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EVALUATION OF SEISMIC HAZARD OF LOW SEISMICITY AREAS: A CASE STUDY OF THE BALTIC REGION

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PLATFORMINIŲ MAŽO SEISMINIO AKTYVUMO SRIČIŲ SEISMINIO PAVOJAUS VERTINIMAS BALTIJOS REGIONO PAVYZDŽIU

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ABBRIVIATIONS

DSHA – Deterministic seismic hazard assessment

EBR – East Baltic region

ESC-SESAME – European Seismological Commission – Seismotectonics and Seismic Hazard Assessment of the Mediterranean and European Basin

GSHAP – Global Seismic Hazard Assessment Program

HUSI – Seismological Institute of Helsinki University

M – Earthquake magnitude

NPP – Nuclear power plant

PGA – Peak ground acceleration

PSHA – Probabilistic seismic hazard assessment

SZ – Seismogenic zone

INTRODUCTION

Importance of the study. The East Baltic Region (EBR) is situated within the East European Craton (EEC). Like all cratons, EEC is notable for low seismic activity. Nevertheless, couple dozens of earthquakes with intensities up to VII (MSK-64) have been recorded since 1616 implying possibility of moderate (M=5.2–5.7) earthquakes in future. Moreover, instrumentally recorded earthquakes in Estonian island of Osmussaar (M=4.7) in 1976 and in Russian Kaliningrad enclave (M_W=5.0 and M_W=5.2; 2004) shows that earthquakes has to be considered seriously in the area. A number of industrial facilities of high vulnerability are situated in EBR: mines for oil shale exploitation and power plants burning that oil shale in Estonia; decommissioned scientific nuclear reactor and the Daugava hydro power plant in Latvia; the decommissioned Ignalina nuclear power plant (NPP), the Nemunas hydro power plant, large nitrogen fertilizer plant, large oil refinery and liquefied natural gas terminal in Lithuania. Moreover, three NPP's are considered being built within the area: Visaginas (near the decommissioned Ignalina NPP) in Lithuania, "Belarus" in north-western Belarus, and "Baltiskaya" in Kaliningrad enclave of Russia. Therefore, considering these important and potentially dangerous facilities even an earthquake of moderate magnitude can trigger large scale environmental accidents.

A few trials to evaluate seismic hazard of EBR have been made in the past using different methodologies. These trials, however, were not consistent in between and/or some kind of deterministic methodology was used. Therefore, a new seismic hazard evaluation of EBR based on more progressive and reliable probabilistic methodology was carried out in this study.

New seismic hazard maps of EBR were compiled in this study and can be used for complex risk assessment of existing or newly constructed potentially hazardous industrial facilities.

Moreover, one of more important results of this study is an established relationship between the local seismicity of EBR and regional seismicity of distant but seismically active Vrancea (Romania) seismogenic zone (SZ).

Target and tasks. The main task of this study is to investigate application of probabilistic seismic hazard assessment (PSHA) methodology for low seismicity platform areas using EBR as a case study. During the project, the following tasks have been accomplished: (1) compilation of a seismic catalogue for EBR, (2) analysis of tectonic and seismotectonic data from EBR, (3) compilation of maps of SZ's and identification of their parameters, (4) evaluation of seismic impact of the distant Vrancea SZ to the seismic hazard of EBR, (5) selection of ground motion attenuation functions appropriate for EBR, (6) systematization of the SZ's characteristics using logic tree methodology, (7) preparation of the appropriate set of input data for software CRISIS2007, (8) calculation of seismic hazard of EBR using PSHA and logic tree methodologies, (9) compilation of seismic hazard maps of EBR, (10) calculation of ground acceleration spectra for selected sites, (11) analysis of the results and generation of conclusions.

Methods. Currently in seismology two main methods are used to estimate seismic hazard: Deterministic Seismic Hazard Assessment (DSHA) method and Probabilistic Seismic Hazard Assessment (PSHA) method. DSHA is mostly used to analyse the largest seismic hazard within certain area which is under the influence of one or several SZ that occur in vicinity. Firstly, the area for a SZ is chosen where an earthquake had been recorded. Then its largest magnitude is found, and seismic hazard for certain area is calculated. This method does not define time intervals during which earthquake of calculated magnitude can affect the area. In contrast, PSHA includes all defined SZ that are situated within various distances, their characteristics and all possible earthquakes exceeding some reference magnitude. Moreover, PSHA allows estimating probabilities of exceedance of some certain ground movement intensity in certain area during some time period.

A logic three method was used in this study. When the data from a certain phenomenon are scarce and imprecise it is impossible to create one reliable model describing the phenomenon. Instead it is possible to create a group of several different models or one model with a group of different parameters and then analyse either all possible separate outcomes or just average (mean, median, or mode) and/or standard deviation.

Novelty of the study.

1) For the first time the seismic hazard of the whole EBR was evaluated using probabilistic seismic hazard assessment (PSHA) methodology.

2) For the first time PSHA and logic tree methods were combined in order to evaluate seismic hazard of EBR and its precision.

3) Evaluating seismic hazard of EBR, for the first time the influence of the remote Vrancea SZ was taken into account.

Statements to be proven:

1) PSHA can be used as most effective method for the regions of low seismic activity.

2) In evaluation of seismic hazard, the use of logic tree is effective allowing managing and estimating uncertainties of the seismic hazard evaluation.

3) In estimation of the seismic hazard in regions of low seismic activity, such as EBR, apart from local SZ it is necessary to include influence of remote active SZ's.

Theoretical and practical significance. Methods applied in estimating seismic hazard of the regions of high seismic activity were adopted for a region of low seismic activity. Seismic hazard of EBR was evaluated. It was concluded that seismic hazard has to be taken into account when planning industrial facilities of elevated risk.

Personal contribution. The author compiled a new united catalogue of seismic events in EBR, created alternative maps of SZ's, developed alternative seismic models, performed calculations of PSHA, compiled maps of peak ground acceleration (PGA) for various probabilities of exceedance for the study region.

Dissemination of study results. Results were presented in 8 international conferences.

Publications. Results were published in 12 papers: two papers in journals included in the Thomson Web of Science index, two papers in journals included in the ISI Master List, four papers in other pear reviewed journals, two papers published in popular science journals and two chapters were contributed to scientific monographs.

Summary of the thesis structure. Thesis consists of introduction, 3 chapters, conclusions and reference list. It contains 139 pages, 36 figures, 7 tables and 116 entries in the reference list.

1. OVERVIEW OF RESEARCH ON THE EAST BALTIC REGION SEISMICITY

1.1. OVERVIEW OF SEISMICITY OF THE REGION AND DATA SOURCES

EBR is situated in the western margin of East European Platform, which is a part of East European Craton (EEC). Geologically it consists of three major Phanerozoic structures, the Baltic syncline, the Mozurian-Belorus anticline and the Latvian saddle. Seismicity of ERB is lower than that in the Fennoscandian Shield (Fig. 1.1.1). EBR has, however, higher seismic activity than almost aseismic regions elsewhere in the East European Platform (Fig. 1.1.2).

Nevertheless EBR is classified as region of low or very low seismic activity (Figs. 1.1.1 and 1.1.2). Only a few tens of weak or moderate earthquakes are mentioned in some historical documents. Until the last decade, seismic network in EBR was sparse, there were only a few seismic stations and even these were operating not continuously. After the 2004 Kaliningrad earthquakes of moderate magnitude, five broadband and several short period seismic stations were installed in the region. Instrumental seismological data, however, is still poor. Analysing seismicity of the region, data from seismic stations in Fennoscandia were often used. Unfortunately, those stations usually record only events with magnitude higher than 2.5, and their localization errors reach on average 50 kilometres but sometimes can be even larger.

At the end of nineteenth to beginning of twentieth century, Professor of Riga University B. Doss collected evidences about 18 moderate seismic events (V–VII on MSK-64 scale) that occurred in Latvia and Estonia from various sources. His catalogue covered time period from 1616 to1911. In the catalogue, there are listed earthquakes of moderate strength, e.g. on June 30, 1616, in surroundings of Bauska and Jelgava (Latvia) an earthquake of VI-VII intensity occurred. It was felt by both people and animals. On January 23, 1821, in Koksene (Latvia) ground was shaking (estimated intensity VI) as strong as church bells were ringing, sound of thunder was heard, people could not keep on their feet, and the ground was strongly shaking. On January 29, 1908, in surroundings of Daugavpils (Latvia) an earthquake of intensity VII was recorded. People heard noise similar to cannon shot, a fracture of 3-4 inch wide appeared in fields and meadows.

After the First and Second World Wars and associating socio-economic disturbances, seismic data collected by Doss were ignored. EBR was considered as aseismic.

The earthquake that occurred on October 2nd, 1976 came as complete surprise to both researches and general public. With epicentre in Osmussaar Island (Estonia) having magnitude of 4.7, it was one of the strongest earthquakes in the region. Apart of the Osmussaar event, on March 4, 1977, earthquake of M=6.9 occurred in the Vrancea Mountains (Romania). It was felt on a large part of EEP. In EBR it was estimated to intensity of III-IV. After those events, interest in seismicity of EBR increased. Thus, in 1988 seismologist of Belarus and Baltic states found again catalogues of Doss and complemented it with new seismic events up to 45 events.

On September 21, 2004, in the Russian Kaliningrad enclave two earthquakes occurred of magnitudes M_W=5.0 and M_W=5.2. These events provided a unique possibility for seismologist to collect valuable macroseismic data, i.e. information on propagation of ground movement and seismic influence on buildings and people in the region. Macroseismic data were collected in the Kaliningrad region as well as in the surrounding countries: Lithuania, Poland, Sweden, Belarus, Latvia, Estonia, Denmark, and Norway. Later all information was combined to a common data set and regional macroseismic maps were compiled for two strongest earthquakes (Gregersen et al., 2007). The strongest Kaliningrad earthquake of intensity VI at epicentre has been observed in the northwest part of the Sambian peninsula. Further from epicentre intensity diminished. The shaking was felt as far as Oslo, the Norwegian capital (~800 km) and on the top floors of high buildings in Sankt-Petersburg of Russia (~840 km).

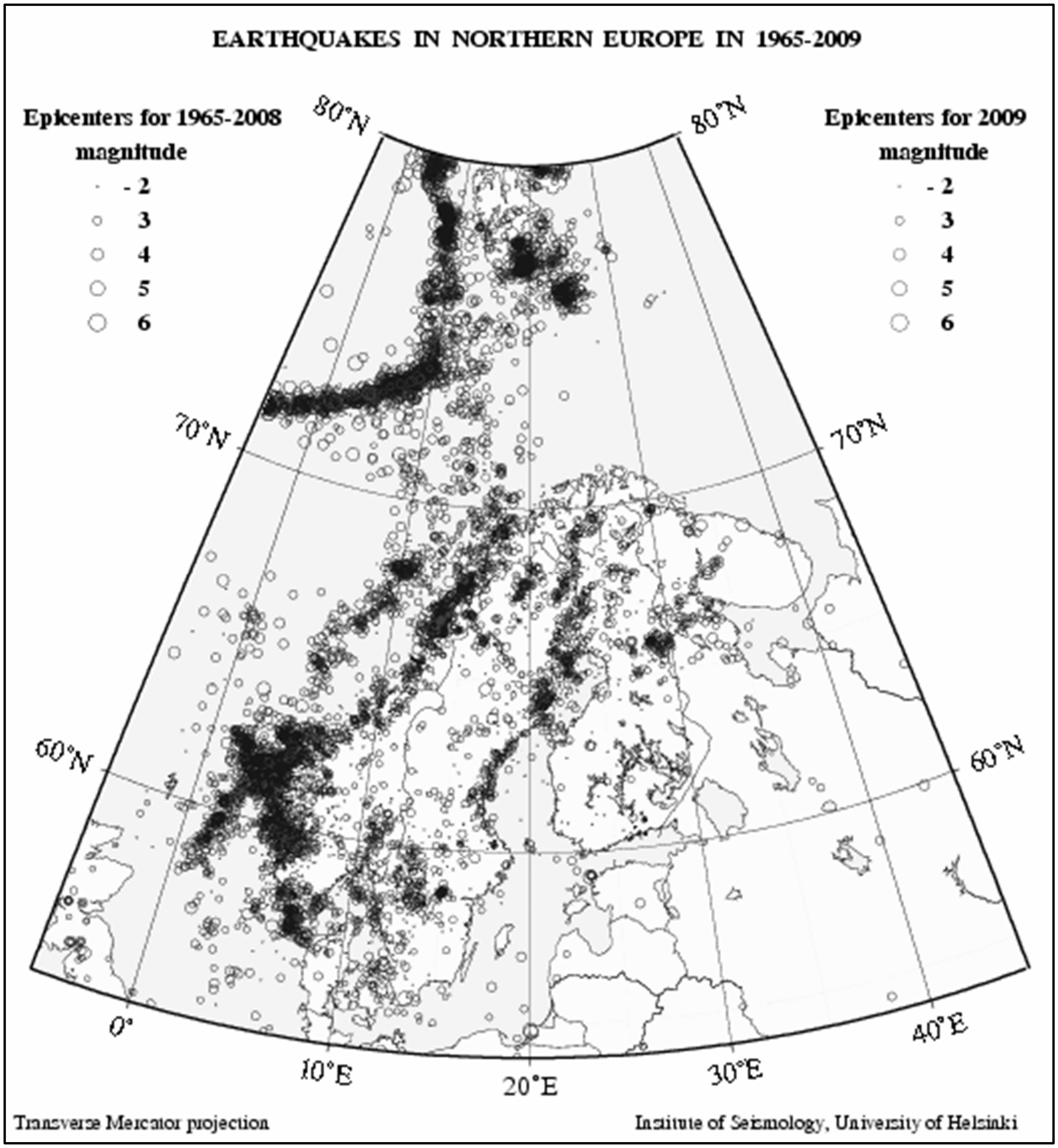

Fig. 1.1.1. Seismic activity of the Northern Europe according to data of Seismological Institute of Helsinki University (HUSI). The figure presents instrumentally recorded seismic events from 1965 to 2009.

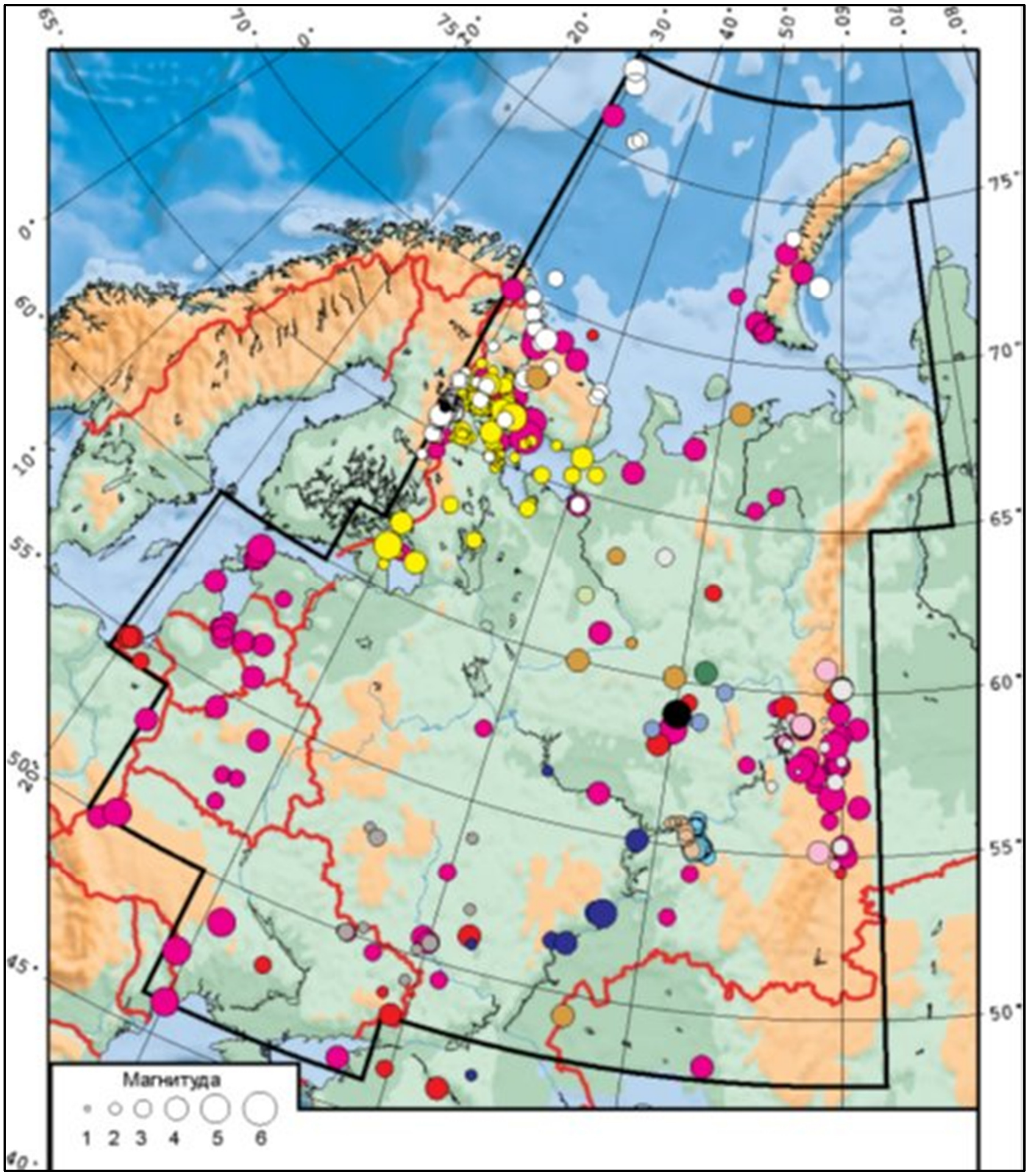

Fig. 1.1.2. Seismic activity of East European platform from year 1467 to 2005. (Sharov et at., 2007). Circles of different size correspond to seismic events of different magnitudes, violet circles – events listed in Specialized Catalogue of North Eurasia covering time span from the oldest times to 1995, red circles – seismic events listed in the 1995-2005 seismological bulletin of the Geophysical Survey of the Russian Academy of Science.

The Osmussaar and Kaliningrad earthquakes made clear that the approach to seismicity of EBR had to be changed. Previously were thought that the strongest earthquakes in the region can reach up to M=4.8, but the Kaliningrad events showed their M=5.2 signature. Including magnitude margin of 0.5 that are applied to low seismic regions, earthquakes of M=5.7 can occur in EBR.

1.2. IMPACT OF STRONG VRANCEA EARTHQAUKES TO THE EAST BALTIC REGION

Almost all East European Platform, including EBR is shaken by strong earthquakes 3-4 times per century from epicentres in SZ of the Vrancea Mountains. The zone is situation where the Carpathian ridge sharply changes its trend from northeast to west. The resent strong earthquakes occurred here in 1940, 1977, 1986, and 1990. In Romania and neighbouring Moldova these earthquakes caused substantial building destructions, people were killed in 1940 and 1977.

The strongest earthquake known occurred in1446 (M=7.6; Kondradskaya and Shebalin, 1982). Vrancea SZ caused 28 destruction earthquakes with intensity at epicentre $I_0 \geq$ VIII occurred during the second millennium.

These earthquakes have intermediate-depth hypocentres, down to 220 km depth (Bokelmann and Rodler, 2014). Earthquakes with deeper hypocentres are felt in much larger region than those with shallow hypocentral depths.

Ground motion caused by strong earthquakes in the Vrancea reaches EBR (Nikonov, 2006). In 1940, a strong earthquake (M=7.3) in the Vrancea caused ground motions of intensity V in southern part and of IV in northern part of EBP. In 1977, earthquake in Vrancea (M=6.9) caused trembling with intensity of IV in the southern part and of III and II in the northern part of EBP.

1.3. PREVIOUS SEISMIC HAZARD ASSESMENTS IN THE EAST BALTIC REGION

Two main approaches are used to estimate seismic hazard – deterministic and probabilistic ones. Probabilistic Seismic Hazard Assessment (PSHA) includes study and aggregation of SZ's, probabilities of ground motions caused by different earthquakes to be exceeded within certain period of time, different attenuation functions of seismic waves, and various uncertainties related to lack of data as well as to randomness of earthquakes. Differently from PSHA, Deterministic Seismic Hazard Assessment (DSHA) does not assess mentioned probabilities and uncertainties, because the maximum effect of only one or several most seismically influential SZ’s is calculated on a certain area. In natural processes, however, uncertainties are always present.

One of the first seismic hazard assessments of areas adjacent to EBR was based on DSHA performed by Soviet scientists in 1937. Later they kept updating maps of seismic hazard with period of ten years: in 1949, 1957, 1968 and 1978. From 1949, the maps of seismic hazard included EBR. For example, the 1978 DSHA map indicated that seismic hazard of EBR has intensity of V (MSK-64), which corresponds to a peak ground acceleration (PGA) of 15–30 cm/s^2. One of the recent seismic hazard maps over the territory of Russian Federation was published in 1997. This map was created using PSHA, however, EBR was not included.

