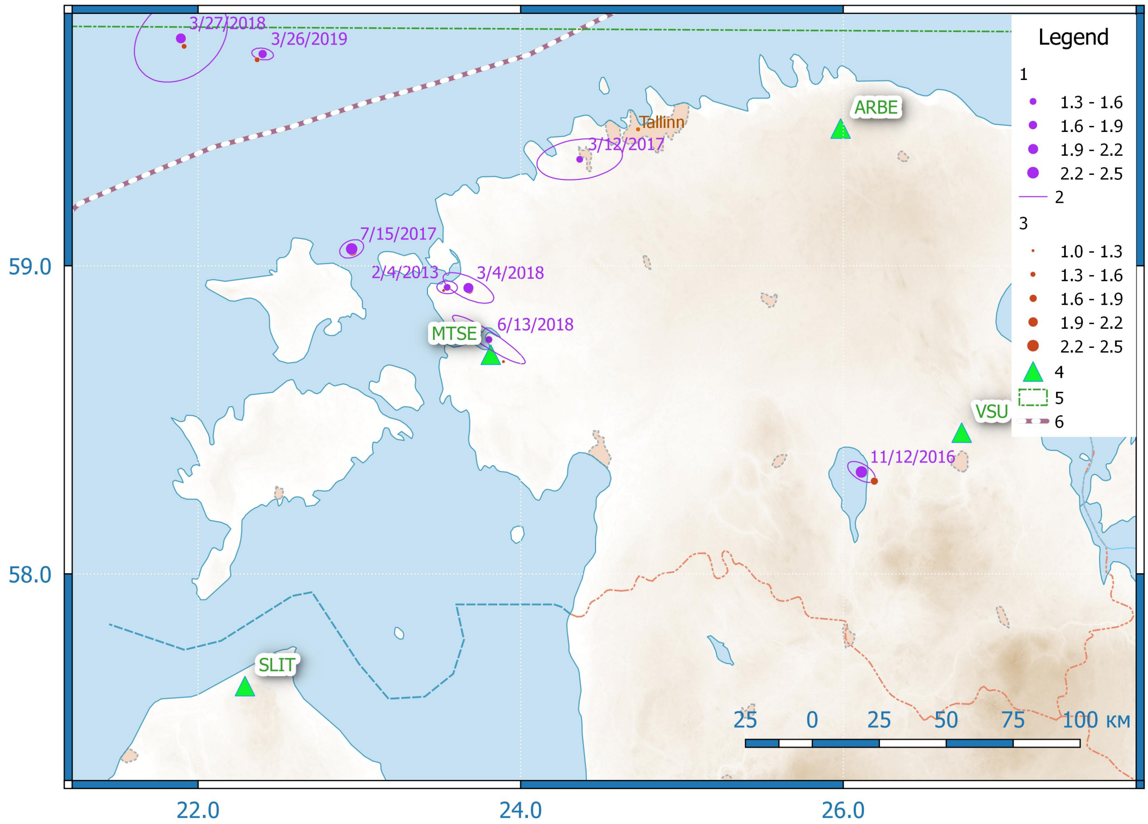

Figure 6.13: *Comparison of earthquake hypocentres of the East Baltic region according to BAVSEN and ISUH data for the period from 2008 to 2019. Labels: 1 - local magnitudes according to BAVSEN; 2 - error ellipse for BAVSEN data; 3 - local magnitudes according to ISUH; 4 - BAVSEN network; 5 - East-Baltic region border; 6 - Nord Stream gas pipeline.*

quarries are located on the territory of the EBR, including several mines in Estonia (*Nikulins*, 2017). Explosions are used in industrial quarries and mines to mine oil shale, dolomite, limestone and gypsum. But the number of explosions carried out in quarries in the EBR changed significantly over time and decreased due to the ongoing economic crisis. In some quarries, the explosions stopped. Active development of oil shale is still ongoing in the north-east of Estonia, in the areas of Mustanina, Kiviõli and Aidu-Liiva. In Latvia, only the Aiviekste quarry, where dolomite is mined, continues to maintain a stable operation. Explosions in other quarries of Latvia and Lithuania are rare at the moment.

The average local magnitude is 1.8 with a standard deviation of ± 0.42. The distribution map of instrumental-recorded, anthropogenic seismic events of the EBR from 2008 to 2019 is shown in Figure 6.14.

