Assessment of the seismic hazard in Latvia. Version of 2007 year

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Abstract. **Seismic hazard in Latvia is appraised on the basis of PSHA method. A seismotectonic analysis allowed discovering 8 sources of earthquakes in Latvia and the same number abroad, near its borders. The assessment of seismic hazard in Latvia shows that PGA with the probability 10%, during 50 years will exceed 10 - 13 cm/s^2 in Sigulda, Riga, Olaine, Aizkraukle, Cesis. Estimations of PGA correspond to Pre-Quaternary deposits of A type. The common seismic hazard includes the estimation of PGA for Pre-Quaternary deposits and response spectrum from the Quaternary deposits.**

Keywords: **earthquake sources, seismic hazard, seismotectonics, probabilistic, Eurocode 8.**

INTRODUCTION

Latvian seismic zoning for the first time was carried out in 1998 and 17 seismic source zones were selected [1]. Seismic sources were subdivided into three categories: 1) sure seismic sources; 2) supposed seismic source and 3) seismotectonic sources. The selected types of seismic sources differ from each other depending on how far, the earthquakes are located from the tectonic faults, which have different seismotectonic activity. The results of the General seismic zoning of Latvia of 1998 year (GSZL-98) on the whole conformed to requirements of the normative base, which existed in Latvia before joining the European Union.

Since Latvia became member of the European Union, there was a necessity to bring a normative base to conformity with the requirements of the European Committee for Standardization *of CEN-CENELEC*. According to these requirements, in the member countries of the European Union by 2010 the European Standard EN 1998-1:2004 „*Eurocode 8: Design of structures for earthquake resistance: General rules – Seismic actions and rules for buildings*” [2] should have been adopted as a national standard; besides, it was permitted to prepare own National Annex. Specific parameters, which might differ from the parameters used in EN 1998-1:2004, could be specified in the National Annex.

The principal differences of GSZL-98 version from recommendations of EN 1998-1:2004 are the following: 1) the level of seismic shakings is appraised to 12 intensity degrees of scale of MSK-64 on the GSZL-98 map; 2) the map of GSZL-98 was prepared on the basis of deterministic *DSHA* (*Deterministic Seismic Hazard Analysis*) approach, without the use of probabilistic methods of estimation of seismic hazard of *PSHA* (*Probabilistic Seismic Hazard Analysis*). Probabilistic characteristics were not specially estimated in 1998. Seismic intensity was taken for recurrence period of 500 years. It was marked that the card of GSZL-98 could be accepted only as a temporal normative document.

In 2005 the Latvian Technical Committee for Standardizations of STK 4 *Būvmateriāli* considered the European Standard of EN 1998-1:2004 and confirmed it as a National Standard, without the change of table of contents (EN LVS 1998-1:2005 „*8.Eirokodekss. Seismiski izturīgu konstrukciju projektēšana. 1.daļa: Vispārīgie noteikumi. Seismiskās iedarbes un noteikumi ēkām*”).

The project of the National Annex and also the project of the corresponding suggestions, was prepared in 2007 with the purpose to introduce amendments to the building codes LBN 005 - 99 „*Inženierizpētes noteikumi būvniecībā*” following the initiative and support of Ministry of Economy of Latvia and in accordance with the recommendations of EN LVS 1998-1:2005.

The primary objective of the research which was carried out within the framework of this work, is the estimation of base seismic risk (for the Pre-Quaternary rock and rock-like geological deposits) on the territory of Latvia and putting forth proposals for taking into account the seismic reaction of different unconsolidated sedimentary deposits, equated as a rule with the Quaternary deposits.

METHODOLOGY

It is necessary to distinguish two types of seismic risk. *Seismic hazard* is a natural phenomenon such as ground shaking that is generated by an earthquake, whereas *seismic risk* is the probability that humans will incur loss or damage to their built environment if they are exposed to a seismic hazard. In other words, *seismic risk* is an interaction between *seismic hazard* and *vulnerability*. The *seismic hazard* behaves directly to the sources of earthquakes and is based on such descriptions as site of seismic source, frequency of origin of perceptible earthquakes and their magnitude. The subject of this research is the *seismic hazard*.

The *seismic hazard* is determined by three factors: 1) spatio-temporal distributing of regional seismicity; 2) attenuation of seismic waves with increase of distance from the earthquake source; 3) the influence of local geological terms on distortion of seismic signal.

The *seismic hazard* was described by using mainly probabilistic (*Probabilistic Analysis Hazard Seismic - PSHA*) method, because seismic influence on the particular ground site is conditioned on the integrated action from several seismic sources. *PSHA* method is more acceptable for the conditions of low seismicity [3].