During 1990–1995, Belorussian researches collectively analysed seismic, geologic, tectonic, neotectonic, and geophysical data from the Baltic States, Belarus and the Kaliningrad area and compiled seismotectonic and DSHA maps (Fig. 1.3.1; Aizberg et al., 1997). According to the DSHA map, intensities can reach up to VII (MSK-64) i.e. 60–120 cm/s^2 PGA within SZ’s.

From 1992 to 1999, Global Seismic Hazard Assessment Program (GSHAP; Giardini et al., 1999) was in action during which PSHA was used. The final result of the seismic hazard assessment appeared as European map of the PGA values that can be exceeded during 50 years period with 10% probability. According this map, EBR is characterised by the PGA values ranging from 0 to 20 cm/s^2.

In 1998, Ilginytė (1998) compiled the map of seismic hazard of Lithuania using DSHA. According to her assessment, intensities of earthquakes in Lithuania may vary from I=V in the largest part of the territory to I=VII in the east, north and west of the country.

Seismic hazard was assessed within the framework of GSHAP for territories of Poland, Czech Republic, and Slovakia (Fig. 1.3.2; Shenk V. et al. 2000). According to this assessment, there is a SZ of elevated hazard where PGA can reach 30–40 cm/s^2 in the north-eastern part of Poland close to Lithuania and Kaliningrad enclave.

Seismic Hazard Assessment of the European-Mediterranean region (ESC-SESAME project) was finished by the European Seismological Commission (ESC) in 2003. The ESC-SESAME map of seismic hazard presented the PGA values, which can be exceeded during 50 years with 10% probability. The PGA values were estimated from 0 to 20 cm/s^2 for EBR.

Latvian map of seismic hazard was published in 2011 (Nikulin, 2011). It was compiled using PSHA. In the map, five domains of the elevated seismic hazard were distinguished, in which the PGA values reached 13 cm/s^2 that could be exceeded in 50 years with probability of 10% for the prequaternary surface. While, the PGA values could reach up to 40 cm/s^2 on the top of quarterly deposits.

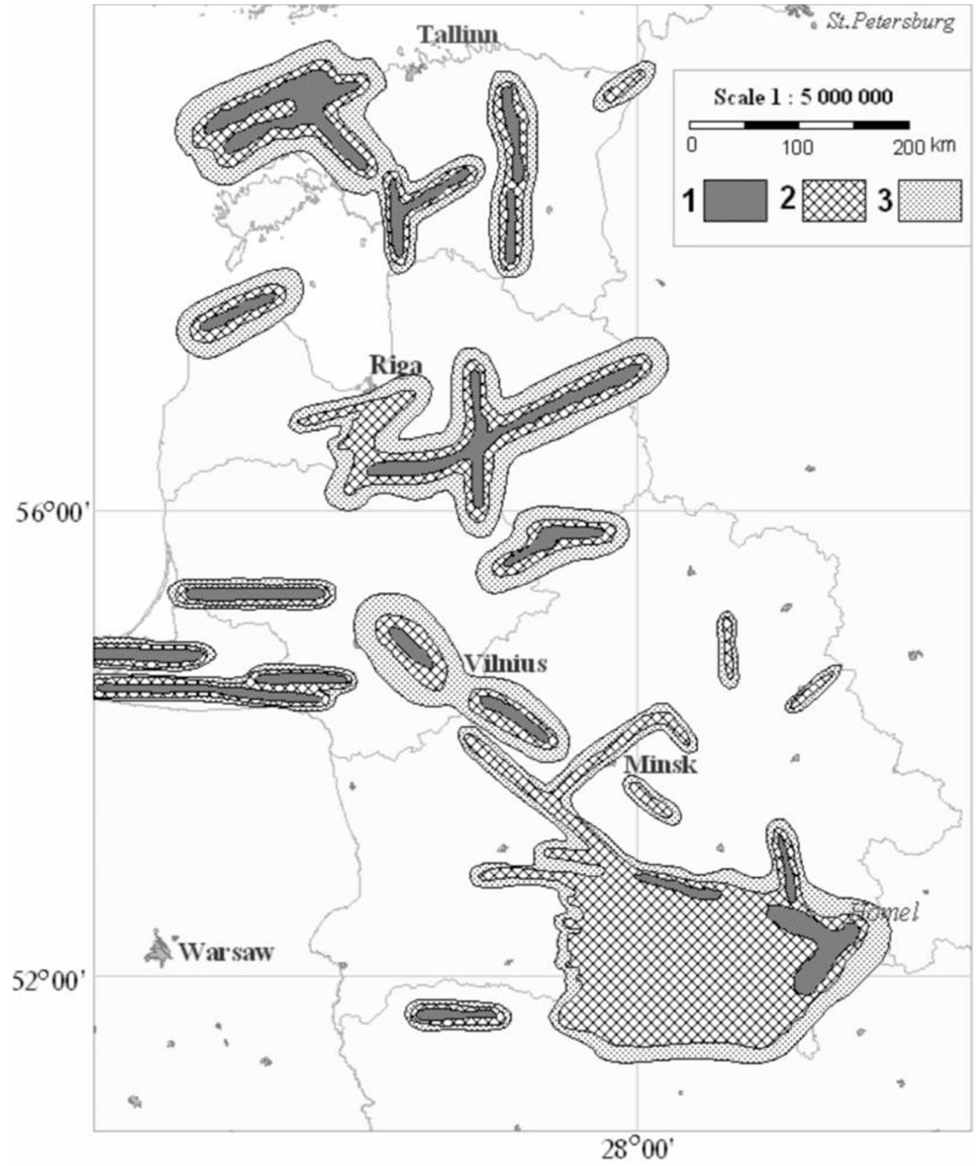

Fig. 1.3.1. DSHA map of Belarus and the Baltic states from Aizberg et al., 1997. Possible intensities (MSK-64 scale): 1 – VII, 2 – VI, 3 – V.

1.4. SUMMARY OF SEISMIC SITUATION OF THE EAST BALTIC REGION

As mentioned above, EBR feature low seismic activity. However, the region is not aseismic. In this region the magnitude of theoretically strongest earthquake can reach M=5.7, the event of such magnitude could have certain destruction potential. It should be noted that there are about ten potentially dangerous industrial facilities that can be affected (disturbance in work routine or even accidents) even by moderate earthquake in the region.

Until present a number studies were performed to assess seismic hazard of separate parts of EBR. However, there is no common map based on PSHA methodology encompassing the whole EBR. Also no impact of Vrancea SZ (Romania) to EBR was assessed.

2. METHODS AND DATA

2.1. METHODOLOGY OF PROBABILISTIC SEISMIC HAZARD ASSESSMENT

Probabilistic seismic hazard assessment methodology

As mentioned above seismic hazard evaluation can be performed using two different methodologies – DSHA (e.g. McGuire, 2001; Bommer, 2002) and PSHA (e.g. Cornell, 1968; Musson and Henni, 2001). As described in Kijko (2011), the classic (Cornell, 1968; McGuire, 1976) procedure known as Cornell-McGuire procedure includes four steps in PSHA (Fig. 2.1.1).

The first step of PSHA consists of the identification and parameterization of the *seismic sources* (known also as *source zones*, *earthquake sources* or *seismic zones*) that may affect the site of interest. These may be represented as area, fault, or point sources. Area sources are often used when one cannot identify a specific fault. In classic PSHA, a uniform distribution of seismicity is assigned to each earthquake source, implying that earthquakes can equally occur at any point within the seismic source zone. The combination of earthquake occurrence distributions with the source geometry results in space, time, and magnitude distributions of earthquake occurrences. Seismic source models can be interpreted as a list of potential scenarios, each with an associated magnitude, location, and seismic activity rate.

The second step consists of the specification of temporal and magnitude distributions of seismicity for each source. The classic, Cornell-McGuire approach, assumes that earthquake occurrence in time is random and follows the Poisson process. This implies that earthquake occurrences in time are statistically independent and that they occur at a constant rate. Statistical independence means that occurrence of future earthquakes does not depend on the occurrence of the past earthquake. The most often used model of earthquake magnitude recurrence is the frequency-magnitude Gutenberg-Richter relationship

$$Log(N(M>M_{min})) = a - b*M \,, \qquad (2.1.1)$$

where N is the number of earthquakes with magnitude M larger than M_{min}, a and b are parameters. It is assumed that earthquake magnitude M belongs to the domain $<M_{min}, M_{max}>$, where M_{min}, is the level of completeness of earthquake catalogue and magnitude M_{max} is the upper limit of earthquake magnitude for a given seismic source. The parameter a, is the measure of the level of seismicity, while b describes the ratio between the number of small and large events. The Gutenberg-Richter relationship may be interpreted either as being a cumulative relationship, if N is the number of events with magnitude equal or larger than M, or as being a density law, stating that N is the number of earthquakes in a specific, small magnitude interval around M.

The third step calculation of ground motion prediction equations and their uncertainty are performed. Ground motion prediction equations are used to predict ground motion at the site itself. The parameters of interest include peak ground acceleration, peak ground velocity, peak ground displacement, spectral acceleration, intensity, strong ground motion duration, etc. Most ground motion prediction equations available today are empirical and depend on the earthquake magnitude, source-to-site distance, type of faulting and local site conditions. The choice of an appropriate ground motion prediction equation is crucial since, very often, it is a major contributor to uncertainty in the estimated PSHA.

The fourth step. Integration of uncertainties in earthquake location, earthquake magnitude and ground motion prediction equation into probability that the ground motion parameter of interest will be exceeded at the specified site during the specified time interval. The ultimate result of a PSHA is a *seismic hazard curve*: the annual probability exceeding a specified ground motion parameter at least once. An alternative definition of the hazard curve is the frequency of exceedance vs. ground motion amplitude. Once the seismic hazard curves are calculated for certain territory covering grid the seismic hazard maps can be compiled.

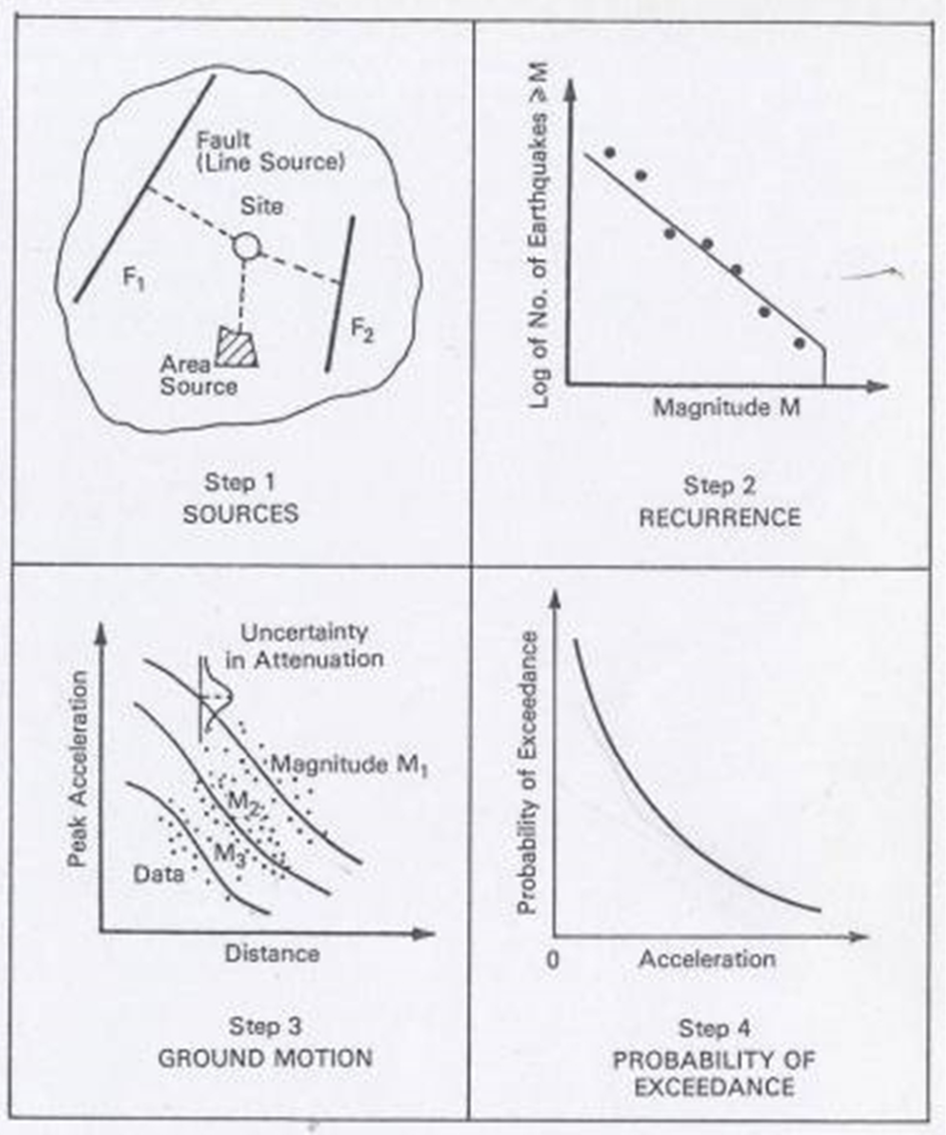

Fig. 2.1.1. Scheme of PSHA.

Evaluation of uncertainty

An important aspect of a probabilistic seismic hazard analysis is the definition and treatment of uncertainties. This involves identifying inherent variability in the earthquake process, defined as *aleatory* variability, as well as considering uncertainty in the distribution models used in the analysis, known as *epistemic* uncertainty. The distinction between these two types of uncertainties is fundamental to understanding where uncertainty originates and further how it is to be appropriately handled in hazard calculations (Abrahamson & Bommer, 2005).

Aleatory variability is defined as the innate randomness in a process. In discrete variables, this is characterized by the probability of each possible value, while in continuous variables it is characterized by probability density functions describing parameter distributions (e.g. magnitude distributions). The aleatory variability in a hazard analysis is included directly in the calculations, specifically through the standard deviation parameter, and thus it directly influences the resulting hazard curve (Abrahamson & Bommer, 2005).

Epistemic uncertainty is often referred to as scientific uncertainty because it is a product of limited data and knowledge. Unlike aleatory variability, as more information becomes available, epistemic uncertainty can be reduced. Originating from parameters that are not random, but rather have some correct, yet unknown value, epistemic uncertainty is characterized by the use of alternative models (i.e. alternative probability density functions). Therefore, epistemic uncertainty is not considered directly in the hazard calculations but rather is treated by developing alternative models that yield respective alternative hazard curves (Abrahamson & Bommer, 2005).

A common way to handle epistemic uncertainty is through the use of logic trees. As mentioned above, epistemic uncertainty is considered by using different models for source characterization or ground motion attenuation relations. With each combination of alternative models, the resulting hazard is recomputed resulting in a collection of hazard curves. A logic tree provides a method for effectively organizing and assessing the credibility of these models and their resulting hazard curves. An example of a logic tree used in this study is shown in Figure 3.4.1.

2.2. DATA SOURCES

Two types of main input data are needed for seismic hazard assessment. The most important is information on seismic activity of a region, i.e. data about earthquakes, their localities, time, magnitude, and depth. The seismic catalogue is compiled based on this information. In this study, data were collected from publications and internet sites with free access, i.e. Belarus and the Baltic states catalogue (Sharov N. V. et al., 2007), United Earthquake Catalogue of the region covering East European Platform, covering the time span from the ancient times until 2005 (Sharov N. V. et al., 2007) and seismic database of the Nordic countries (FENCAT), that produced and maintained by HUSI. Beside these sources data from various publications, e.g. Nikonov and Sildvee (1991), Gregersen et al. (2007) and Guterch (2009), were used.

Other data body is based on tectonic information of the region. While modelling seismic hazard the seismically active zones (linear or areal) should be defined. The following sources were used: Aronova (2007; Fig. 3.1.4), Grigelis (1981; Fig. 3.1.5), Aizberg et al. (1999; Fig. 3.1.6), Stirpeika (1999), and Suveizdis (1979).

The Vrancea information was collected from publication by Mantiniemi et al. (2003).

3. SEISMIC HAZARD ASSESMENT OF THE EAST BALTIC REGION

3.1 SEISMIC CATALOGUE AND SEISMOGENIC ZONES

The seismic catalogue of EBR

When primary seismic catalogues overlap in space and time, a seismic event may get into several data sets. Therefore many efforts have been made to analyse records in order to identify and remove duplicates (Fig. 3.1.1).

Conventional PSHA method is based on assumption that earthquakes are random events that obey to Poisson's distribution. Therefore interrelated events (foreshocks and aftershocks) were removed from the United EBR seismic catalogue (Table 3.1.1).

Since the United catalogue was compiled from several different sources, magnitude of each seismic event remained as in the primary source. In many instances, in the primary catalogues local magnitudes were used. In instrumental part of the catalogue several events were described by Bergen University coda magnitude or local HUSI magnitude. Regression relations were made and all magnitudes were converted to the HUSI local magnitude (Table 3.1.1) when it was possible to made such conversions.

In PSHA it is recommended to convert all magnitudes to moment magnitudes. Since the United EBR catalogue has rather small volume it was no possible to construct appropriate regression relationships and convert local magnitudes to moment ones. An assumption has been made that difference between local and moment magnitudes was insignificant and thus local magnitudes were left in the United catalogue.

Fault tectonics of EBR

Various authors present rather different tectonic maps of EBR (e.g. Aronova, (2007), Fig. 3.1.4; Grigelis (1981), Fig. 3.1.5; Aizberg et al. (1999), Fig. 3.1.6). For example, Aronova (2007) suggests the fault crossing the Ignalina NPP site tending SW–NE (Fig. 3.1.4). According to Aizberg et al. (1999), the super-regional fault of the same trend ends there (Fig. 3.1.6), while tectonic map of the Baltic States (Grigelis, 1981) shows the fault crossing E–W the Ignalina NPP area (Fig. 3.1.5).

Furthermore, the most part of EBR seismic catalogue comprises historical events that do not contain the epicentre location errors; coordinates of historical epicentres may have tens of kilometres in error. This makes difficult to relate seismic events to individual faults or fault zones.

The northern part of EBR shows higher seismic activity than the southern part (Fig. 3.1.1). The border between these two areas roughly coincides to the Lithuanian-Latvian state border. This border was also identified on the seismogenic source models of GSHAP (Giardini et al., 1999) and ESC-SESAME (Giardini et al., 2003).

Even though, different authors prefer to draw rather different faults and faults zones on their tectonic maps of EBR, generalization allows distinguishing certain dominant fault trends and their density heterogeneities in different parts of the region. For example, E–W trending faults with a change in orientation towards the E to NE dominate in the western Latvia and NW part of Lithuania. In eastern Latvia, SW–NE faults prevail. This fault zone is denser than others in the region. In Estonia, faults trend mainly SW–NE, NW–SE, and E–W.

Table 3.1.1. The final "clean" United seismic catalogue of EBR. Catalogue is presented in NORDIC format. Types of magnitudes: W – moment, L – local. Data sources and seismological agencies: BLR – Aronova (2007); EEP – Joint catalogue of the East Europe platform (Sharov et al., 2007); BER – Bergen University; HEL – HUSI; NAO – Seismological Research centre NORSAR; UPP – Uppsala University; USG – Geological Survey of the US; DNS – Nikonov and Sildvee (1991),; GRE – Gregersen et at., 2007; KJW – Wahlström, according Kjellen, 1990; POL – Guterch, 2009; WAH – Wahlström and Ahjos, 1987.