Over the indicated period of time (2008 - 2019), 5778 seismic events (including tectonic events) were localised in the EBR. Man-made events included all events that did not have confirmation as tectonic earthquakes from other seismic networks, for example, ISUH. The total number of regional seismic events in the entire Baltic region, localised by the BAVSEN network from 2008 to November 2019 reaches 12449 (with an epicenter distance of up to 800 - 1000 km). Several zones of concentration of epicentres of seismic events can be noted, with man-made seismic events being confined to quarries and the coastal zone of the EBR where blasting operations also occur. The distribution of seismic events during the day clearly indicates their predominantly man-made genesis (Fig. 6.15).

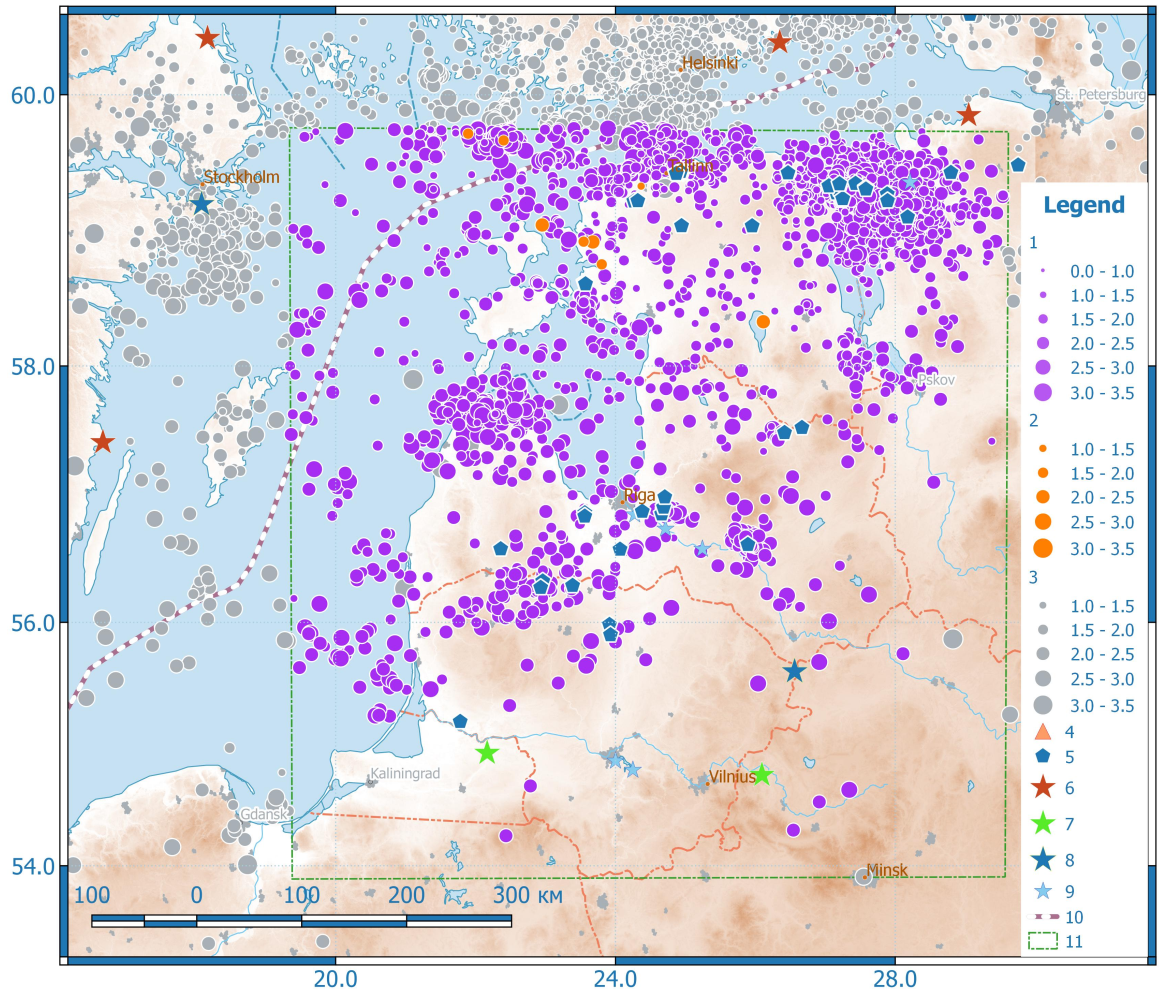

Figure 6.14: *Integrated seismicity of the East Baltic region from 2008 to 2019 according to the BAVSEN network. Labels: 1 - local magnitude of technogenic seismic events (explosions); 2 - local magnitude of tectonic earthquakes; 3 - local magnitude of summary seismic events outside the East Baltic region; 4 - seismic stations of the BAVSEN network; 5 - quarries in which blasting may be carried out; 6 - operating nuclear power plants (NPP); 7 - NPPs under construction; 8 - closed NPPs; 9 - hydroelectric power station; 10 - Nord Stream gas pipeline; 11 - East Baltic region's contour.*

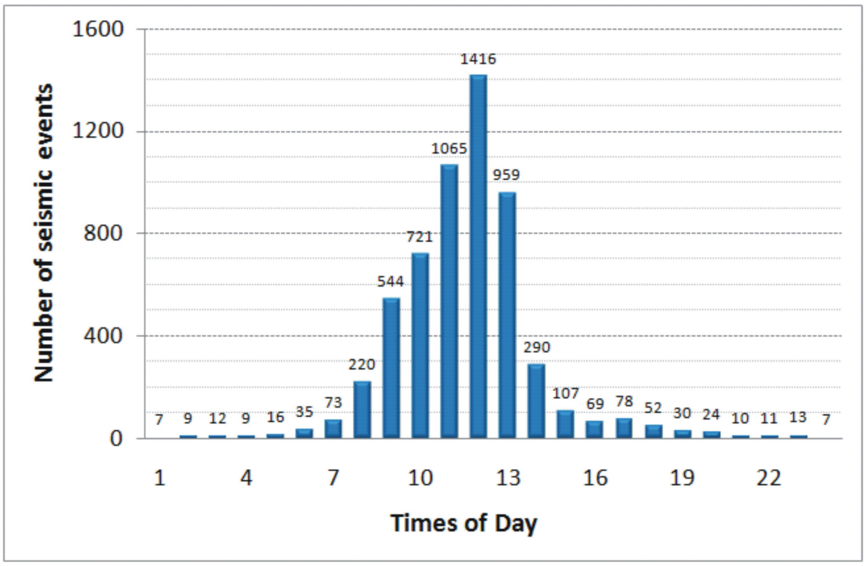

Figure 6.15: *The daily distribution of seismic events in the East Baltic region from 2008 to 2019.*

Agency	Origin time	Lat deg	Lon deg	Depth km	Mag
LEGMC	2015/06/12 08:18:28	55.461	21.357	0.0	2.6 ML
UHIS	2015/06/12 08:18:28	55.489	21.450	0.0	2.5 ML
SNSN	2015/06/12 08:18:29	55.420	21.502	0.4	2.6 ML
NORSAR Automatic GBF	2015/06/12 08:18:29	55.490	21.690	-	2.51
EST	2015/06/12 08:18:27	55.486	21.417	0.0	-
GEUS	2015/06/12 08:18:27	55.435	21.488	0.0	-

Table 6.4: *Hypocentres of an induced event in Lithuania. Notation: LEGMC - Latvian Environment (latest relocation), Geology and Meteorology Center; UHIS - University of Helsinki Institute of Seismology; SNSN - Sweden National Seismic Network; NORSAR - Norwegian Seismic Array; EST - Geological Survey of Estonia; GEUS - Geological Survey of Denmark and Greenland*

Most seismic events (96% - 97%) occur during daylight hours. Even those seismic events that occurred before the start (6 a.m.) or after the end (5 p.m.) of the working day could also be associated with anthropogenic sources, including marine explosions. Marine explosions can occur at any time of the day or week. These are associated with technical, geophysical work at sea, operations on the destruction of WWI and WWII sea mines and naval exercises.

Another example of man-made seismicity is the event on June 12, 2015 (08:18:26 GMT) that was identified as a probable induced earthquake caused by the production of geothermal resources in Lithuania, near Klaipeda (*Nikulins and Assinovskaya*, 2018). The local magnitude of this event reached 2.6 and the depth of the hypocentre 0.9 km. This event was also localised by Finnish, Swedish seismic networks and the Norwegian array NORSAR (Tab. 6.4).