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YYYY MMDD mmhh ss.s RILatitudLonitudeDepth  AGENSt RES MAG1AGE MAG1AGE MAG1AGE
1375                L  57.500  18.500 10.0  KJW        4.0LKJW                1
1540                L  57.700  18.700  5.0  KJW        4.3LKJW                1
1602                L  59.500  24.700  5.0  BLR        3.8LBLR 6.0IBLR        1
1607                L  59.700  24.700  5.0  BLR        3.8LBLR 6.0IBLR        1
1616 0630 0530      L  56.400  24.200  5.0  EEP        4.1LEEP 6.5IBLR        1
1670 0201 22        L  58.400  24.500  8.0  DNS        3.9LBLR 3.9 DNS 6.0IBLR1
1783 03             L  56.900  23.600       BLR        4.0LBLR 4.0IBLR        1
1785 1011           L  57.400  21.600       BLR        3.5LBLR 3.5IDNS 5.0IBLR1
1803 0108 2315      L  53.100  23.100  5.0  BLR        3.6LEEP 6.0IBLR 3.6 BLR1
1821 0222 0730      L  56.600  25.300 13.0  EEP        4.5LEEP 7.0IBLR 4.5 BLR1
1823 0206 00        L  58.000  26.200  7.0  DNS        3.9LBLR 7.0IBLR 3.9 DNS1
1827 0928 12        L  59.000  23.500 14.0  EEP        4.0LEEP 4.0 DNS 5.0IBLR1
1844 0112 22        L  58.600  23.700  6.0  BLR        2.5LBLR 2.5 DNS 4.0IBLR1
1853 0205 02        L  56.700  25.600       BLR        3.5LBLR 6.0IBLR 2.9IDNS1
1853 0326 0130      L  59.500  24.700  5.0  BLR        1.2LBLR 1.2 DNS 2.5IBLR1
1853 1229 2345      L  56.960  24.130       BLR        3.5LBLR 3.5IDNS 6.0IBLR1
1857 0518 09        L  57.700  22.200 10.0  EEP        4.5LEEP 3.0 DNS 7.0IBLR1
1858 0115 1410      L  59.300  22.600  8.0  BLR        3.0LBLR 3.0 DNS 5.0IBLR1
1869 0215 03        L  59.500  24.700  6.0  BLR        2.5LBLR 2.5 DNS 5.0IRBS1
1870 0206 0445      L  56.960  24.130       BLR        3.5LBLR 3.5IDNS 5.0IBLR1
1877 1016 0525      L  58.900  23.400 10.0  EEP        4.2LEEP 3.5 DNS 6.0IBLR1
1881 0128 1415      L  59.400  28.200  4.0  BLR        3.2LBLR 3.0 DNS 5.5IBLR1
1887 1210           L  54.200  28.500 10.0  EEP        3.7LEEP 6.0IBLR        1
1896 0920 15        L  56.600  23.700  5.0  EEP        3.5LEEP 3.5IDNS 5.0IBLR1
1907 0122 02        L  56.900  24.070  7.0  EEP        3.5LEEP 5.0IBLR 3.5 BLR1
1908 1228 05        L  54.600  25.800  9.0  BLR        4.5LEEP 7.0IBLR 4.5 BLR1
1908 1229 01        L  56.800  26.300 10.0  EEP        4.5LEEP 7.0IBLR 4.5 BLR1
1908 1229 0330      L  56.940  24.070 10.0  BLR        3.5LBLR 5.5IBLR        1
1908 1229 22        L  55.800  26.700 11.0  EEP        4.5LEEP 6.5IBLR 4.5 BLR1
1908 1229           L  57.500  25.700       BLR        3.5LBLR 6.0IBLR        1
1908 1230           L  54.308  22.300       POL        3.0LBLR 4.0IPOL        1
1909 0131 0715      L  56.900  24.100  6.0  EEP        3.5LEEP 5.0IBLR 3.5 BLR1
1909 0212 01        L  56.560  21.090       BLR        3.5LBLR 3.0IBLR        1
1909 0602 0830      L  58.400  25.600  7.0  BLR        1.8LBLR 1.8 DNS 3.0IBLR1
1910 0521 03        L  56.950  24.050 10.0  EEP        4.0LEEP 4.0 BLR 6.0IBLR1
1912 0615           L  59.700  25.000  6.0  BLR        2.0LBLR 2.0 DNS 3.5IBLR1
1931 0712 22        L  59.400  25.300  5.0  BLR        3.0LBLR 4.5IBLR        1
1932 0210           L  52.600  20.030       POL        4.3LPOL 6.0IPOL        1
1972 0904 0026 33.0 L  57.100  18.400       WAH        2.4LWAH                1
1976 1025 0839 45.0 L  59.260  23.390 10.0  EEP        4.7LEEP 6.5IBLR        1
1978 0510 0905      L  52.800  27.700 10.0  EEP        3.5LEEP 3.5 BLR 4.5IBLR1
1979 0724 1602 46.4 L  55.450  19.700       HEL        2.7LHEL                1
1980 0109 0124 52.4 L  58.910  22.990       HEL        2.4LHEL                1
1981 0622 1927 37.7 L  59.450  22.660  7.0  HEL        2.6LHEL                1
1982 0602 0758 17.7 L  57.040  21.940       HEL        2.3LHEL                1
1983 1201 2226 34.0 L  52.950  27.810  7.0  BLR        2.8LBLR 4.5IBLR        1
1985 1017 0132 24.0 L  52.900  28.400  7.0  EEP        3.5LEEP 4.0IBLR 3.4 BLR1
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1987 0408 2302 22.0 L  58.400  26.100 14.0  BLR        3.5LBLR 3.5 DNS 5.0IBLR1
1987 0705 0242 11.7 L  58.300  26.000  8.0  BLR        2.9LBLR 3.5IBLR        1
1987 0922 1825      L  58.700  26.400  9.0  BLR        3.0LBLR 4.5IBLR        1
1988 0429 1536 52.0 L  56.970  19.530  1.0  BER        3.5LHEL 3.3CBER        1
1988 0429 1541 22.7 L  56.320  21.400  7.0  BER        3.3LHEL 3.2CBER 3.1LBER1
1988 0902 1917      L  58.800  26.400  7.0  BLR        2.9LBLR 5.0IBLR        1
1994 0312 0756 58.6 L  55.200  17.910  0.0  BER        2.7LHEL 2.4LBER        1
1994 0601 1640 30.0 L  53.750  22.790       NAO        4.0LPOL 5.5IPOL 2.3LNAO1
1995 0306 1024 24.3 L  55.040  30.820 18.0  BER        2.5LHEL 2.2LBER        1
2002 1218 2114 21.9 L  55.888  18.203  2.2  BER 17 0.5 3.5LHEL 4.2BUSG 3.5LBER1
2003 0112 1143 47.8 L  59.402  23.415 10.0F HEL  8 1.0 1.2LHEL                1
2004 0128 1540 00.2 L  58.792  23.851 10.0F HEL  9 0.9 1.6LHEL                1
2004 0921 1332 31.9 L  54.834  20.025 10.0F HEL 71 0.8 5.2WGRE 4.7WHRV 5.2LUPP1
2006 1106 0111 40.3 L  59.677  24.857  2.7  HEL  5 0.1 1.1LHEL                1
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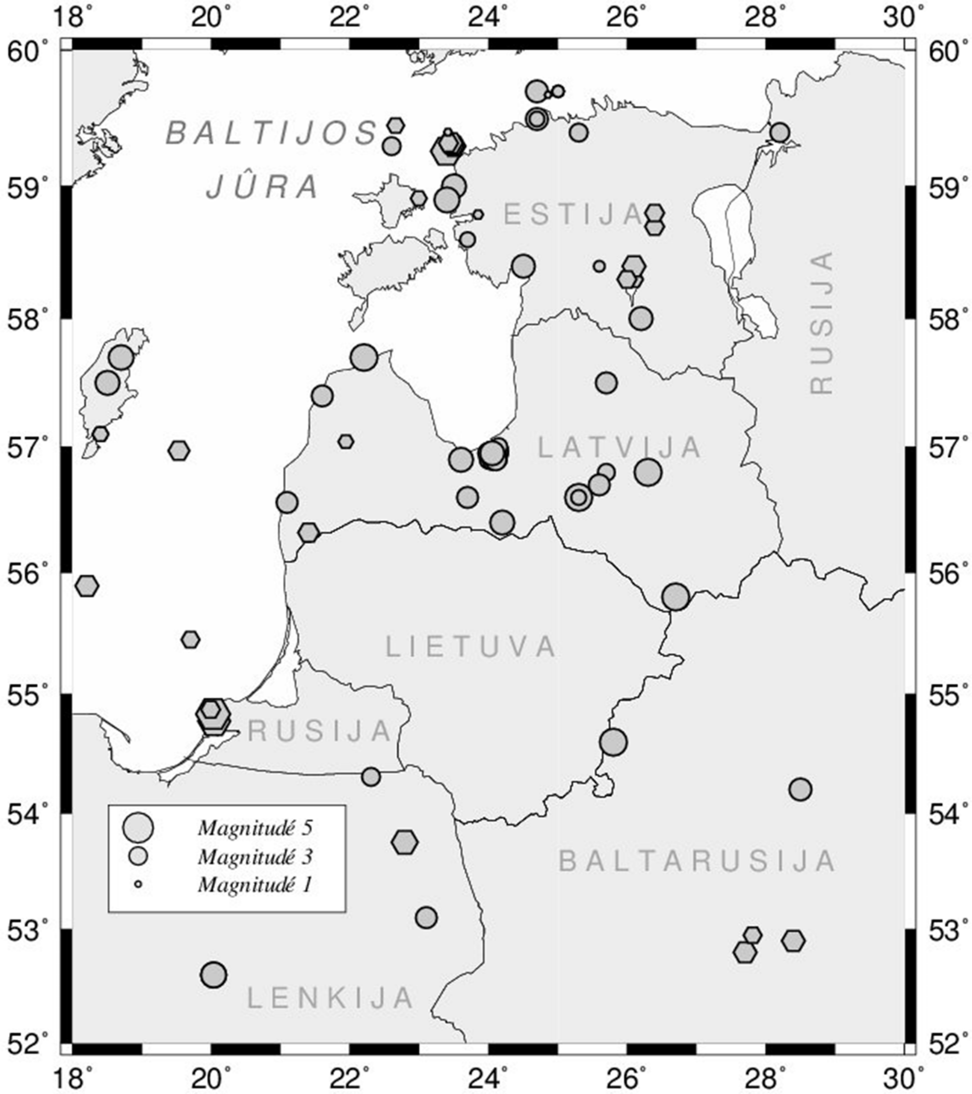

Fig. 3.1.1. Earthquakes of EBR according to the United seismic catalogue of EBR. Foreshocks and aftershocks are not removed. Circles correspond to historical seismic events (from ancient times until 1964), hexagons – instrumentally recorded events (from 1964 until 2009).

Previous seismotectonic models of EBR

Several recent studies suggest some ways of dividing EBR into SZ. Different models show different interpretations of local and regional seismicity, seismotectonic setting and structural geology. Some of the models are discussed below.

GSHAP (Giardini et al., 1999) Region No. 3, which occupies western, central, northern, and north-western Europe consists of 196 seismic zones (Fig. 3.1.2). EBR was divided into northern and southern provinces (Fig. 3.1.2).

In ESC-SESAME seismic hazard project the Europe was divided into 463 SZ (Jiménez et al., 2003). SZ were identified in accordance to GSHAP, supplemented by information from various publications. EBR seismic zones are the same as in GSHAP study.

Wahlström and Grünthal (2000) proposed SZ model in Sweden, Finland, and Denmark. Assessment included the three alternative seismogenic zonations. The same three models were later used to assess seismic hazard in Fennoscandia (Wahlström and Grünthal, 2001). In this study, EBR comprises one SZ that roughly coincides to the northern EBR province suggested by GSHAP.

Seismogenic zonation consisting of 6 regions (Fig. 3.1.3) was suggested by Varpasuo et al. (2001) in order to assess seismic hazard of Leningrad NPP site using PSHA. This model includes the central and northern part of the Baltic Sea, Lithuania, Latvia, Estonia, southern Finland, and northern Sweden. This model is distinct because it contains areas of total aseismicity. This is in contradiction to generally accepted opinion that such totally aseismic zones should not be in seismic hazard calculations (e.g. Chen and Scawthorn, 2003).

In conclusion, presented seismotectonic models of EBR by various authors are based on rather free interpretations of seismic, tectonic, geologic, and other type of data.

Seismotectonic models of EBR

Taking into account the uncertainty of tectonic fault framework and seismic zonation presented by various authors, three alternative seismotectonic models are presented in the dissertation.

Seismotectonic model A of the East Baltic Region

The first model A (Fig. 3.1.4) is similar to the one used in GSHAP and ESC-SESAME projects, however, with some modifications. The main changes involve division of the northern province of EBR in to two zones that have slightly different seismic intensities and are separated by somewhat less seismic area roughly coinciding with Estonian-Latvian state border. Borders of SZ were adjusted according to higher rank regional faults.

Seismotectonic model B of the East Baltic Region

The second model was compiled according to seismic event clusters related to individual faults and fault zones. In this model, seven SZ of diffuse seismicity were distinguished (Fig. 3.1.5). One zone out of these is a background zone that encompasses entire EBR.

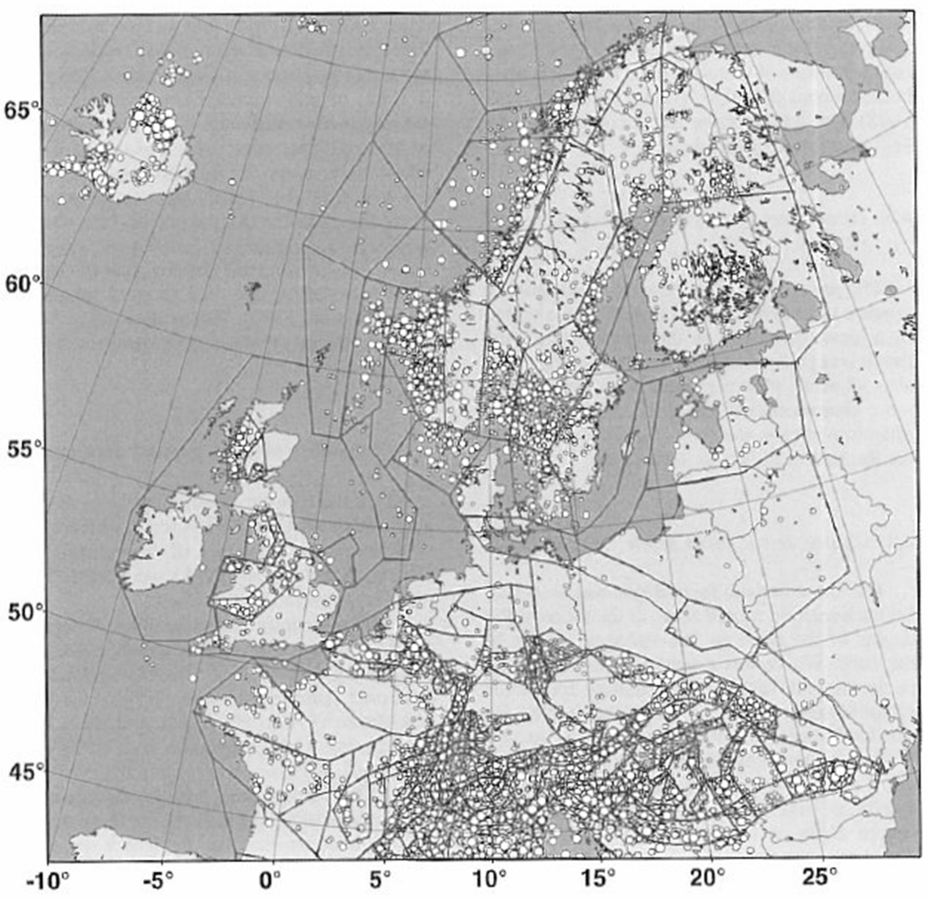

Fig. 3.1.2. Seismotectonic model of the Europe according to GSHAP Region No. 3 (Grünthal et al., 1999).

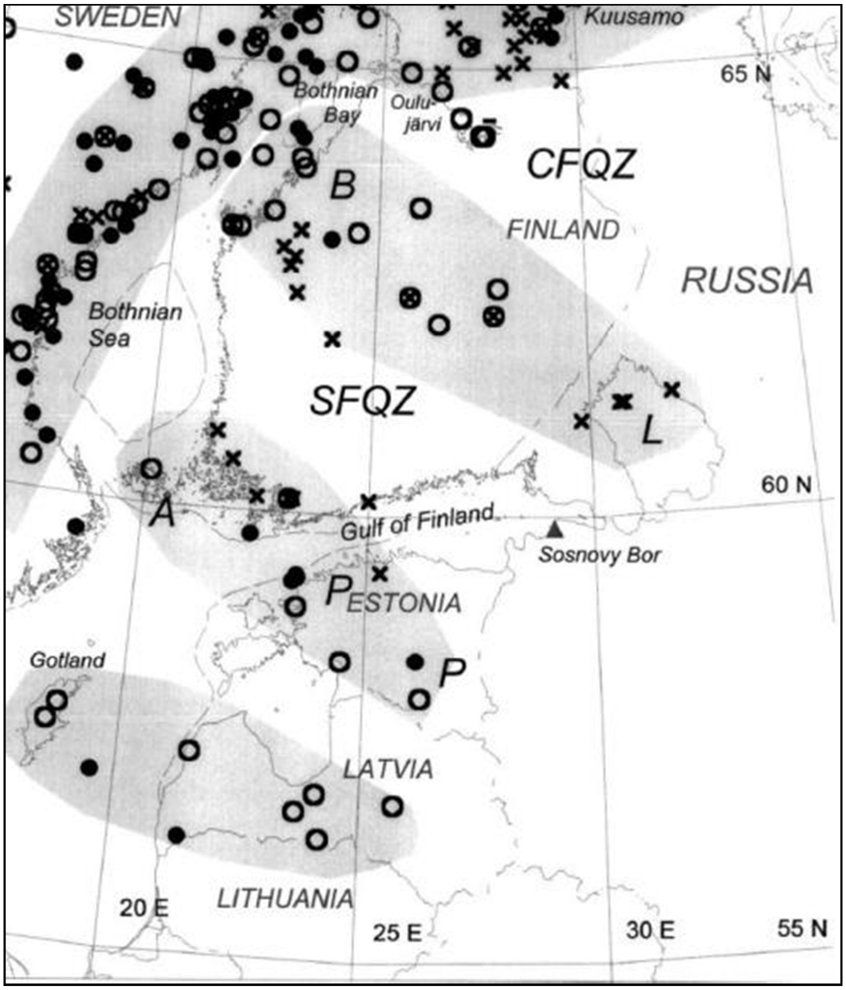

Fig. 3.1.3. Seismotectonic model of EBR and part of the Fennoscandia according to Varpasuo et al., 2001.

Seismotectonic model C of the East Baltic Region

The model C, like the model B, was compiled according to seismic event clusters and related to individual faults and fault zones. Differently from B, seismic event clusters were distributed somewhat differently. Earthquakes located along the coast of the Baltic Sea were combined as a single SZ as suggested by Lithuanian, Latvian and Russian researches in Oslo (2009) workshop of SHARE project of Seismic Hazard Assessment of Europe that was dedicated to seismogenic zonation of the Baltic Sea region. Also, comparing model C and B, B1, B3 and B5 zones were modified, B2 was combined to other zones, and B6 zone was merged with a background zone B0 (Fig. 3.1.6)

Seismotectonic model of the Vrancea region

The primary task of this study was to assess seismic hazard of EBR. As mentioned in the first chapter, seismic hazard of EBR is markedly influenced by the Vrancea SZ. Characteristics of the Vrancea SZ were used from authors who analysed the mentioned zone in detail (Mantiniemi et al. 2003).

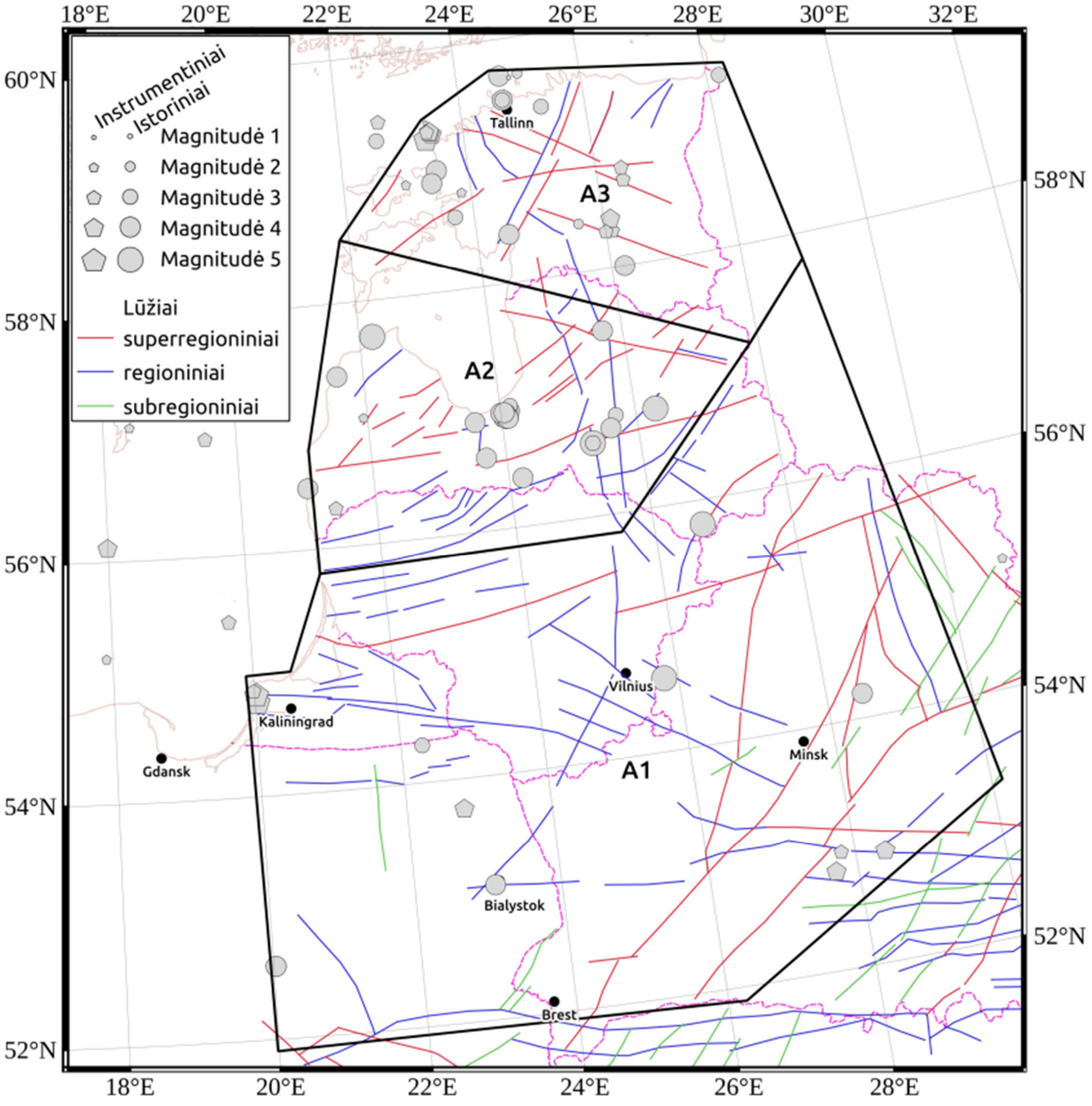

Fig. 3.1.4. Seismotectonic model A of EBR. Seismic events are taken from the United catalogue of EBR. Tectonic map is from Aronova (2007). Circles correspond to historical earthquakes, hexagons – instrumentally recorded earthquakes, red lines – superregional faults, blue lines – regional faults, and green lines – subregional faults.