The effectiveness of the applied velocity models was investigated based on reliable explosions in the Aiviekste quarry. Between 2013 and 2019, a data set of 60 explosions was accumulated. The standard deviation of the seismic event epicenter from the quarry position according to the BAVSEN network data is 10.8 km. Comparing the hypocentres to those of other agencies is difficult as the Regional Reviewed Bulletin of NORSAR (RRB NORSAR) does not contain those events because it includes only reliably defined seismic events which were localised and confirmed by at least three seismic arrays. The events are listed in NORSAR's GBF Bulletin, which hypocentres show much larger deviations to the quarry location as the BAVSEN hypocentres, but as this is an automatic, unchecked bulletin it cannot be used for this purpose. The UHIS seismic network practically does not cover the East Baltic region south of 56°N and localises only quarry blasts in the Aiviekste quarry with relatively large magnitudes (> 2.0). About 77% of all explosions in the Aiviekste quarry were localised by the BAVSEN network using the baltic08 model. In 17% of cases, the explosions were better localised using the fen model. Thus, the baltic08 model turned out to be more effective when localizing seismic events within the central part of the East Baltic region.

The Problem of Identifying the Genesis of Regional Seismic Events

For EBR, the problem of recognizing the nature of seismic events is very relevant. A significant factor that makes it difficult to recognize the nature of seismic events is the geological structure. The reflecting and refracting seismic boundaries of the sedimentary cover contribute to the appearance of a complex interference and wave pattern. The main reference, reflecting horizon is the surface of the Ordovician, which lies at depths of 800 - 2050 m (*Sadov and Penzina*, 1986) and can be traced over most of the territory of the EBR. To a lesser extent, reflecting seismic properties are inherent in the surface of the Silurian and, especially, the surface of Devonian, which are fragmentarily traced in the sections.

Due to the presence of numerous reflecting boundaries in the sedimentary cover, the first P-waves from regional seismic events are weakened and therefore it is difficult to distinguish them in seismograms. For regional seismic events, the first P-wave arrival is most often determined by the BAVSEN network stations located on the Scandinavian shield (MEF and RAF). At stations located in the EBR, the arrival of the first P-wave is difficult to distinguish, and sometimes almost impossible. At the same time, many methods for identifying the nature of seismic events are based precisely on the first P-waves. The large distances between the BAVSEN network stations, the low magnitudes of regional seismic events (from 1.3 to 2.3) and the limited number of waveforms from regional EBR earthquakes, due to the low level of seismic activity, also complicate the identification of the nature of seismic events. Testing of various identification methods (spectral characteristics, P/S ratio, spectral-time analysis (STA) and complexity (ratio of integrated power of the P and S wave) have not yet revealed reliable discriminators (*Nikulins*, 2017).

Teleseismic Earthquakes and man-made Seismic Events

During 2008 - 2019, 1172 teleseismic events were localised, mainly strong earthquakes with magnitudes greater than 5.5. These were mainly tectonic earthquakes. At the same time, several nuclear explosions from North Korea were recorded.

The possibility of identifying nuclear explosions on a remote, regional seismic network was tested (*Nikulins*, 2019b), where the ratio of magnitudes MS/Mb was used as a discriminator (Fig. 6.16). The number of nuclear explosions recorded by the BAVSEN network for an 11 year period was limited. From 2006 to 2017, the power of Korean nuclear explosions gradually increased and only for the last three explosions was it possible to determine the corresponding magnitudes.

The results of the identification of nuclear explosions according to the BAVSEN network were compared with similar results obtained using the Aswan Seismic Network (ASN) in Egypt (*Kebeasy et al.*, 1998). In the case of studies of the Aswan network, the epicentres of nuclear explosions were located in Russia (Novaya Zemlya), China and Kazakhstan. Epicentral distances varied between 5,600 and 8,700 km. The records were obtained by the Aswan seismic network, but the parameters for these explosions were taken from the NEIC (National Earthquake Information Center) catalogues.

In the case of the BAVSEN network research, the epicentres of nuclear explosions were located in North Korea. Epicentral distances reached 11,500 km. Thus, for a sufficiently large range of distances, the discriminator MS/Mb can be used to identify nuclear explosions. Both studies show similar results regarding the linear regression of the magnitude ratios MS/Mb (Fig. 6.16).