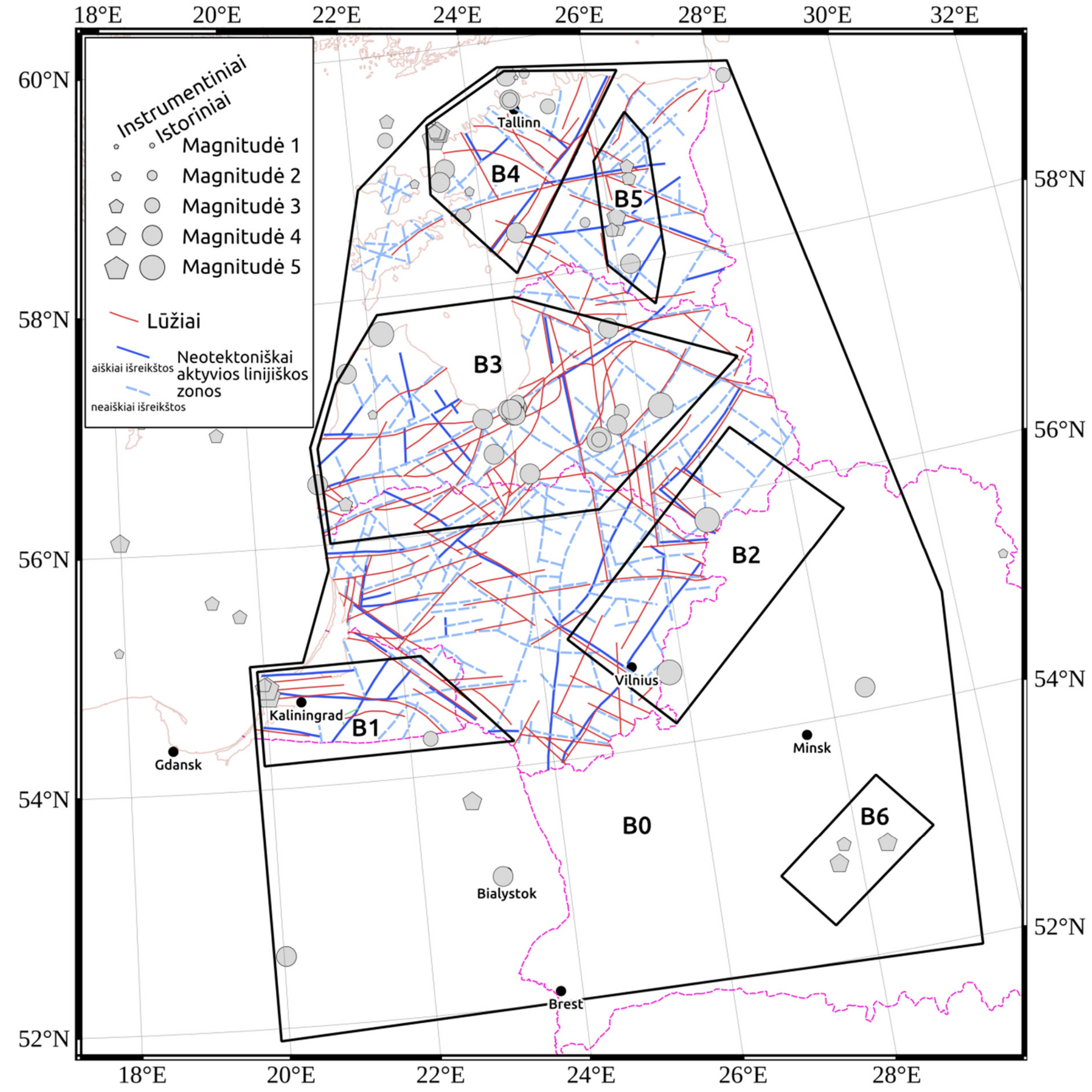

Fig. 3.1.5. Seismotectonic model B of EBR. Seismic events are taken from the United catalogue of EBR. Tectonic map is from Grigelis (1981). Circles correspond to historical earthquakes, hexagons – instrumentally recorded earthquakes, red lines – faults, blue lines – clearly expressed neotectonic zones and light blue dashed lines – unclearly expressed neotectonic zones.

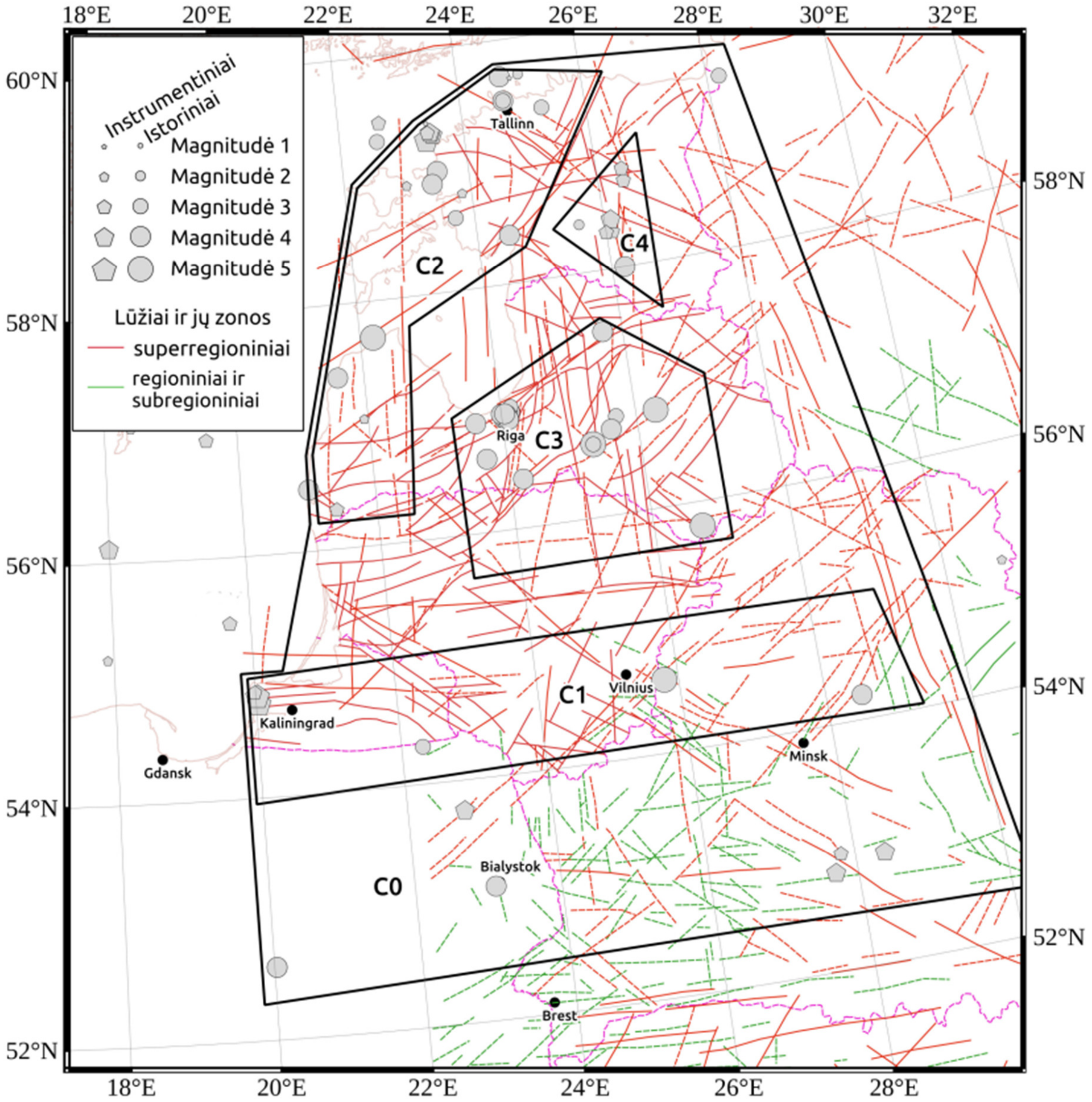

Fig. 3.1.6. Seismotectonic model C of EBR. Seismic events are taken from the United catalogue of EBR. Tectonic map is from Aizberg et al. (1999). Circles correspond to historical earthquakes, hexagons – instrumentally recorded earthquakes, red lines – superregional faults and light blue lines – subregional faults.

3.2. CHARACTERISTICS OF SEISMIC ZONES

Completeness of the seismic catalogue

After visualization of distribution in time of earthquakes of the United East Baltic catalogue, completeness of the catalogue was analysed. It was noticed natural tendency – the older seismic events the fewer records of low magnitude historical events were recorded in the catalogue. It was established that the seismic catalogue can be considered as complete from 1844 to 2009 for magnitudes higher than 3.5.

Only one event is included in the United East Baltic catalogue from 1912 to 1972. It remains unclear whether the absence of records during this period means the lack of natural events or just the lack of records because of social-historical perturbation during the First and Second World Wars, revolutions in Russia and Stalinism epoch in the Soviet Union. Therefore, to check these two hypotheses, it was chosen to use the "Full time" catalogue from 1844 to 2009 and it's "artificially Shortened time" version. Two periods were excluded from the "Full time" catalogue: one from 1914 to 1920, i.e. the First World War and post war time, and second – from 1940 to 1958, occupations of the Baltic States and Second World War until the end of Stalin era.

The "Shortened time" catalogue is shorter by 24 years than the full one, i.e. it spans from 1868 to 2009, but seismic events were used from 1844 to 2009. This "artificially shortened" catalogue somewhat increase seismic hazard level in later calculations, however it can "include" seismic events that possibly hasn't been recorded during unrest times.

Distribution of magnitudes

The parameter b (Eq. 2.1.1) reflects distribution of weaker and stronger seismic events. It is calculated using statistical methods, therefore number of seismic events have to be sufficiently large in seismic catalogue. Number of seismic events listed in the United catalogue of EBR is rather limited, while it is even smaller in separate SZ. Thus, due to the lack of information the parameter b for each zone cannot be estimated precisely enough. It can be generally expected that geological structure of the region is quite uniform and tectonic stress is homogeneous. Therefore common b value can be assumed for the entire region and for the each SZ. The parameter b was calculated using the United East Baltic catalogue and was found to be equal to 0.66 (standard deviation 0.12).

Saari (2000) calculated b = 0.76 ± 0.07 for a seismic zone spanning from the Aland archipelago in the Baltic Sea through Estonia to Pskov (Russia), i.e. it coincides within error limits with the value calculated for EBR in this study. For renewed seismic catalogue of the East European Platform from the ancient times to 2005 b value was calculated b=0.8 ± 0.08 (Sharov et al., 2007).

This raised uncertainty which b value should be used in seismic hazard assessment of EBR. It was decided to use two alternative b values: b = 0.66 ± 0.12, i.e. the one that was obtained from the United catalogue of EBR, and b=0.8 ± 0.05, i.e. the one obtained from the renewed seismic catalogue of the East European Platform (Sharov et al., 2007).

Parameters of seismic zones

In order to characterise seismic hazard of a certain region using PSHA it is required that each SZ is assigned parameter b and its standard deviation, seismic activity parameter a, threshold magnitude M_0, the largest observed magnitude(M_{obs}), the largest possible magnitude (M_{max}), lower magnitude limit (M_{min}) and hypocentral depth of earthquakes.

As mentioned in previous subsection, two alternative b values were used in this study. The largest magnitudes of each SZ were assessed analysing seismic sub-catalogues of each SZ. The largest possible magnitudes were calculated based on commonly accepted approach for areas of low seismicity, i.e. adding 0.5 magnitude value to the largest observed magnitude value in the zone (e.g. dePolo and Slemmons, 1990).

Lower magnitude limit (M_{min}) is a threshold magnitude when seismic events below are not considered in the calculations of seismic hazard. It is commonly assumed M_{min} = 4.0 (e.g. Bender and Campbell, 1989). On the other hand, M_{min} was set to 3.5 in assessment of seismic hazard of France (Beauval and Scoti, 2004). Therefore in EBR with rather limited seismic catalogue and only a few seismic events in each SZ, it was decided to set lower magnitude limit M_{min} to 3.5.

The necessary parameter sets including alternative b values and alternative “full” and “artificially shortened” seismic catalogues were set to all the three seismotectonic models.

As mentioned before, characteristics of the Vrancea SZ were obtained from Mantiniemi et al. (2003). They assumed $b = 0.78$, $M_0 = 4.5$, $M_{obs} = 7.4$, $M_{max} = 8.1$ and $M_{min} = 4.0$. These values were used in this study.

It is generally accepted that Poisson's exponential model is most applicable to diffused SZ. None of characteristic earthquakes was found in the United catalogue, therefore it was assumed that earthquakes have random spatial distribution and appears in time according to Poisson’s model.

3.3. GROUND MOTION ATTENUATION RELATIONS

Alternative ground motion attenuation functions

Selection of the appropriate ground motion functions that correspond to the study region is one of the most important stages in seismic hazard modelling of a certain region. Numerous theoretical and empirical attenuation relations with wide range of parameters are published. Three ground motion attenuation functions were chosen that correspond to the geological specifics of EBR, i.e. Ambraseys et al. (2005), Atkinson and Boore (2006), and Campbell and Bozorgnia (2003) with later improvements (Campbell and Bozorgnia, 2003b, c, 2004).

Ambraseys et al. (2005) performed a comprehensive analysis of a few hundreds of accelerograms of earthquakes located in Europe and Middle East. Ambraseys et al. (2005) developed function of horizontal ground motion attenuation that takes into account various focal mechanisms and therefore this function was used in this study. Moreover, the function allows calculating ground motion spectrum.

The attenuation function proposed by Atkinson and Boore (2006) is based on observations of the eastern part of the North American Craton having similar seismic setting. Attenuation relationship was created in order to estimate ground motions in hard rocks and soils for seismic event magnitudes from M=3.5 to M=8.0. The relationship described in the study is in accordance with requirements of this work because EBR is also cratonic and earthquakes are not strong. Therefore, the function of Atkinson and Boore (2006) was used in this study.

Campbell and Bozorgnia (Campbell and Bozorgnia, 2003, b, c and 2004) have analysed 1403 accelerograms recorded of 85 earthquakes in the entire globe. The ground motion attenuation function may be applied to EBR because earthquakes analysed were of shallow setting, hypocentres depths are less than ~40 km and one variety of the attenuation functions were developed for medium hard soils.

Ground motion attenuation of the East Baltic region

The seismic station network of EBR is sparse, but until the 2004 Kaliningrad earthquake's the number of stations was even less. There were almost no stations near epicentres which makes difficult the establishment of ground motion patterns in the region.

The Kaliningrad earthquakes of 2004 were one of rare possibilities to obtain information on attenuation of seismic waves from strong earthquakes in the region. The peak ground motion accelerations (PGA) of the Kaliningrad earthquakes (M_W=5.0, M_W=5.2), recorded in ten seismic stations closest to the epicentre (SUW, GKP, and WAR in Poland; BLEU and GOTU in Sweden; BSD in Denmark; IDID, IIGN, ISAL and IZAR in Lithuania), were compared with the three functions of ground motion attenuation mentioned above (e.g. Fig. 3.3.1). Even though the scatter of the PGA values vs distance (Fig. 3.3.1) from the epicentres is rather large and the data exist only from limited range of distances from epicentre, the chosen attenuation functions fit rather well.

Attenuation of ground motion of the East European Platform

Ground motion attenuation function for seismic waves generated in the Vrancea SZ is a separate task in this study. All reviewed hypocentres of earthquakes that occurred in EBR are located in the Earth's crust. The strongest earthquakes in the Vrancea, however, are generated at the depths from 100 to 150 km. Since earthquakes have deep hypocentres it was thought that the seismic function of these seismic events are best described by deep source earthquakes. Experiments with ground motion functions for subduction zones with sources reaching to the depths of 600-700 km (Zhao et al., 2006 and Kano et al., 2006) were performed.

On the other hand, macroseismic estimations of the Vrancea zone are lacking. Nikonov (2006), the only source found, presented a few rather poor quality schemes.

Comparison of seismic attenuation functions for subduction zones by Zhao et al., 2006 and Kano et al., 2006) with the ones assessed for the East European Platform showed that they are significantly different (Fig.3.3.2). Ambraseys et al., (2005) function, on the other hand, fitted the ground motion intensities quite well (Fig. 3.3.2). Therefore, the function by Ambraseys et al. (2005) was used to describe the propagation of seismic waves caused by the earthquakes originated in the Vrancea area.

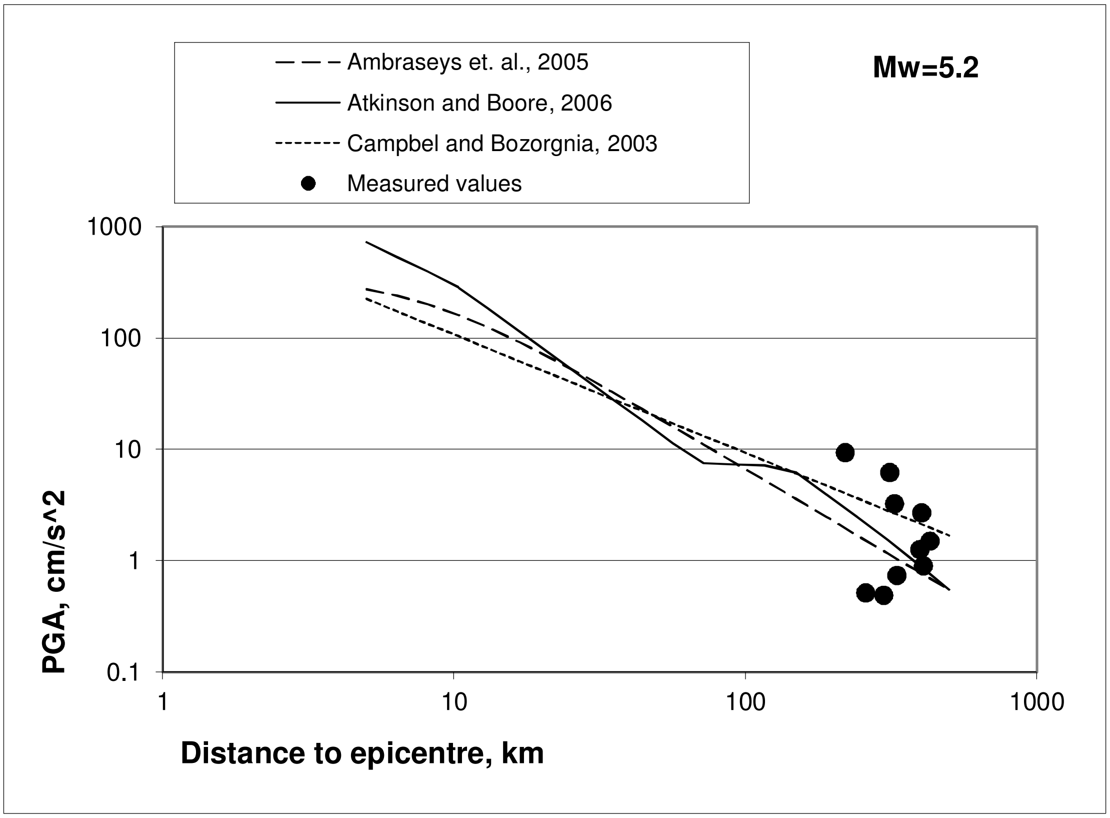

Figure 3.3.1. The measured PGA of the second Kaliningrad earthquake in 2004 (M_W=5.2) in comparison with the theoretical ground motion attenuation function of Ambraseys et al., (2005); Atkinson and Boore (2006), and Campbell and Bozorgnia (2003, b, c, 2004)

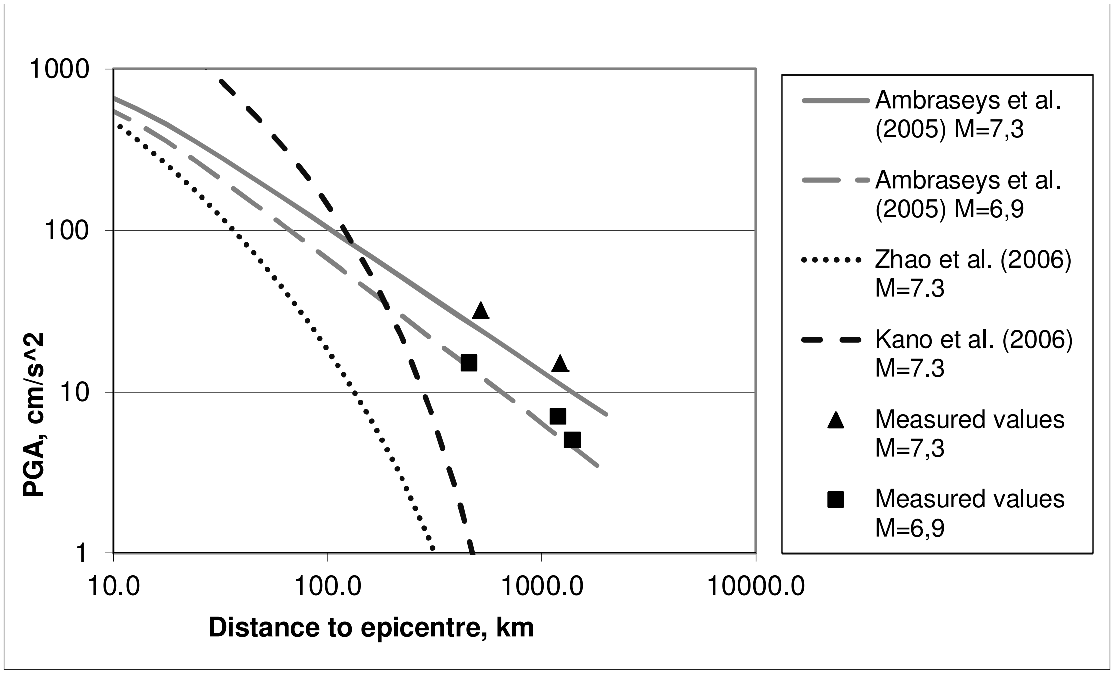

Figure 3.3.2. Comparison of ground motion intensities cause by the Vrancea earthquakes in 1940 (black triangles) and in 1977 (black squares) with theoretical seismic wave attenuation functions: black dotted line corresponds M = 7.3 (Zhao et al., 2006), black short dashed line – M = 7.3 (Kano et al., 2006), grey solid line – M = 7.3 (Ambraseys et al., 2005), grey dashed line – M = 6.9 Ambraseys et al., 2005).

3.4. LOGIC TREE

As mentioned in earlier sections describing steps of PSHA, it is rather often uncertainties related to lack of data arise. Due to such uncertainties while creating seismotectonic model or models it is not possible to describe precisely all the factors influencing the seismic activity of EBR. In order to improve the calculations accounting to uncertainties of PSHA a logic tree of seismotectonic models and their parameters was created (Fig. 3.4.1).

Logic tree describes features of each individual model and presents comfortable way to divide large and complex assessment task into smaller, simpler and easier calculable components. The result of PSHA logic tree is PGA or some certain spectral accelerations corresponding to some exceedance rate. The final result is obtained by summing all possible alternatives with assigned weights of each corresponding alternative.

Firstly, three seismotectonic models of EBR, described in section “Seismotectonic models of the East Baltic Region” were created. In the second level “Full time” and “Shortened time” seismic catalogues were assigned to each seismotectonic model. In the third level, two possible values of parameter b were assigned (0.66 and 0.80) to each branch of the logic tree. Finally, in the fourth level, three alternatives of ground motion attenuation functions: Ambraseys et al. (2005), Atkinson and Boore (2006), and Campbell and Bozorgnia (2003, b, c, 2004) were assigned to each branch. In this way, 36 branches of the logic tree (3x2x2x3=36) or 36 alternative models were constructed to calculate the PGA values (Fig. 3.4.1).

At each of the logic tree levels, corresponding weight coefficients have to be assigned to each branch. It was found no any objective reasons that would allow consider one alternative more likely than others. Therefore all possible hypotheses were considered equally possible at each level.

3.5. RESULTS AND DISCUTION

Seismic hazard assessment of EBR was performed using PSHA methodology. Three alternative seismotectonic models with alternative parameters and three alternative ground motion attenuation functions were created. The sets of input data were organised using logic tree approach (Fig. 3.4.1).

The assessment was performed at the regional scale. CRISIS 2007 software (Ordaz M. et al., 2013) developed for seismic hazard calculation was used in this study. The seismic hazard region was encompassed by polygon with coordinates of lower left corner 19.00° E and 53.00° N; and top right – 30.00° E and 60.00° N. Geographic grid was segmented each 0.25°.

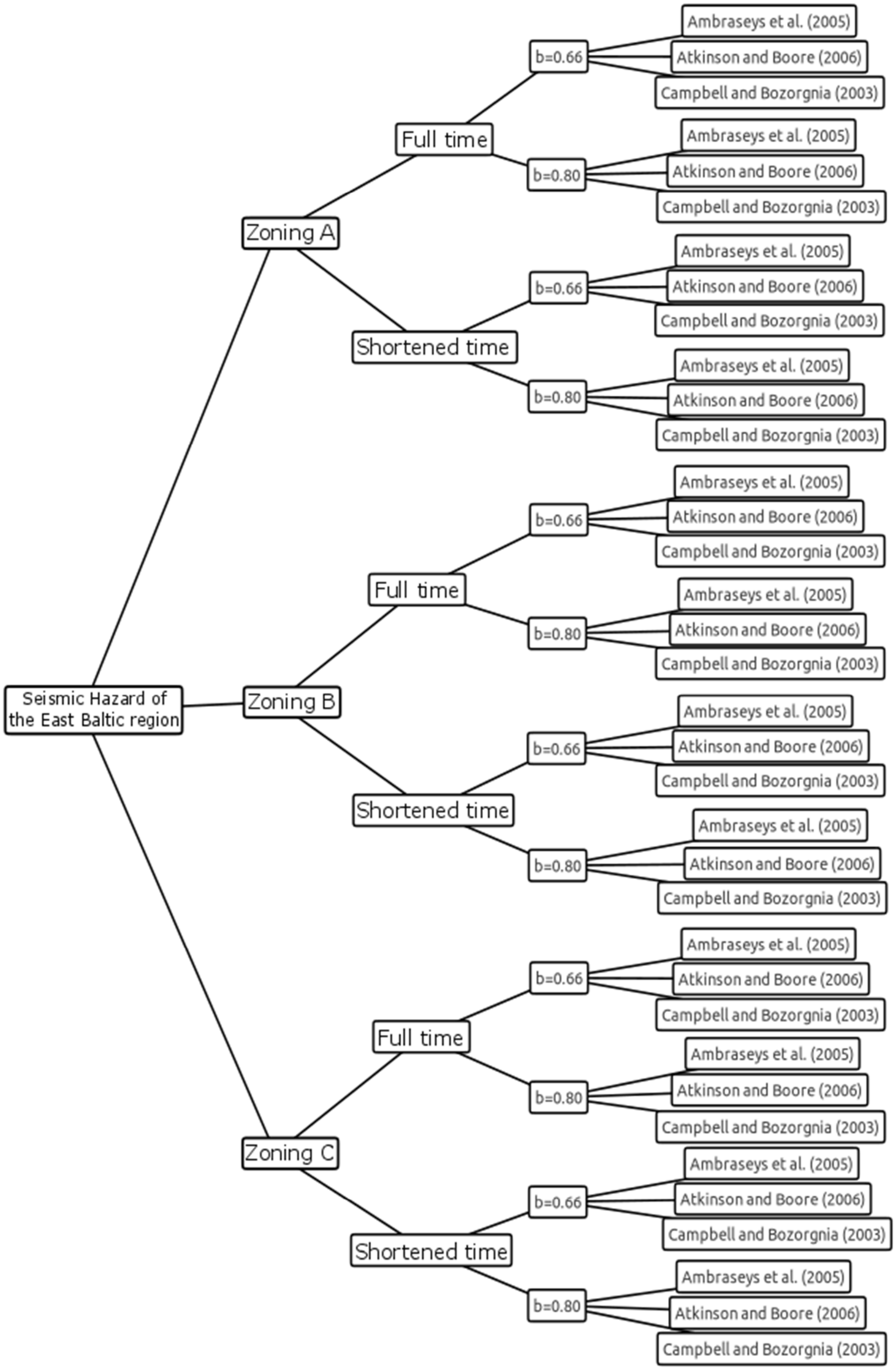

Fig. 3.4.1. The logic tree used in PSHA of EBR.

Return periods

In PSHA, the peak ground acceleration (PGA) that can be exceeded in 50 years with probability of 10% is commonly calculated for civil engineering purposes. It is shown mathematically; that this probability corresponds to the return period of 475 years, that is, the calculated PGA can be reach every 475 years, on average. Such probabilities or return periods of PGA is normally used in civil constructions and design. In construction of nuclear power plants (NPP) two hazard levels SL-1 and SL-2 are considered. SL-2 is associated with the highest safety requirements and thus the largest possible seismic influence. National standards of different states define SL-2 level as average probability from 10^{-3} to 10^{-4} for PGA to be exceeded once in a year. SL-1 is associated with the safe operation of NNP. Most of national standards define SL-1 as average probability of 10^{-2} for PGA to be exceeded once in a year. Accordingly, return periods of 100, 475, 1000, 10 000 and 100 000 years were selected for calculating the PGA values.

Calculation of PGA

Seismic hazard calculations resulted in two sets of arrays of the PGA values that correspond to two varieties of the logic tree. The first one considers only SZ’s of EBR. The second one incorporates both EBR and the Vrancea SZ’s. Every array of the PGA values consists of 180 (36 branches of the logic tree x 5 return periods) separate PGA value grids or PGA surfaces corresponding to certain seismic zoning approach, SZ’s parameters, attenuation function alternatives and five different return periods.

Comparison of several surfaces is not a straightforward task. Comparison of 180 different surfaces that depend on four interdependent parameters is even a more complex task. Because of that a simple approach was chosen; an average of each PGA value grid (surface) was calculated and then these corresponding to 100 000 return period were sorted in ascending order. The PGA value grid averages, when only SZ’s of EBR were included are listed in Table 3.5.1. Table 3.5.2 shows the averages when both SZ’s of EBR and Vrancea were considered. In the both tables, corresponding parameters that influenced each PGA grid values are shown: AF – ground motion attenuation function, SZM – method of seismotectonic zoning, CT – seismological catalogue time interval, and b – parameter b. In order to detect dependences of PGA grids from four independent parameters, each of cells with certain parameter value was assigned specific grey shading in the tables. Both tables show certain tendency of averaged PGA grid (surface) values, i.e. generalised levels of seismic hazard are mostly influenced by AF and SZM, while the choice of the time period of seismic catalogue (CT) and the parameter b affects the average PGA grid values to less extent when the return periods are longer (100 000 or 10 000). Influence of AF, CT and parameter b to the averages of PGA grids (surfaces) are more, however pronounced than influence of SZM when the return periods are shorter (1 000, 475 or 100).

Also it can be noticed the natural tendency of increasing of PGA grid mean values or generalised hazard level with increase of return periods. On the other hand, if we compare return periods of 100 000 years when PGA grid (surface) mean values were calculated using only SZ's of EBR and when those were calculated using both EBR and the Vrancea SZ's (Tables 3.5.1 and 3.5.2) we notice that the PGA grid averages vary from 72 to 181 cm/s^{-2} (the mean of averages is 130 cm/s^{-2}) for the first case and from 125 to 199 cm/s^{-2} (the mean of averages is 161 cm/s^{-2}) for the second case. This suggests that when considering return period of 100 000 years, the Vrancea SZ influence to seismic hazard of EBR is rather significant (~44%). Calculations also show that the Vrancea SZ has even greater (~64%) effect on the hazard level of EBR when return period of 100 years is considered. With longer return periods, however, the Vrancea SZ has less influence to general hazard of EBR: ~58% when return period is 475 years, ~55% – 1 000 years, ~48% – 10 000 years, ~44% – 100 000 years. This is illustrated in Figure 3.5.1. The figure also shows that seismic hazard of EBR is more influenced by Vrancea SZ when return periods are from 100 to ~5 000 years. When it equals to ~5 000 years, the influence of both Vrancea and EBR SZ's is more or less the same. When return periods are longer the seismic hazard in the ERB is increasingly dominated by local SZ's.

Table 3.5.1. Averages of PGA arrays (surfaces) [cm/s^{-2}] corresponding to all branches of the logic tree and all return periods then only EBR SZ's were assessed. Here AF correspond to different ground motion attenuation functions, AF1 – Ambraseys et al. (2005), AF2 –Atkinson and Boore (2006), AF3 – Campbell and Bozorgnia (2003, b, c, 2004); SZM – type of seismotectonic zonation, A – seismotectonic model A, B – seismotectonic model B, C – seismotectonic model C; CT – time of seismic catalogue, FT – "Full time" catalogue, ST – "Short time" catalogue; b – value of the parameter b.

					Return periods, years				
No.	**AF**	**SZM**	**CT**	**b**	**100**	**475**	**1000**	**10000**	**100000**
1	AF2	B	FT	0.66	2.5	7.0	10.7	31.7	72.3
2	AF2	B	FT	0.80	2.7	7.4	11.2	32.2	72.6
3	AF2	B	ST	0.66	2.9	7.7	11.7	34.0	76.2
4	AF2	B	ST	0.80	3.2	8.4	12.5	35.1	77.3
5	AF2	C	FT	0.66	2.4	7.1	11.2	35.8	85.5
6	AF2	C	FT	0.80	2.7	7.7	11.9	36.9	86.5
7	AF2	C	ST	0.66	2.7	7.7	12.1	38.1	89.8
8	AF2	C	ST	0.80	3.0	8.4	12.9	39.3	90.8
9	AF3	B	FT	0.66	5.9	15.1	21.9	56.4	115.3
10	AF3	B	FT	0.80	6.5	15.9	22.8	57.5	116.0
11	AF2	A	FT	0.66	2.3	7.0	11.3	42.5	117.6
12	AF3	B	ST	0.66	6.7	16.6	23.8	60.1	121.0
13	AF3	B	ST	0.80	7.5	17.8	25.3	61.9	122.6
14	AF2	A	ST	0.80	2.7	8.0	12.9	46.4	122.8
15	AF1	B	FT	0.66	4.0	12.4	19.1	56.3	128.1
16	AF1	B	FT	0.80	4.5	13.4	20.4	58.3	131.0
17	AF3	C	FT	0.66	5.6	15.2	22.7	61.9	131.2
18	AF3	C	FT	0.80	6.3	16.4	24.1	63.8	133.0
19	AF1	B	ST	0.66	4.7	13.9	21.2	60.8	136.2
20	AF3	C	ST	0.66	6.2	16.5	24.4	65.4	136.3
21	AF1	C	FT	0.66	3.5	12.2	19.4	60.1	137.5
22	AF3	C	ST	0.80	6.9	17.7	25.9	67.3	138.0
23	AF1	B	ST	0.80	5.5	15.4	22.9	63.4	139.8
24	AF1	C	FT	0.80	4.2	13.6	21.3	63.1	141.7
25	AF1	C	ST	0.66	4.0	13.4	21.1	63.9	144.6
26	AF2	A	FT	0.80	8.9	20.1	28.0	67.8	145.5
27	AF2	A	ST	0.66	3.5	10.0	15.9	57.3	147.3
28	AF1	C	ST	0.80	4.7	14.9	23.2	66.9	148.7
29	AF3	A	FT	0.66	5.3	15.3	23.7	72.3	165.8
30	AF1	A	FT	0.66	3.0	11.4	19.6	70.2	168.4
31	AF3	A	FT	0.80	6.1	17.1	26.1	76.8	171.3
32	AF3	A	ST	0.66	5.7	16.4	25.3	76.1	172.3
33	AF3	A	ST	0.80	6.3	17.6	26.8	78.2	173.7
34	AF1	A	ST	0.66	3.3	12.4	21.2	73.9	175.1
35	AF1	A	FT	0.80	3.7	13.6	23.0	77.2	179.0
36	AF1	A	ST	0.80	3.9	14.1	23.8	78.9	181.9
Averages, cm/s^2					**4.5**	**12.9**	**19.8**	**58.0**	**130.4**
Standard deviation, cm/s^2					**1.7**	**3.8**	**5.4**	**14.4**	**32.0**
Standard deviation, %					**37.0**	**29.5**	**27.4**	**24.9**	**24.6**

Table. 3.5.2. Averages of PGA arrays (surfaces) [cm/s^{-2}] corresponding to all branches of the logic tree and all return periods then both EBR SZ and Vrancea SZ were assessed. Here AF correspond to different ground motion attenuation functions, AF1 – Ambraseys et al. (2005), AF2 –Atkinson and Boore (2006), AF3 – Campbell and Bozorgnia (2003, b, c, 2004); SZM – type of seismotectonic zonation, A – seismotectonic model A, B – seismotectonic model B, C – seismotectonic model C; CT – time of seismic catalogue, FT – "Full time" catalogue, ST – "Short time" catalogue; b – value of the parameter b.

					Return periods, years				
No.	**AF**	**SZM**	**CT**	**b**	**100**	**475**	**1000**	**10000**	**100000**
1	AF2	B	FT	0.66	8.7	19.7	27.4	63.8	124.9
2	AF2	B	FT	0.80	8.8	19.9	27.6	64.2	125.0
3	AF2	B	ST	0.66	8.9	20.1	27.9	65.0	127.0
4	AF2	B	ST	0.80	9.1	20.4	28.3	65.8	127.9
5	AF2	C	FT	0.66	8.7	19.8	27.4	64.8	130.8
6	AF2	C	ST	0.66	8.9	20.0	27.8	66.1	133.6
7	AF2	C	ST	0.80	9.0	20.3	28.2	66.8	134.5
8	AF2	A	FT	0.66	8.7	19.8	27.5	66.5	143.1
9	AF2	A	FT	0.80	8.9	20.1	28.0	67.8	145.5
10	AF2	A	ST	0.80	8.9	20.2	28.2	68.3	146.9
11	AF3	B	FT	0.80	11.1	24.7	34.1	78.2	147.7
12	AF3	B	ST	0.66	11.3	25.2	34.8	79.8	150.9
13	AF3	B	ST	0.80	11.8	26.0	35.8	81.3	152.2
14	AF3	C	FT	0.66	10.7	24.1	33.6	79.9	158.0
15	AF1	B	FT	0.66	10.0	23.7	33.5	80.4	160.8
16	AF3	C	ST	0.66	11.0	24.9	34.7	82.4	161.6
17	AF1	B	FT	0.80	10.3	24.4	34.5	82.1	163.1
18	AF3	C	ST	0.80	11.4	25.7	35.8	84.0	163.2
19	AF1	B	ST	0.66	10.5	24.8	34.9	83.4	166.4
20	AF2	A	ST	0.66	9.3	21.2	29.7	75.3	166.9
21	AF1	C	FT	0.66	9.8	23.3	33.1	82.1	167.5
22	AF1	C	FT	0.80	9.8	23.3	33.1	82.1	167.5
23	AF2	C	FT	0.80	9.8	23.3	33.1	82.1	167.5
24	AF3	C	FT	0.80	9.8	23.3	33.1	82.1	167.5
25	AF1	B	ST	0.80	11.0	25.8	36.3	85.8	169.7
26	AF1	C	ST	0.66	10.0	24.0	34.2	84.7	172.8
27	AF1	C	ST	0.80	10.4	25.1	35.7	87.3	176.7
28	AF3	A	FT	0.66	10.5	24.2	33.8	84.9	180.0
29	AF3	B	FT	0.66	10.5	24.2	33.8	84.9	180.0
30	AF3	A	FT	0.80	11.0	25.2	35.3	88.3	184.9
31	AF3	A	ST	0.66	10.8	24.8	34.8	87.8	185.7
32	AF1	A	FT	0.66	9.6	22.9	32.6	85.6	186.7
33	AF3	A	ST	0.80	11.2	25.6	35.8	89.6	187.0
34	AF1	A	ST	0.66	9.7	23.4	33.4	88.4	192.6
35	AF1	A	FT	0.80	10.0	24.1	34.5	91.0	196.3
36	AF1	A	ST	0.80	10.1	24.4	35.0	92.4	199.0
Averages, cm/s^2					**10.0**	**23.1**	**32.4**	**79.0**	**161.4**
Standard deviation, cm/s^2					**0.9**	**2.1**	**3.1**	**8.8**	**21.1**
Standard deviation, %					**9.0**	**9.1**	**9.5**	**11.2**	**13.0**

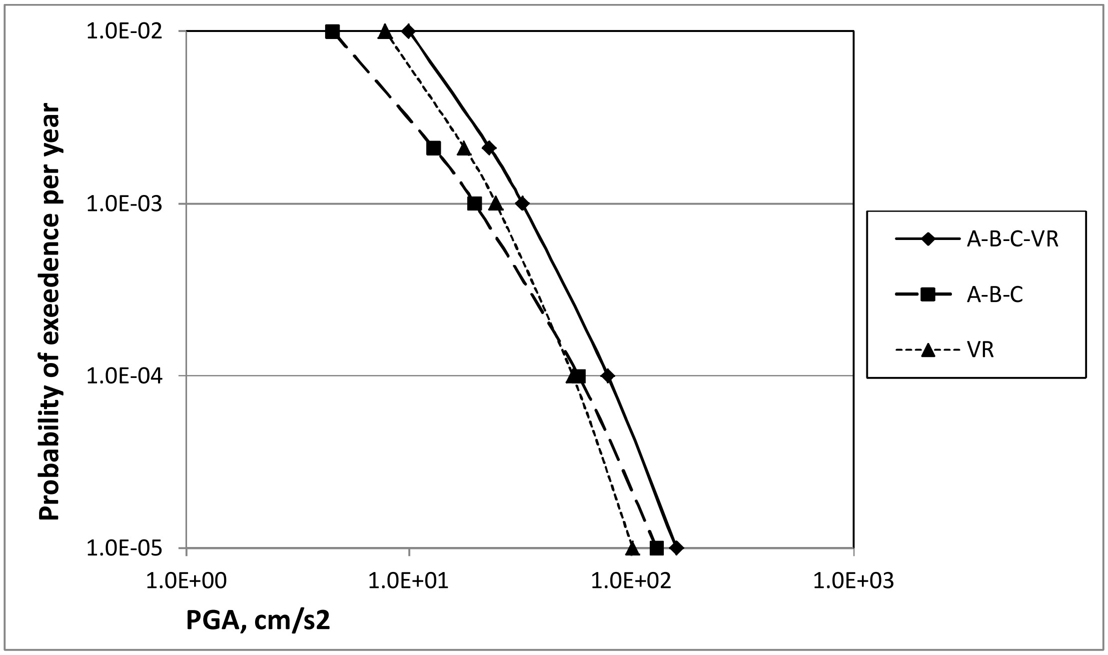

Fig. 3.5.1. Averages of EBR for different exceedance levels (return periods). Here „A-B-C-VR“ curve correspond to average seismic hazard caused by the local EBR seismicity and Vrancea SZ seismicity, „A-B-C“ – average seismic hazard caused by the only local EBR seismicity, „VR“ – seismic hazard caused only by the Vrancea SZ.