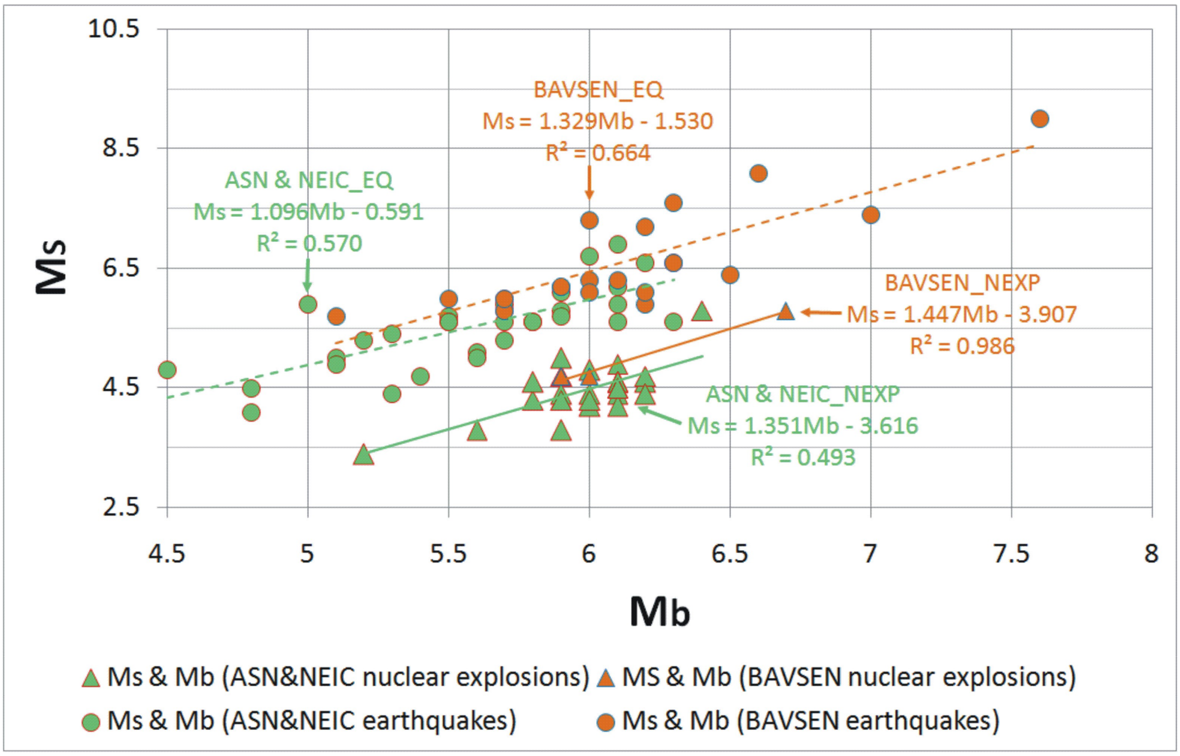

Figure 6.16: *Correlation between the magnitude types Ms and Mb for teleseismic earthquakes and nuclear explosions according to BAVSEN (orange) and ASN (green) seismic network data.*

6.2.4 Seismic Hazard of Latvia

The ultimate goal of seismic monitoring is to assess the seismic hazard of a particular area, that is, to conduct seismic zoning. Areas for monitoring in Latvia are the areas around the Plavinu hydroelectric power station and the densely populated Riga agglomeration. Plavinu hydroelectric station is located almost inside an active graben structure which is formed by two tectonic faults. One of the faults is directly adjacent to the station's dam. The tectonic structure only became known years after the construction of the Plavinu hydroelectric station. Through the territory of Riga, the Olaine-Inčukalns fault extends with signs of geodynamic activity (*Nikulin*, 2019a).

Latvia's seismic hazard was evaluated twice, in 1998 and 2007. In 1998, the Latvian Geological Survey, together with the Crimean Seismology Department of the Institute of Geophysics of the Academy of Sciences of Ukraine, prepared a map of seismic zoning at a scale of 1:1,000,000 (*Safronovs and Nikulins*, 1999). Due to insufficient numbers of tectonic earthquakes in the East Baltic region two methods were used to estimate the maximum magnitude, PSHA and a method to assess the seismotectonic potential that is based on a number of geological and geophysical parameters which is more suitable for areas with low to moderate seismicity (*Borissoff et al.*, 1976; *Reisner et al.*, 1991; *Reisner and Ioganson*, 1992). Three types of seismogenic zones were identified: zones of occurrence of earthquake foci (ZOEF), potential zones of occurrence of earthquake foci (PZOEF) and seismotectonic zones (STZ). As a result, 6 ZOEF, 7 PZOEF and 5 STZ were allocated. The intensity of seismic tremors in two ZOEF (Daugavpils and Bauska) was estimated at VII points on the MSK-64 scale while the intensity of seismic shocks in the remaining ZOEF, PZVOZ and STZ zones was estimated at VI points on the MSK-64 scale. The 1998 studies had several drawbacks, namely: 1) the studies were based on the deterministic method,