PGA maps

One of the main tasks of the presented study was compilation of seismic hazard maps of EBR for different probability levels. In compiling a map of a certain probability level PGA grids (surfaces) were calculated that matched all 36 alternatives of the logic trees used. The PGA maps corresponding to a certain probability level were compiled. Figure 3.5.4 shows the map of EBR that PGA values can be exceeded in 50 years with 10% probability (return period of 475 years). Influence of both EBR and the Vrancea SZ's was taken into account. Figure 3.5.5 shows the PGA values with probability of exceedance 10^{-3} per year (return period – 1 000 years), while probability of exceedance of 10^{-4} per year (return period – 10 000 years) is presented in figure 3.5.6, and probability of exceedance of 10^{-5} per year (return period – 100 000 years) is presented in figure 3.5.7. The impact of both EBR and the Vrancea SZ's was assessed in those maps. The observed trend is rather natural; the lower PGA exceedance probability the higher maximum PGA values. Therefore peculiarities of PGA lateral distribution is best observed on the map for return period of 100 000 years (Fig. 3.5.7) even though they are obvious on maps with shorter return periods (Figs. 3.5.6, 3.5.5

and 3.5.4). Figure 3.5.7 shows the local PGA maximum exceeding 280 cm/s^{-2} in the Kaliningrad area (A). The local PGA maximum exceeding 260 cm/s^{-2} is situated in the area of Vilnius (B). The local PGA maximum exceeding 240 cm/s^{-2} is calculated in the western and central-southern parts of Latvia (D). The local PGA maximum exceeding 220 cm/s^{-2} is located in the western part of Estonia (E), and local maxima exceeding 200 cm/s^{-2} are situated in the western and central Belarus (F) and central-southern Estonia (G). The local PGA maxima found in the seismic hazard maps of EBR are related to individual SZ's. Local maximum A is related to SZ's B1 and C1. Local maximum B is confined to SZ's B2 and C1, maximum C – to SZ's A2, B3 and C2, maximum D – to SZ's A2, B3 and C3, maximum E – to SZ's B4 and C2, maximum G – to SZ's B5 and C4, maximum F – to SZ's A1 and C1.

Figure 3.5.2 shows seismic hazard of EBR in sense of the PGA values that can be exceeded in 50 years with 10% probability; seismic hazard is influenced by only the Vrancea SZ. According to this map, the Vrancea SZ induce rather uniform seismic hazard in the entire region. At the very southern margin of EBR (Belarus), the calculated PGA value is 25 cm/s^2. Towards the north the PGA values systematically decrease to 13 cm/s^2 in the northern Estonia.

Figure 3.5.3 shows the EBR seismic hazard map with the PGA values that can be exceeded in 50 years with 10% probability when only SZ's of EBR are included in calculations. The local PGA maxima exceed 30 cm/s^2 in Kaliningrad area and in central-south Latvia. The local maxima exceeding 25 cm/s^2 are observed near Vilnius, western Latvia and central south Estonia. The average PGA value of the entire region equals to 12.9 with 3.8 cm/s^2 standard deviation (Table 3.5.1).

Figure 3.5.4 shows the PGA values that can be exceeded in 50 years with 10% probability when both EBR and the Vrancea SZ's impacts were estimated. The local PGA maxima exceed 35 cm/s^2 in the Kaliningrad area, central Latvia and central Estonia. The local maxima exceeding 30 cm/s^2 are observed near Vilnius and in the larger part of Latvia. The average PGA value of the entire region equals to 23.1 with 2.1 cm/s^2 standard deviation (Table 3.5.2).

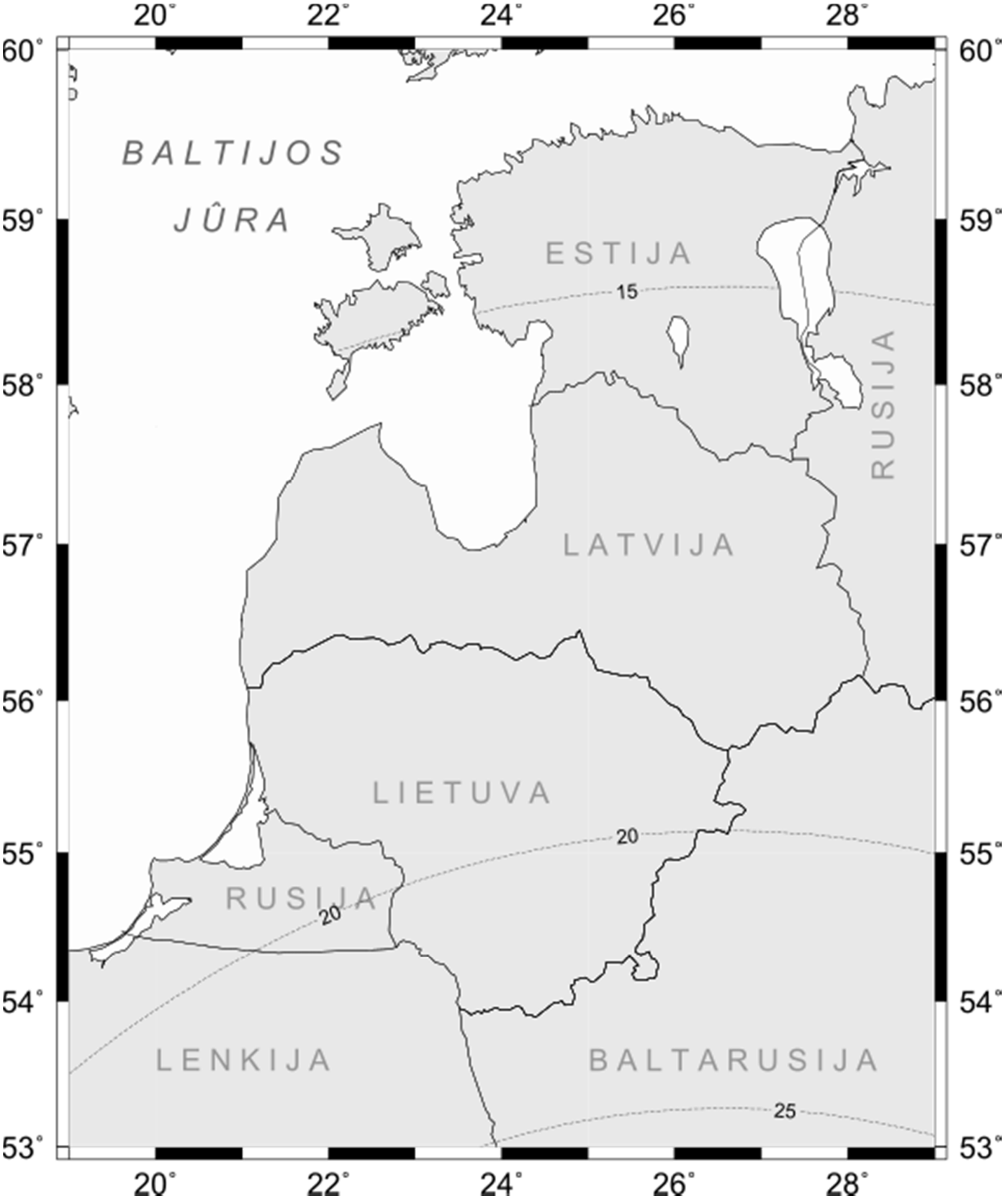

Fig. 3.5.2. Map of seismic hazard in terms of PGA (cm/s^2) of EBR when only Vrancea SZ is considered. Contour lines correspond to the PGA values (cm/s^2), which can be exceeded with 10% of probability within 50 years period (return period 475 years).

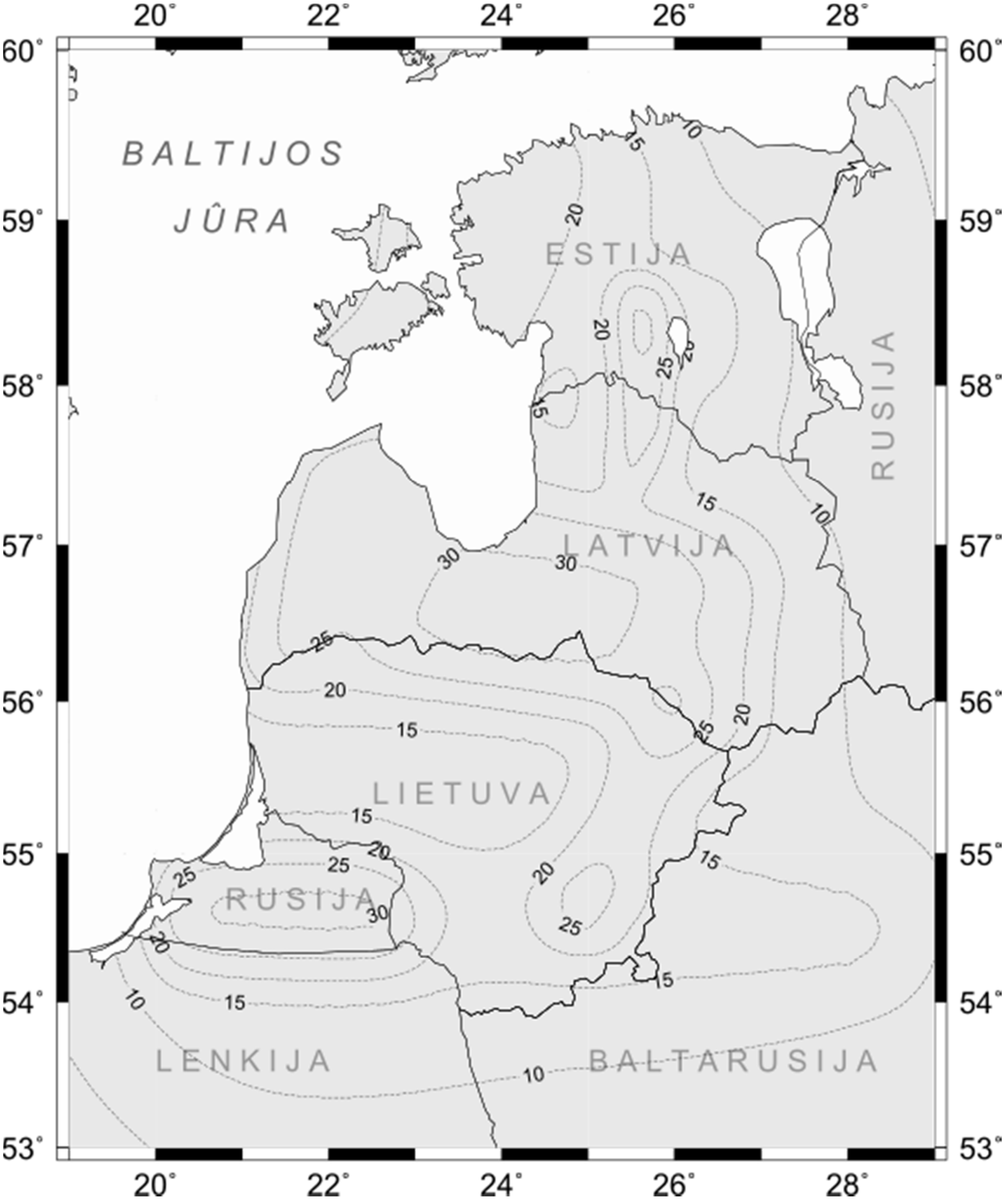

Fig. 3.5.3. Map of seismic hazard in terms of PGA (cm/s^2) of EBR when only local seismicity of EBR is considered. Contour lines correspond to the PGA values (cm/s^2), which can be exceeded with 10% of probability within 50 years period (return period 475 years).

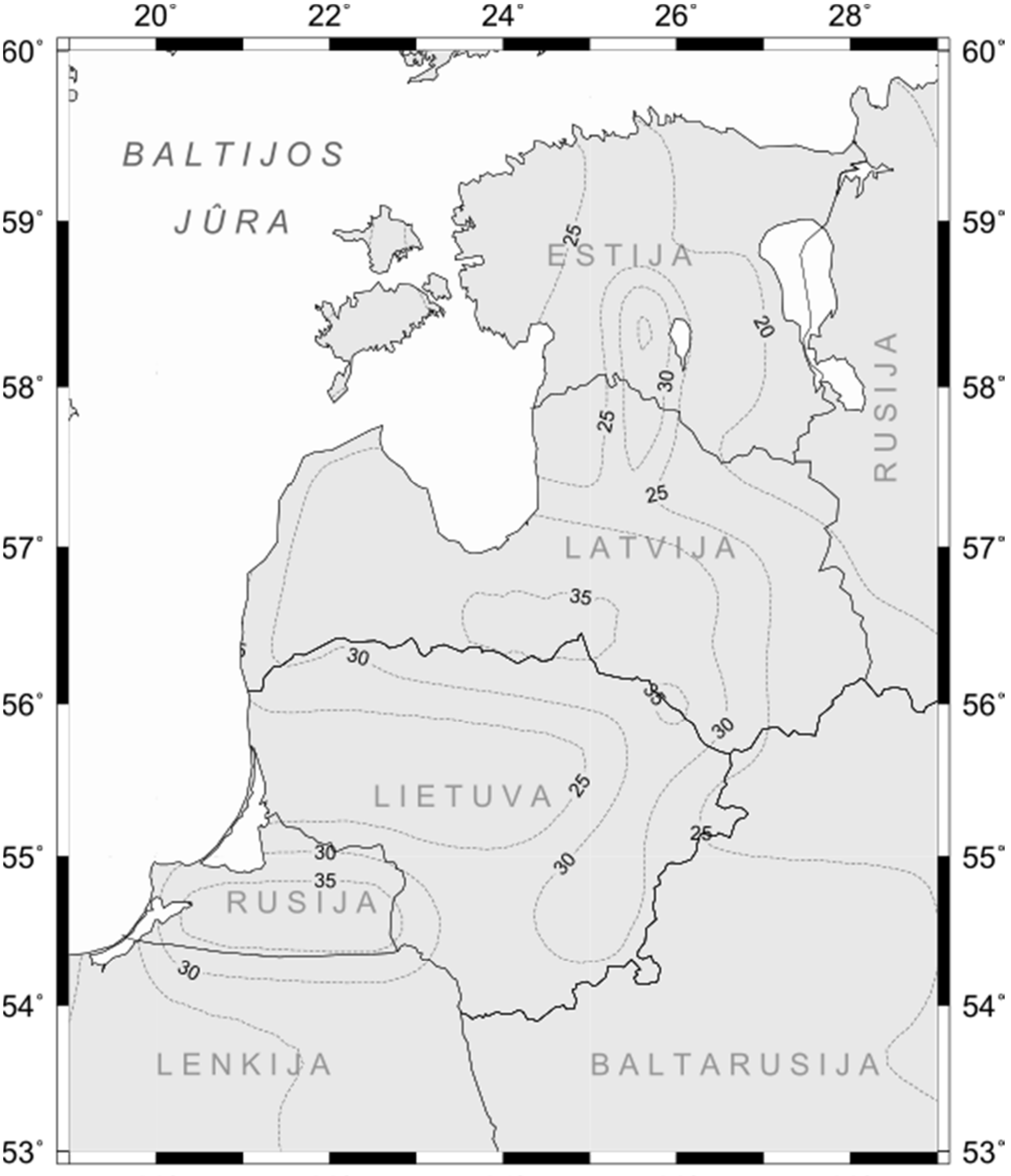

Fig. 3.5.4. Map of seismic hazard in terms of PGA (cm/s^2) of EBR when local seismicity of EBR and Vrancea SZ are considered. Contour lines correspond to the PGA values (cm/s^2), which can be exceeded with 10% of probability within 50 years period (return period 475 years).

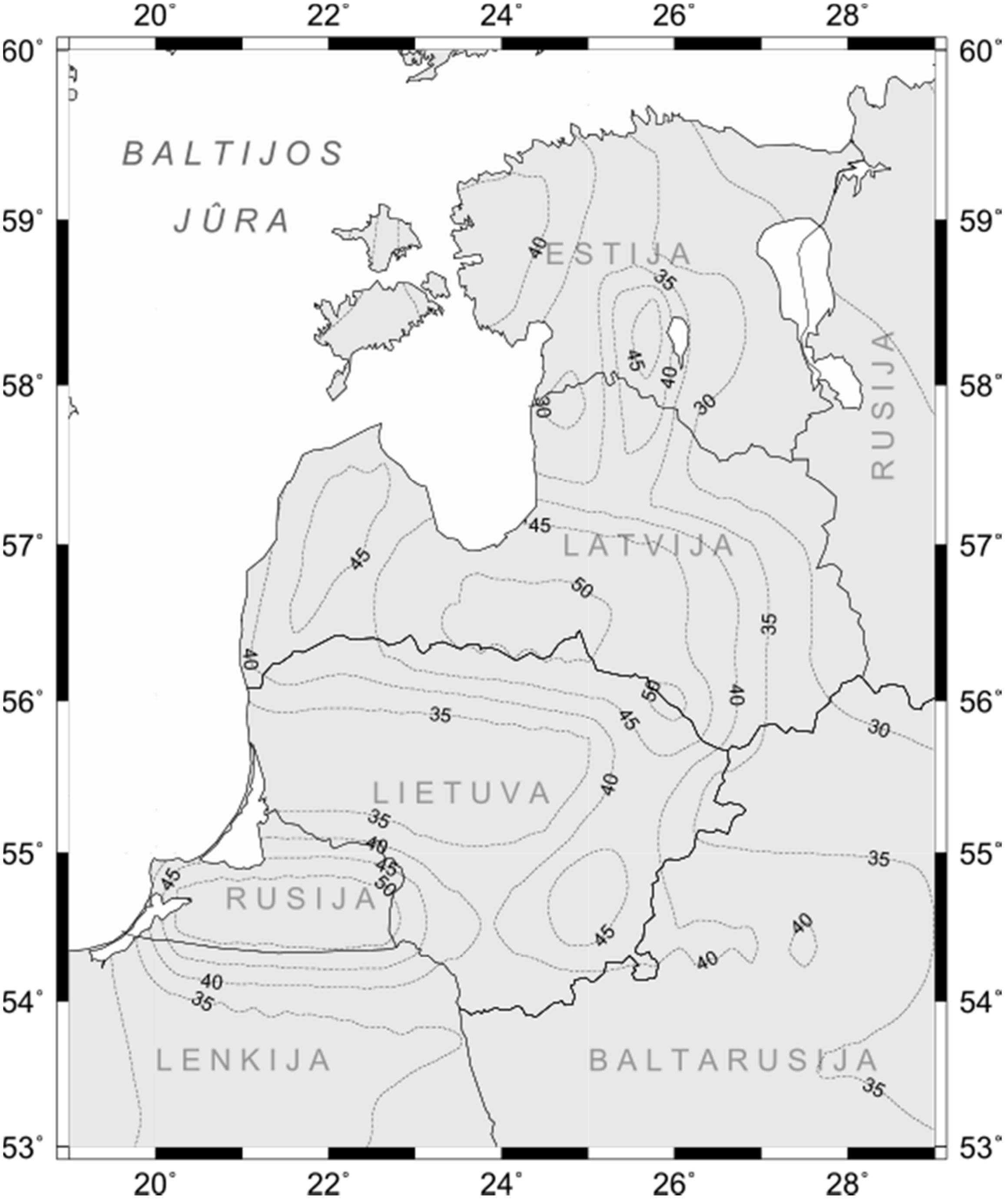

Fig. 3.5.5. Map of seismic hazard in terms of PGA (cm/s^2) of EBR when local seismicity of EBR and Vrancea SZ are considered. Contour lines correspond to the PGA values (cm/s^2), which can be exceeded with 10^{-3} of probability within one year (return period 1 000 years).