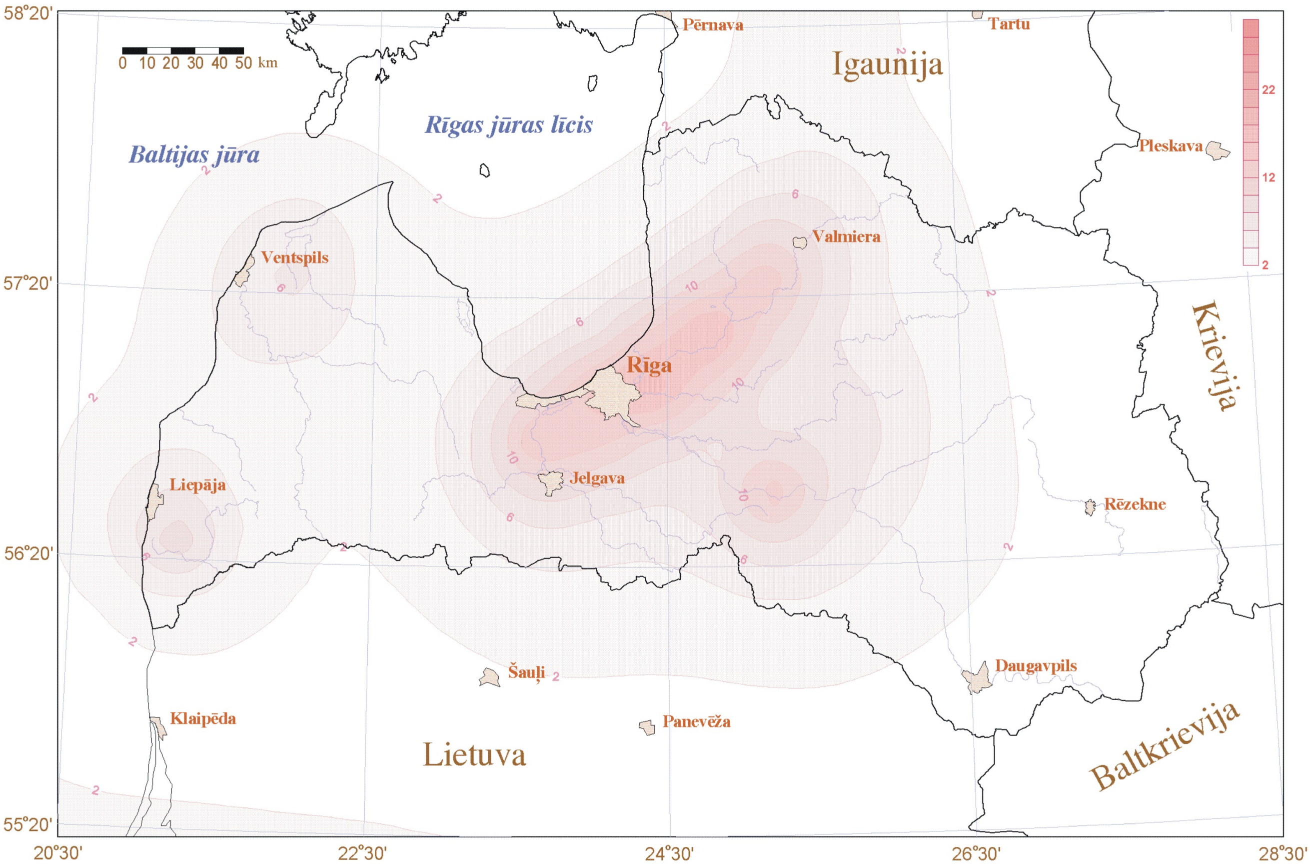

Figure 6.17: *Map of maximum horizontal acceleration (PGA) on solid ground (in cm/s2), with a 10% probability of exceedance in 50 years.*

which did not allow reliable estimates of the recurrence of earthquakes; 2) the studies used tectonic maps issued before 1991, which did not have a reliable topographic reference; 3) the catalogue of earthquakes used for analysis included several technogenic seismic events, in particular in 1995; 4) magnitudes were not unified and reduced to a single magnitude scale (for example Mw).