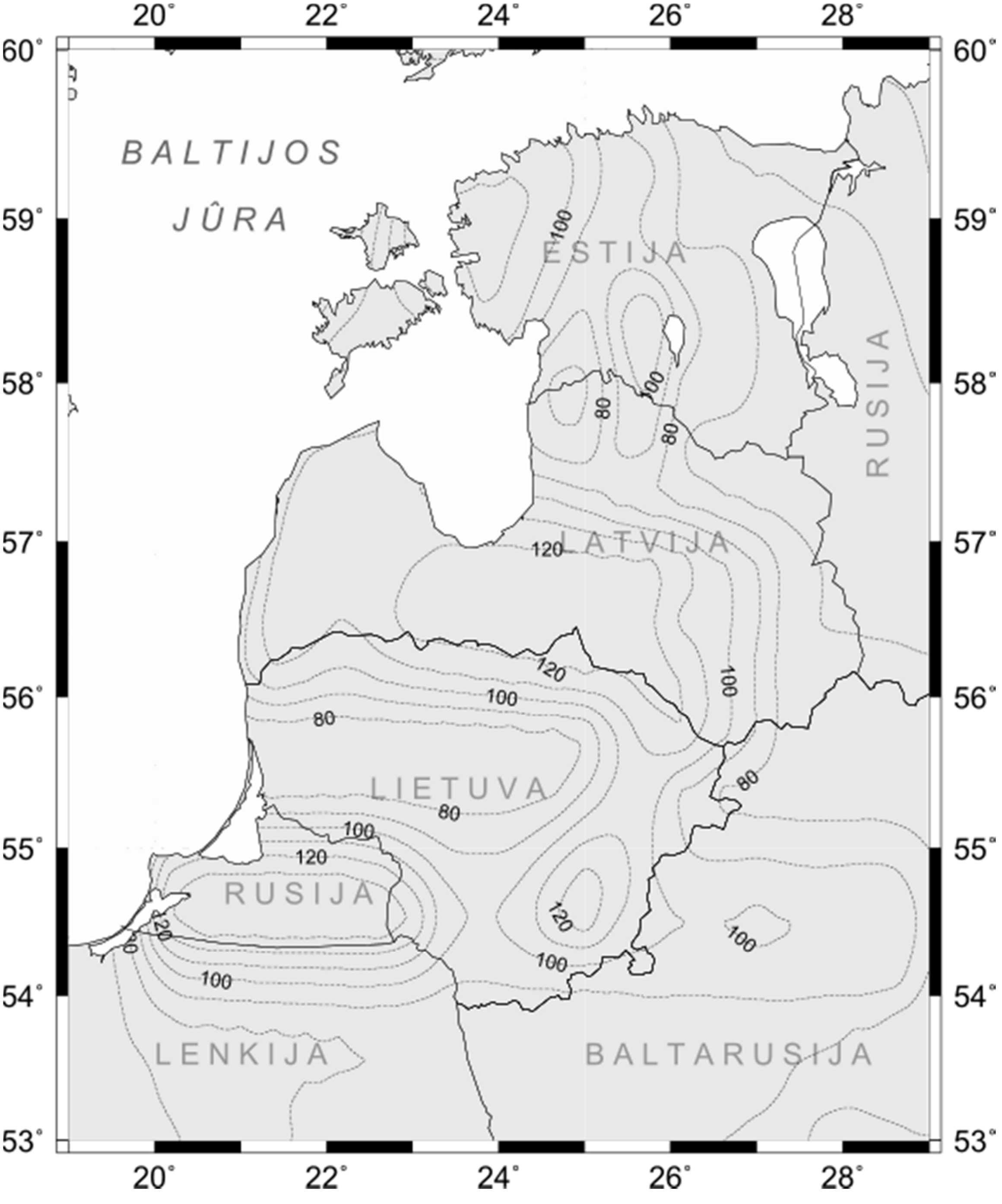

Fig. 3.5.6. Map of seismic hazard in terms of PGA (cm/s^2) of EBR when local seismicity of EBR and Vrancea SZ are considered. Contour lines correspond to the PGA values (cm/s^2), which can be exceeded with 10^{-4} of probability within one year (return period 10 000 years).

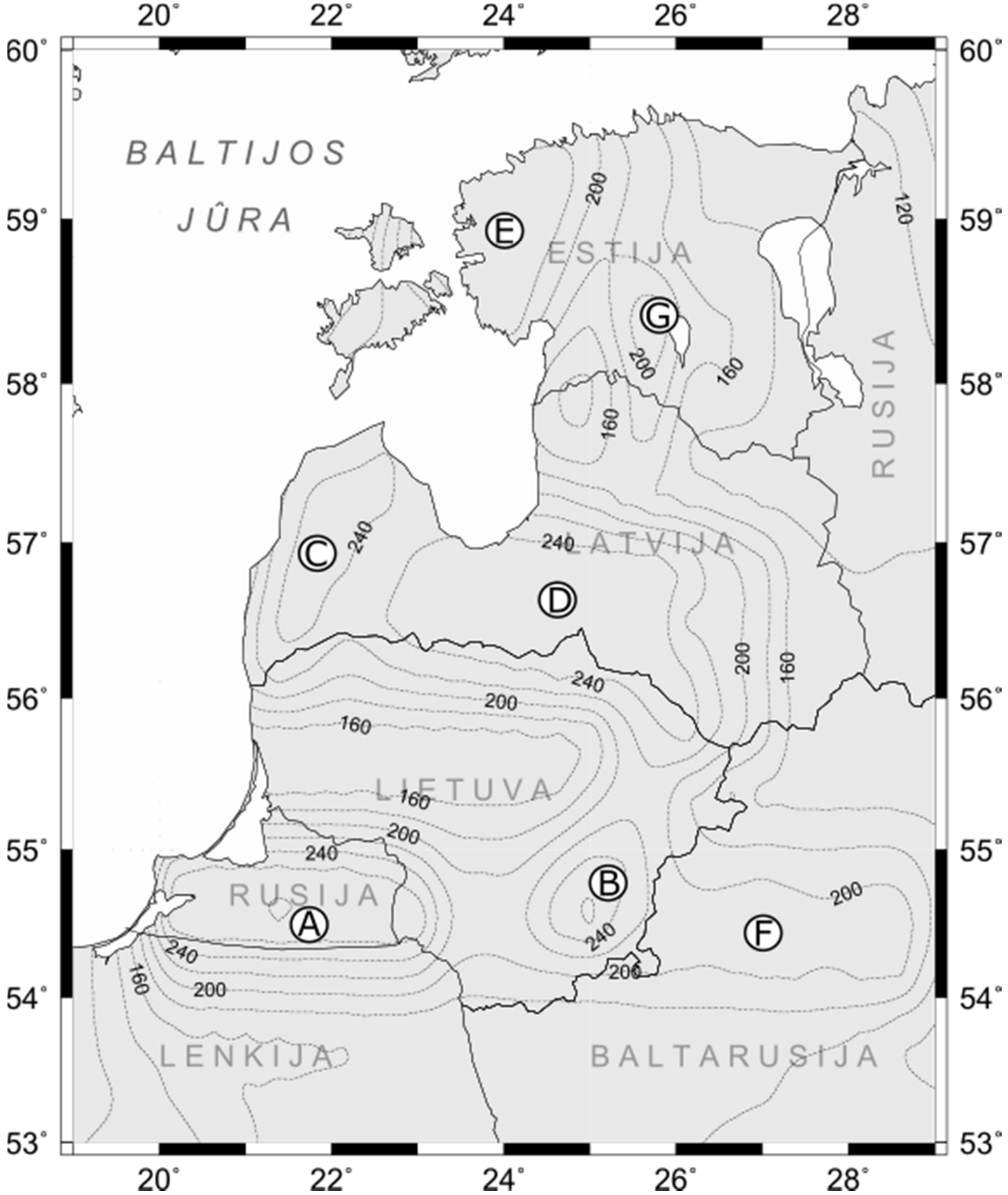

Fig. 3.5.7. Map of seismic hazard in terms of PGA (cm/s^2) of EBR when local seismicity of EBR and Vrancea SZ are considered. Contour lines correspond to the PGA values (cm/s^2), which can be exceeded with 10^{-5} of probability within one year (return period 100 000 years).

Spectra of ground motions

Ground motion attenuation function by Ambraseys et al., (2005) was used to calculate ground acceleration spectra for selected sites. For such calculations, only one seismotectonic model A was used out of four possible hypothesis in this model. The spectra were obtained using the “Full time” seismic catalogue and parameter b=0.8. The spectra were calculated for three different cases: when only EBR SZ’s were considered, when only the Vrancea SZ was considered, and when both sources were considered. To calculate spectral acceleration values the same exceedance probabilities as for PGA were chosen: 10^{-5} in one year (return period of 100 000 years); 10^{-4} in one year (return period of 1 000 years); 10^{-3} in one year (return period of 1000 years) and 10^{-2} in one year (return period of 100 years). Spectra were composed based on 13 different periods of ground motion: 0.05, 0.075, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, 2.0 and 2.5 s for the decommissioned Ignalina NPP site (55.60° N and 26.56° E).

Ground motion acceleration spectra with 5% damping with various exceedance probabilities are showed in figures 3.5.8, 3.5.9, 3.5.10, and 3.5.11. The obtained spectra confirm earlier conclusion that the seismic hazard of the Ignalina NPP is mostly influenced by the Vrancea SZ while the local SZ’s influence is low for short return period (100 years) (Fig. 3.5.8). When return period is 1 000 years, the seismic hazard of the Ignalina NPP is nearly equally influenced by the Vrancea SZ and EBR SZ’s, even though the former remains larger (Fig. 3.5.9). When return period of 10 000 years the influence of EBR SZ is more significant (Fig. 3.5.10). When the return period is 100 000 years, the seismic hazard of the Ignalina NPP is mainly influenced by the local EBR SZ’s, while influence by the Vrancea SZ is insignificant (Fig. 3.5.11). Also, analysing ground acceleration spectra (Figs. 3.5.8, 3.5.9, 3.5.10 and 3.5.11) it may be noticed that the spectral part, which is influenced by the Vrancea SZ, has a local maximum at 0.4 s (2.5 Hz). It also has a “plateau” from 0.2 to 0.75 s (from 5 to 1.33 Hz). Spectral part that is influenced by EBR SZ’s has well defined maximum near 0.2 s (5 Hz). These different spectra in the local and the Vrancea SZ’s can be explained in two ways. The peak in EBR spectra is determined by the largest possible magnitudes (M = 5.7) in SZ A1 (Table 3.2.1). The spectral part of the Vrancea SZ has an offset toward longer periods because there much stronger earthquakes occur there the strongest can be up to M = 8.0 (Table 3.2.1). This also because the Vrancea is situated far away from EBR (~1300 km) and wave energy with higher frequency is dispersed faster in short distances from the source than the low frequency seismic energy.

Ground motion acceleration spectra with 5% damping were also analysed for other potential NPP's in the region, i.e. in Belarus (54.76° N and 26.09° E) and in Kaliningrad (54.94° N and 22.16° E). These spectra are shown in figure 3.5.12. As one can see the ground acceleration spectra are similar for all NPP sites. This similarity is explained by the fact that the seismic hazard for the three areas is influenced by the same SZ A1 (Fig. 3.1.8) and due to similar distances to the Vrancea SZ.

Long-termed observations of buildings reaction to earthquakes (as well as theoretical calculations) provide an empirical rule implying fundamental period of building is proportional to height of the building divided by ten (e.g. Arnold, 2006). Thus, fundamental period of one story building is ~0.1 s, five stories - ~0.5 s, ten stories - ~1 s etc. Therefore, the Vrancea earthquakes will influence mainly 2-8 stories buildings, while local earthquakes will influence 1-2 stories buildings. Destructive ground acceleration could be expected once in 10 000 years or less frequently (Figs. 3.5.10 and 3.5.11). Therefore, considering whole shape of the acceleration spectra one can assume that buildings having 1 to 9 stories would be affected mostly.

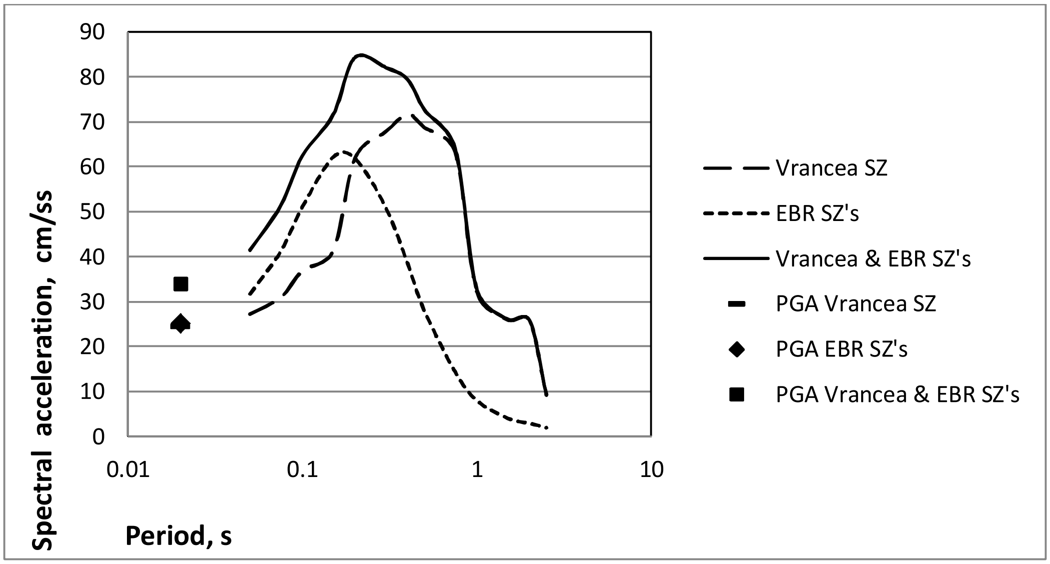

Fig. 3.5.8. Ground motion acceleration spectra with 5% damping and the PGA values at the Ignalina NPP site (55.60°N and 26.56°E) which can be exceeded with 10^{-2} probability within one year (return period 100 years).

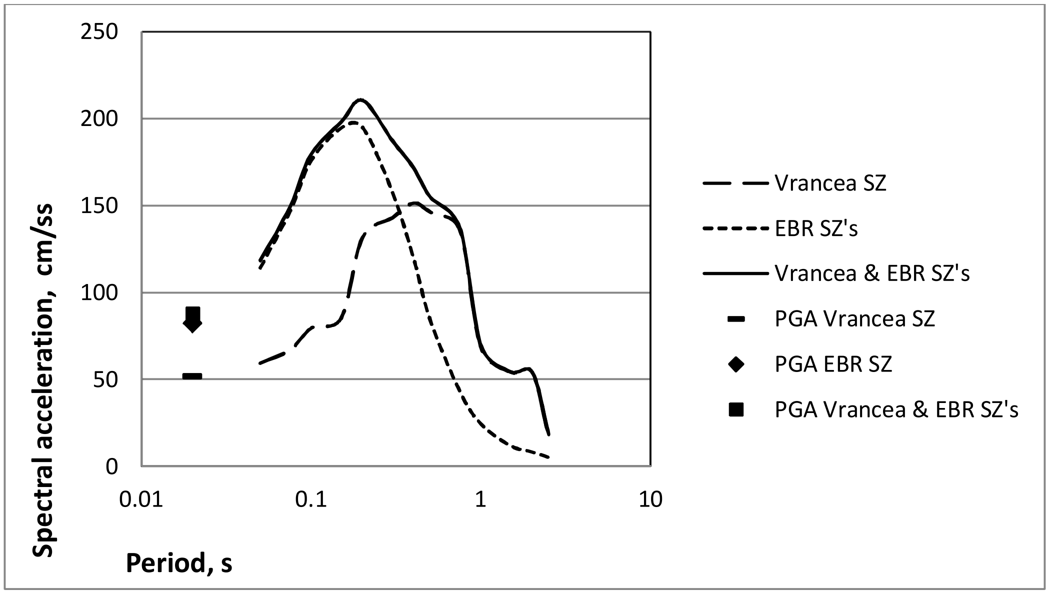

Fig. 3.5.9. Ground motion acceleration spectra with 5% damping and the PGA values at the Ignalina NPP site (55.60°N and 26.56°E) which can be exceeded with 10^{-3} probability within one year (return period 1 000 years).

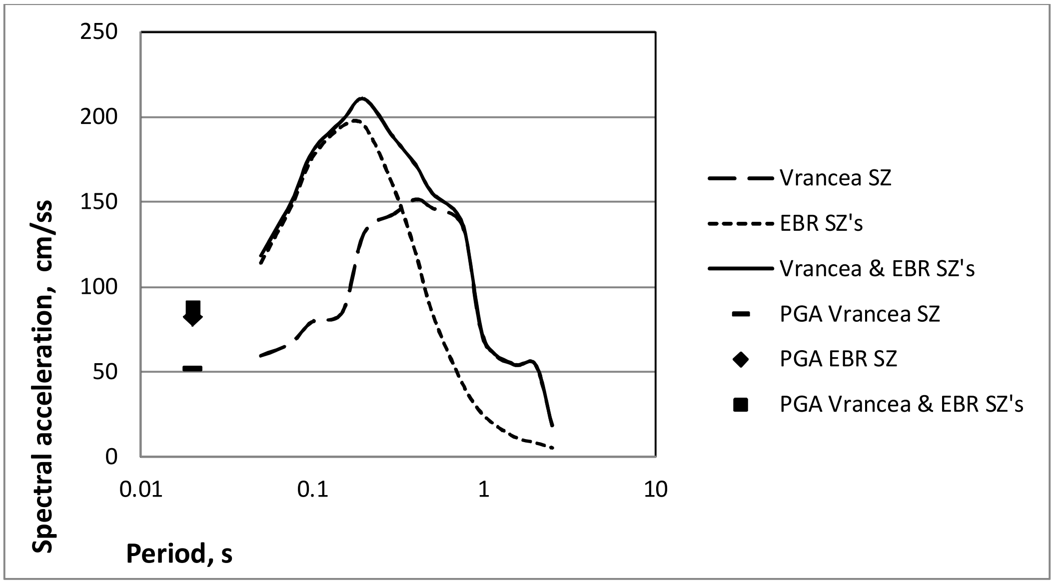

Fig. 3.5.10. Ground motion acceleration spectra with 5% damping and the PGA values at the Ignalina NPP site (55.60°N and 26.56°E) which can be exceeded with 10^{-4} probability within one year (return period 10 000 years).

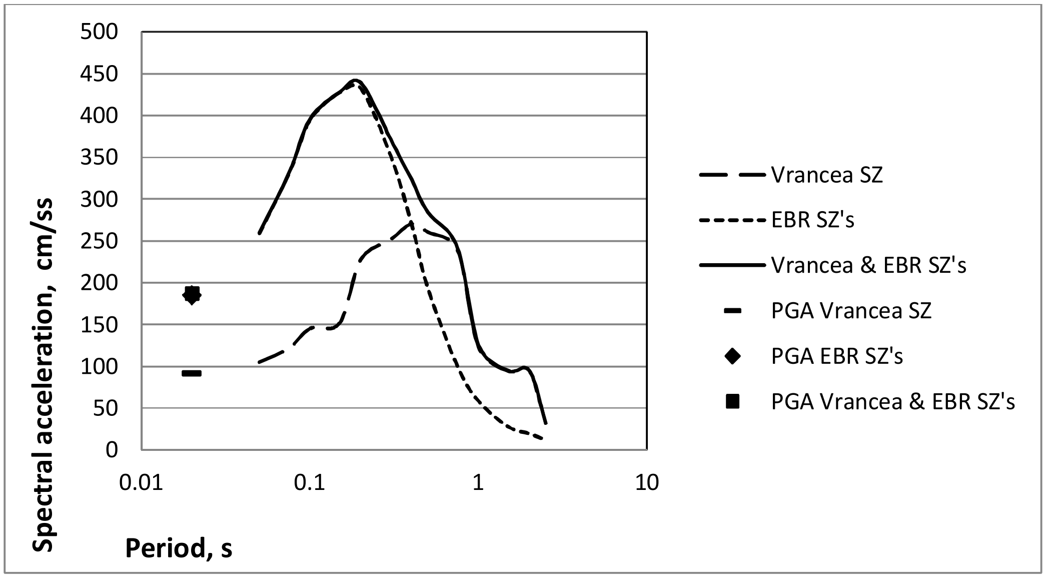

Fig. 3.5.11. Ground motion acceleration spectra with 5% damping and the PGA values at the Ignalina NPP site (55.60°N and 26.56°E) which can be exceeded with 10^{-5} probability within one year (return period 100 000 years).