Given the above drawbacks, in 2007, under an agreement with the Ministry of Economy of Latvia, a second version of the seismic zoning of Latvia was prepared (*Nikulins*, 2011). In addition to eliminating the above-mentioned drawbacks of the 1998 version, the new 2007 version took into account the damping function. Seismotectonic analysis made it possible to identify eight seismogenic zones in the territory of Latvia and another eight seismogenic zones in the East Baltic region. As a result of the calculations, a set of maps of maximum horizontal acceleration in solid ground (PGA) was prepared with a probability of 10%, 5%, 1% and 0.5% over 50 years. With a probability of 10% over 50 years on solid pre-Quaternary deposits of Latvia, the PGA can exceed 10–13 cm/s2 in Sigulda, Riga, Olaine, Aizkraukle, Cesis and their environs (Fig. 6.17).

6.2.5 Data Distribution

Data distribution is an important part of the exchange of information within the international seismological community. The LEGMC first shared its data with the European-Mediterranean Seismological Centre (EMSC) and provided the East-Baltic seismic event bulletins from 2008 to 2010. The EMSC uses real-time data for their Earthquake Notification Service for potentially devastating earthquakes in the Euro-Mediterranean region, and disseminates messages to users within an hour after the earthquake. Since the LEGMC does not provide real-time epicenter determinations, the EMSC recommended that the LEGMC collaborates with the ISC to share seismological data.

Therefore, in 2012, LEGMC began to send their bulletins to the International Seismological Centre (ISC) under the agency code LVSN. LEGMC currently provides bulletins of seismic events in the Eastern Baltic region from January 2012 to December 2017 (`http://www.isc.ac.uk/cgi-bin/collect?Reporter=LVSN`). General information on the seismicity of the East Baltic region is also located on the LEGMC page (`https://www.meteo.lv/lapas/geologija/monitorings/monitorings-geologija?id=1759&nid=826`). Information on seismic events in the East Baltic region is available only on LEGMC's internal work resources.

6.2.6 Conclusion and Future Steps

Modern seismological studies carried out in Latvia during 2008 - 2019 have made it possible to localise a few tectonic earthquakes and a great amount of man-made seismic events in industrial quarries and in the Baltic Sea using a Baltic Virtual Seismic Network. Low natural seismic activity was noted along the western and northern coasts of Estonia, in the Gulf of Finland and in the area of Lake Võrtsjärv, in Estonia. Man-made seismicity is predominant in EBR. This is mainly due to explosions in open industrial quarries and marine explosions. The problem of identifying the genesis of seismic events in the EBR has not yet been resolved for a number of objective reasons, among which the seismic-geological factor due to sedimentary cover, a sparse seismic network (average distances between stations from 120 to 280 km) and only small seismic events should be highlighted. To reduce the high level of seismic noise the seismic sensors were buried a little deeper between 2 and 10 m, which did not reduce the noise sufficiently. Calibrated explosions in the Aivikste quarry made it possible to choose the optimal model of seismic wave propagation velocity for the central part of the EBR (Latvia). To detect nuclear explosions in North Korea on the BAVSEN remote regional seismic network the Ms/Mb ratio was tested as a discriminator.

For the further development and optimization of seismological monitoring in EBR, the following tasks need to be solved: 1) expansion of the database of waveforms of regional earthquakes and explosions in EBR; 2) search for optimal discriminators, including amplitude P/S ratios, spectral ratios, STA, complexity and other methods for identifying the genesis of weak, regional seismic events (ML $<$2.5); 3) optimization of the velocity model based on the collection of data on calibrated seismic sources; 4) expansion of the seismic network with uniform coverage by seismic stations of the studied territory of the EBR; 5) the use of geophones placed in deep pits or wells to increase the effective sensitivity of observations; 6) the creation of the National Data Center of Latvia to access the data of the International Monitoring System and the International Data Center (CTBTO), to obtain additional information (e.g. waveforms, radionuclide data and infrasound data).

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