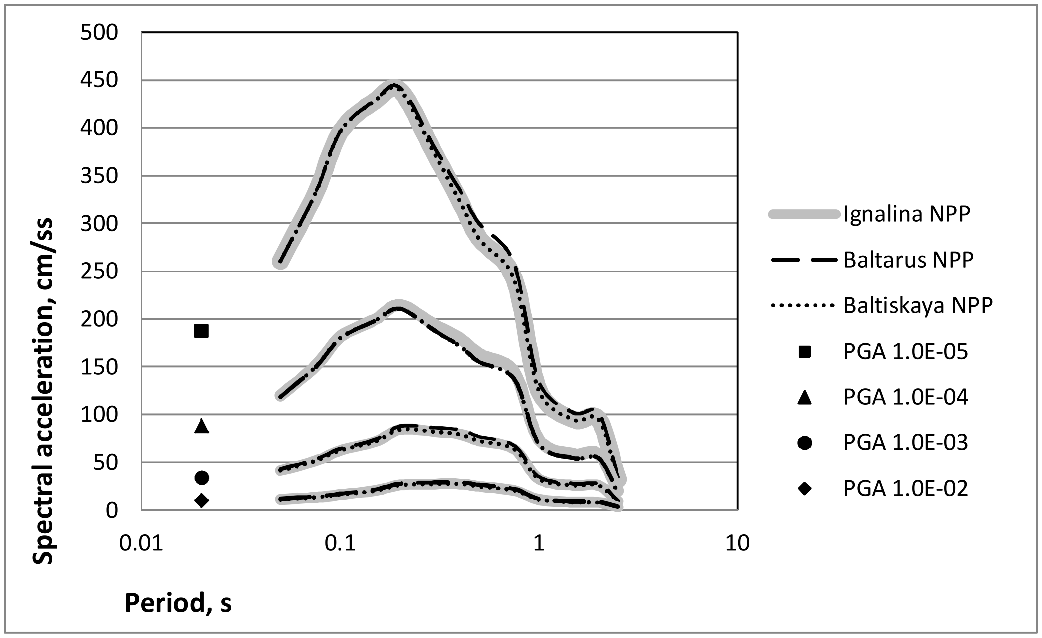

Fig. 3.5.12. Ground motion acceleration spectra with 5% damping and the PGA values at the Ignalina NPP site (55.60°N and 26.56°E), the Belarus NPP site (54.76°N and 26.09°E) and the "Baltiskaya" NPP site (Kaliningrad enclave; 54.94°N and 22.16°E) which can be exceeded with 10^{-5} probability (return period 100 000) – upper curves; 10^{-4} probability (return period 10 000) – curves below the upper ones, 10^{-3} probability (return period 1 000) – second curves below the upper ones and 10^{-2} probability (return period 100) – the lowest curves.

CONCLUSIONS

1. Seismic hazard estimation of the East Baltic Region is mainly affected by the ground motion attenuation relationships and the manner of seismotectonic zonation, while the influence of the length of the seismic catalogue and parameter b are less critical.

2. It was found that the average value of PGA (Peak Ground Acceleration) is equal to 23.1 ± 2.1 cm/s^2 for the return period of 475 years in the East Baltic region (EBR). The Vrancea seismogenic zone had the major influence comparing with the local EBR seismicity for the return period of 475 years. The PGA values vary from ~140 to ~250 cm/s^2 for return period of 100 000 years and the local seismicity had major influence for seismic hazard of EBR.

3. Analysis of ground motion acceleration spectra revealed that Vrancea seismogenic zone (SZ) had stronger influence for the period domain from 0.25 to 0.75 s (4-1.33 Hz), while local SZ's of the Eastern Baltic region are responsible for the peak at 0.2 s (5 Hz).

4. Probabilistic seismic hazard assessment (PSHA) can be employed effectively and reliably in seismic hazard assessment of the law seismicity platform regions. The reliability of seismic hazard assessment can be evaluated using alternative models which are organized with the logic tree methodology.

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PLATFORMINIŲ MAŽO SEISMINIO AKTYVUMO SRIČIŲ SEISMINIO PAVOJAUS VERTINIMAS BALTIJOS REGIONO PAVYZDŽIU

SANTRAUKA

Rytų Baltijos regionas (RBR) pasižymi labai mažu seisminiu aktyvumu, tačiau per visą rašytinę šio regiono istorijos periodą (~700 metų) čia buvo užregistruota virš 40

juntamų ar net vidutinio stiprumo žemės drebėjimų. Galimų drebėjimų pavojingumas ypač išryškėjo po 1976 m. Osmusarės saloje Estijoje įvykusio 4,7 magnitudės ($M = 4{,}7$) žemės drebėjimo ir 2004 m. Kaliningrado srityje (Rusija) įvykusių dviejų žemės drebėjimų, kurių momento magnitudės įvertintos $M_W = 5{,}0$ ir $M_W = 5{,}2$. Taip pat RBR 3-4 kartus per šimtmetį pasiekia gana tolimos, bet seismiškai aktyvios Vrančos (Rumunija) seisminės zonos galingų žemės drebėjimų atgarsiai, kurie šiame regione sukelia iki IV-V intensyvumo (EMS-98 skalėje) balų grunto virpesius. Todėl, atsižvelgiant į gana išplėtotą pramonę šiame regione, net ir vidutinio stiprumo žemės drebėjimai gali sukelti nemažus pavojus.

Iki šiol RBR buvo atlikta keltas seisminio pavojingumo tyrimų, tačiau jie rėmėsi, dabar nešiuolaikiniu laikomu, deterministiniu seisminio pavojingumo vertimo (DSPV) metodu arba šiuolaikinis tikimybinis seisminio pavojingumo vertinimo (TSPV) metodas buvo taikomas tik atskiroms regiono dalims. Šiame disertaciniame darbe buvo tiriamas viso RBR seisminis pavojingumas atsižvelgiant tiek į vietines seismines zonas (SZ) tiek ir į gana tolimą (~1300 km) Vrančos SZ. Seisminio pavojingumo vertinimui buvo naudojamas TSPV metodas. TSPV metodas susideda iš keturių pagrindinių etapų: (1) SZ išskyrimas, (2) SZ parametrų radimas, (3) seisminių virpesių slopimo funkcijos ar funkcijų radimas ar adaptavimas, (4) PGA (angl. *Peak Ground Acceleration*) – maksimalių horizontalių grunto virpesių pagreičių skaičiavimas ir seisminio pavojingumo žemėlapių sudarymas. Pirmas etapas dar skirstomas į mažesnius žingsnius: (a) žemės drebėjimų katalogo sudarymą, (b) seisminio katalogo magnitudžių suvienodinimą, (c) pirminių (angl. *foreshocks*) ir pakartotinių (angl. *aftershocks*) drebėjimų identifikavimą ir jų eliminavimą, (d) seisminio katalogo periodo, kur jis gali būti laikomas pilnu radimą, (e) tektoninių ir neotektoninių žemėlapių analizę ir (f) SZ išskyrimą.

Sudarius ir išanalizavus RBR žemės drebėjimų katalogą buvo nustatyta, kad šis katalogas gali būti laikomas pilnu nuo 1844 iki 2009 m. magnitudėms didesnėms nei 3,5. Tačiau buvo pastebėta, kad tik vienas žemės drebėjimas buvo užregistruotas laiko periodu nuo 1912 iki 1972 m. Čia buvo susidurta su pirmu neapibrėžtumu – ar seisminiai įvykiai nebuvo užfiksuoti dėl istorinių-socialinių perturbacijų, o būtent – I ir II pasaulinių karų, 1917 m. revoliucijos Rusijoje ir stalinizmo epochos Sovietų sąjungoje, ar dėl objektyviai RBR nebuvusių žemės drebėjimų. Todėl, siekiant išnagrinėti abi šias galimas hipotezes, buvo nuspręsta naudoti „pilną“ katalogą nuo 1844 iki 2009 m. ir „dirbtinai sutrumpintą“ pilno katalogo versiją. Du laiko periodai buvo dirbtinai pašalinti iš pilno katalogo: pirmasis periodas apėmė 1914–1920 m., kuris siejamas su I Pasauliniu karu. Antras laikotarpis apėmė 1940–1958 m. ir buvo siejamas su Baltijos šalių okupacija, II Pasauliniu karu iki Stalino valdymo laikmečio pabaigos. „Dirbtinai sutrumpintas“ katalogas yra 24 metais trumpesnis, lyginant su „pilnu“ katalogu, t.y., katalogas apėmė laikotarpį nuo 1868 m. iki 2009 metų, o seisminiai įvykiai buvo panaudoti nuo 1844 iki 2009 m. Šis „sutrumpintas“ katalogas kažkiek padidino seismingumo lygį vėlesniuose seisminio pavojaus skaičiavimuose, kita vertus, toks Jungtinio RBR katalogo sutrumpinimas galėjo įskaičiuoti ir tuos praeities žemės drebėjimus, kurie galimai nebuvo užregistruoti vykstant istoriniams-socialiniams neramumams.

Išanalizavus keletą RBR seismotektoninių žemėlapių, buvo padaryta išvada, kad kol kas neegzistuoja vieno visuotinai pripažinto RBR tektoninio žemėlapio. Čia buvo susidurta su antru neapibrėžtumu sietinu su tektoniniais žemėlapiais. Todėl buvo nuspręsta naudoti tris skirtingus RBR tektoninius žemėlapius sudarytus sekančių autorių: Aronova (2007; 3.1.4 pav.), Grigelis (1981; 3.1.5 pav.), Aizberg et al. (1999; 3.1.6 pav.). Naudojantis šiais tektoniniais modeliais ir jungtiniu RBR seisminiu katalogu buvo sudaryti trys alternatyvūs seismotektoniai modeliai (3.1.4, 3.1.5 ir 3.1.6 pav.).

Trečias neapibrėžtumas buvo susijęs su b parametro verte. b parametro vertę įvertinus pagal jungtinio RBR seisminį katalogą, buvo nustatyta, kad b buvo lygus 0,66 su standartiniu nuokrypiu 0,12. Kita vertus analizuojant atnaujintą Rytų Europos platformos seisminių įvykių katalogą nuo seniausių laikų iki 2005 m. buvo nustatyta, kad $b = 0{,}8 \pm 0{,}08$ (Sharov et al., 2007). Todėl buvo nuspęsta naudoti abi b parametro vertes, atitinkamai konstruojant skirtingus seismotektoninius modelius.

Vienas pagrindinių konkretaus regiono seisminio pavojingumo modeliavimo etapų – tiriamo regiono specifiką atitinkančių seisminių bangų slopimo funkcijų parinkimas. Literatūroje pateikta gana daug įvairių teorinių ir empirinių grunto virpesių slopimo funkcijų. Čia iškilo ketvirtas neapibrėžtumas kurias seisminių slopimo funkcijas naudoti RBR seisminio pavojingumo vertinimui. Atsižvelgiant į Baltijos regiono specifiką buvo pasirinktos trys alternatyvios funkcijos: Ambraseys et al. (2005), Atkinson and Boore (2006) ir Campbell and Bozorgnia (2003, b, c, 2004). Taip pat buvo parodyta, kad tolimos

Vrančos SZ seisminių virpesių slopimo funkcija geriausiai atitinka Ambraseys et al. (2005) publikacijoje pateiktoje grunto virpesių slopimo funkcijai.

Esant keturiems neapibrėžtumams buvo sudarytos 36 seismotektoninių modelių alternatyvos, kai buvo vertintos tik vietinės RBR SZ ir 36 seismotektoninių modelių alternatyvos, kai buvo vertintos tiek vietinės RBR SZ tiek ir Vrančos SZ. Kad susisteminti visas alternatyvas buvo panaudota loginio medžio metodika (3.4.1 pav.), kuri leido nuosekliai analizuoti kiekvieną galimą seismotektoninio modelio alternatyvą ir aiškiau suprasti gautus rezultatus.

Seisminio pavojingumo modeliavimui buvo pasirinkti sekantys tikimybės viršijimo lygmenys: 10^{-2} per metus (pasikatojamumo periodas 100 m.); 10% viršijimo tikimybė per 50 m. (pasikartojamumo periodas 475 m.); 10^{-3} per metus (pasikartojamumo periodas 1000 m.); 10^{-4} per metus (pasikatojamumo periodas 10 000 m.) ir 10^{-5} per metus (pasikartojamumo periodas 100 000 m.). 475 m. pasikartojamumo periodas yra standartinis pasikartojamumo periodas naudojamas civilinėse statybose, tuo tarpu kiti tikimybės viršijimo lygmenys yra siejami su atominių elektrinių (AE) projektavimu ir saugiu jų eksploatavimu.

Apskaičiavus visas galimas seismotektoninių modelių alternatyvas buvo nustatyta, kad didžiausią įtaką PGA gardelėms (paviršiams) daro skirtingos seisminių virpesių slopimo funkcijos ir seismotektoninio zonavimo būdas, o „pilno“ ar „dirbtinai sutrumpinto“ seisminio katalogo laikas bei b parametro vertės turi mažesnę įtaką (3.5.1 ir 3.5.2 lentelės).

Analizuojant seisminio skaičiavimo rezultatus (3.5.1 ir 3.5.2 lentelės) buvo nustatyta, kad Vrančos SZ įtakos įskaičiavimas ženkliai (~64%) įtakoja RBR bendrą seisminį pavojingumą 100 m. pasikartojamo periodui, tačiau ilgėjant pasikartojamumo periodams Vrančos SZ įtaka bendram RBR seisminiam pavojingumui mažėja: ~58% – 475 m. pasikartojamumui, ~55% – 1 000 m. pasikartojamumui, ~48% – 10 000 m. pasikartojamumui ir ~44% – 100 000 m. pasikartojamumui. Pastarąjį teiginį patvirtina ir iliustruoja 3.5.1 pav. Šis pav. taip pat parodo, kad RBR seisminį pavojingumą stipriau įtakoja Vrančos SZ kai pasikartojamumo periodai kinta nuo 100 iki ~5 000 m. Pasikartojamumo periodui esant ~5 000 m. Vrančos SZ įtaka susilygina su vietinių RBR

SZ-nų įtaka ir toliau pasikartojamumo periodui didėjant RBR seisminį pavojingumą daugiau nulemia vietinės RBR SZ-nos, o Vrančos SZ įtaka mažėja.

Vienas iš pagrindinių šio darbo tikslų buvo PGA RBR sudarymas. Sudarant PGA žemėlapius buvo naudotos visos 36 loginio medžio šakos arba alternatyvios hipotezės. PGA žemėlapis 475 m. pasikartojamumui, kai buvo vertinta tik Vrančos SZ parodė, kad ši SZ sukuria gana tolygų seisminį pavojingumą visame regione (3.5.2 pav.), kris pietinėje RBR dalyje yra ~25 cm/s^2, tolygiai mažėja einant į šiaurę ir yra ~13 cm/s^2 ties šiaurine Estijos pakrante. PGA žemėlapis kai buvo vertintos tik vietinės RBR SZ (3.5.3 pav.) parodė, kad seisminis pavojingusmo maksimumai buvo ~30 cm/ s^2, PGA verčių vidurkis buvo 12,9 ± 3,8 cm/s^2. PGA žemėlapis kai buvo vertintos tiek vietinės RBR SZ tiek ir Vrančos SZ (3.5.4 pav.) parodė, kad seisminio pavojingumo maksimumai buvo ~35 cm/ s^2, PGA verčių vidurkis buvo 23,1 ± 2,1 cm/s^2. Kitų pasikartojamumo periodų RBR PGA žemėlapiai pateikti 3.5.5, 3.5.6 ir 3.5.7 pav. Buvo pastebėta natūrali tendencija, kad, didėjant pasikartojamumo periodams, seisminis pavojingumas didėja, o PGA verčių maksimumai yra sietini su didesnio aktyvumo SZ arba tų SZ superpozicija.

Panaudojant vieną grunto virpesių slopimo funkcijų (Ambraseys et al., 2005) ir viena seismotektoninį modelį (A) Ignalinos AE aikštelei buvo sudaryti grunto dalelių virpesių pagreičių spektrai, esant 5% slopinimui, skirtingiems pasikartojamumo periodams 3.5.8, 3.5.9, 3.5.10 ir 3.5.11 pav. Išanalizavus apskaičiuotus spektrus buvo patvirtinta ankščiau padaryta išvada, kad esant mažesniems pasikartojamumo periodams (100 m.) Ignalinos AE aikštelės seisminį pavojingumą stipriausiai įtakoja Vrančos SZ, o vietinių RBR SZ įtaka yra nedidelė (3.5.8 pav.). Kai pasikartojamumo periodas yra 1 000 m. Ignalinos AE aikštelės seiminį pavojingumą panašiai įtakoja tiek Vrančos SZ tiek ir RBR SZ, nors Vrančos SZ įtaka išlieka didesnė (3.5.9 pav.). Kai pasikartojamumo periodas yra 10 000 m. seisminį pavojingumą labiau įtakoja vietinės RBR SZ (3.5.10 pav.). Kai pasikartojamumo periodas yra 100 000 m. aikštelės seisminį pavojingumą pagrindinai lemia vietinės RBR SZ, o Vrančos SZ įtaka yra nereikšminga (3.5.11 pav.). Taip pat analizuojant grunto dalelių pagreičių spektrus (3.5.8, 3.5.9, 3.5.10 ir 3.5.11 pav.) galima pastebėti, kad Vrančos SZ įtakota spektro dalis turi vietinį maksimumą ties 0,4 s (2,5 Hz). Taip pat Vrančos SZ įtakota spektro dalis taip pat turi tam tikrą „plato“ nuo 0,2 iki 0,75 s (nuo 5,0 iki 1,33 Hz). Vietinių RBR SZ įtakota spektro dalis turi aiškiai išreikštą maksimumą ties 0,2 s (5,0 Hz). Skirtingas vietinių ir Vrančos SZ pasireiškimas skirtinguose dažniuose gali būti aiškinamas dviem aspektais. Vietinių RBR SZ pikas spektre yra apspręstas didžiausių galimų magnitudžių (M = 5,7) SZ A1 (3.2.1 lentelė). Vrančos SZ įtakota spektro dalis yra pasislinkusi į ilgesnių periodų pusę dėl to, kad Vrančos SZ vyksta kur kas galingesni žemės drebėjimai, o pats galingiausias drebėjimas gali siekti (M = 8,0) (3.2.1 lentelė). Be to, spektro dalis yra pasislinkusi į ilgesnių periodų pusę, nes Vrančos SZ yra gana toli nutolusi (~1000 km) ir aukštesnio dažnio seisminių bangų energija yra išsklaidoma greičiau negu žemesnio dažnio (arba ilgesnio periodo) seisminių bangų energija joms nueinant didesnius atstumus.

Iš daugiamečių stebėjimų kaip pastatų konstrukcijos sąveikauja su žemės drebėjimų virpesiais bei pastatų konstrukcijų modeliavimo yra žinoma empirinė taisyklė – tam tikro pastato savitasis (rezonansinis) virpesių periodas yra lygus jo aukštingumui padalintam iš 10 (Arnold, 2006). Todėl vieno aukšto pastato savitasis virpesių periodas yra ~0,1 s, penkių aukštų – ~0,5 s, dešimties aukštų – ~1 s ir t.t. Atsižvelgiant į RBR pietinės dalies grunto dalelių pagreičių spektrus, galima teigti, kad Vrančos žemės drebėjimai intensyviau veiks pastatus turinčius nuo 2 iki 8 aukštų, o vietiniai žemės drebėjimai intensyviau turėtų paveikti 1 - 2 aukštų pastatus. Griaunamojo pobūdžio grunto pagreičių intensyvumų galima tikėtis tik kartą per 10 000 m. ar rečiau (3.5.10 ir 3.5.11 pav.), tai atsižvelgus į bendrą grunto dalelių spektro formą galima manyti, kad daugiausia nukentėtų pastatai turintys nuo 1 iki ~9 aukštų.

Disertacinį darbą (140 psl.) sudaro sekantys skyriai: įvadas, problematika ir ankstesnių tyrimų apžvalga, tyrimų metodai, tyrimų rezultatai, išvados ir literatūros sąrašas (114 pozicijų). Jis iliustruotas 37 paveikslais ir 7 lentelėmis.

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ATTENDED COURSES

1. Regional Training Course on NDC Capacity Building: Access and Analysis of IMS Data and IDC Products under EU Joint Action V. CTBTO Preparatory Commission. Bucharest, Romania. From 23.06.2014 to 27.06.2014.
2. SeisComP3 training course. Gempa GmbH, Potsdam, Germany. From 07.05.2012 to 10.05.2012.

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