The principle model, which was used for estimation of *seismic hazard*, was developed by *Cornell* [4]. The occurrence of earthquakes on a fault is assumed to be a Poisson process. The Poisson model is widely used as a reasonable assumption in regions where data are sufficient to provide only an estimate of average recurrence rate.

The probability that a ground motion parameter *Z* exceeds a specified value *z* in a time period *t* is given by:

$$p(Z > z) = 1 - e^{-v(z) \cdot t} \tag{1}$$

where $v(z)$ is the annual mean number (or rate) of events in which *Z* exceeds *z*.

The annual mean number of events is obtained by summing the contributions from all sources, that is:

$$v(z) = \sum_{n} v_n(z) \tag{2}$$

where $v_n(z)$ is the annual mean number (or rate) of events on source n for which *Z* exceeds *z* at the site.

The parameter $v_n(z)$ is given by expression:

$$v_n(z) = \sum_{i}\sum_{j} \beta_n(m_i) \cdot p(R = r_j \mid m_i) \cdot p(Z > z \mid m_i r_j) \tag{3}$$

where $\beta_n(m_i)$ is the annual mean rate of recurrence of earthquakes of magnitude increment m_i on source *n*; $p = (R = r_j \mid m_i)$ is probability that given the occurrence of an earthquake of magnitude m_i on source *n*, r_j is the closest distance increment from the rupture surface to the site; $p(Z > z \mid m_i r_j)$ is probability that given an earthquake of magnitude m_i at a distance of r_j, the ground motion exceeds the specified level *z*.

Results

The estimation of seismic risk consisted of several stages: 1) drafting of catalogue of earthquakes and standardization of magnitude of earthquakes; 2) creation of seismotectonic map and selection of seismic sources; 3) magnitude - frequency relationship and estimation of parameters of seismic sources; 4) characteristics of attenuation of seismic waves described by the attenuation function; 5) calculation of probabilistic seismic effects.

The catalogue of earthquakes includes 123 seismic events, which were identified as earthquakes. They happened from 1302 to 2007 year on the territory of the Baltic region with geographical co-ordinates of latitude from 54.0°N up to 60.0°N and of longitude from 18.0°E up to 30.0°E. A considerably larger region than the area of Latvia was taken into account, because it allowed a more reliable estimation of the parameters of seismic activity (*b-value*), necessary for the assessment of *seismic hazard*.

The information presented in the catalogue, is not homogeneous. Seismic activity of earthquakes is unevenly distributed along the time axis. The historical earthquakes are based on the information, which was obtained from various archived sources (for example church manuscripts), reports of press and also by questioning of eyewitnesses of seismic shocks. By 1757 there was very limited information about the earthquakes occurring in the Baltic region (10 earthquakes). For historical period, an increase of seismic activity is registered from 1821 up to 1908 [5, 6, 7]. Instrumental information about the earthquakes in the Baltic region appeared only after the 60-s of the XX century [8], after installation of the short period stations.

Seismic influence of the historical and modern earthquakes was estimated through different macroseismic scales (scales of seismic intensity). Thus, there was the necessity of magnitude standardization. Different types of shakings intensity and magnitudes of the earthquakes (mb, Mms, Ml, MI, MC, and MS) were counted to a single universal moment magnitude. Moment magnitude is expressed through a seismic moment [9] and is directly related to physical and mechanical characteristics in the earthquake source. It is expressed by the following dependence:

$$Mw = \frac{2}{3} \times \log Mo - 6.07 \tag{4}$$

Known and new correlations relationships between seismic intensity, different types of magnitude and moment magnitude were used.

Selection of seismic sources was conducted on the basis of seismotectonic analysis by taking into account distribution of epicentres of earthquakes, tectonic faults in a sedimentary cover and more deep faults of the Earth's crust, amplitudes of neotectonic motions, modern vertical motions, direction of action of tectonic forces, potential geophysical fields (gravitation, magnetic, geothermic), neotectonic structures, structure of blocks of crystalline basement, structure of sedimentary cover. The seismotectonic analysis allowed to discover connection of seismicity with the tectonic structure and other geological and geophysical characteristics that was reflected in the series of seismotectonic maps. One of them is shown on fig.1.

Earthquakes, active tectonic faults, boundaries of tectonic blocks of the Earth's crust and other signs [10] were used as the basic criteria for selection of seismic sources. In particular, the following data was used: seismological information (the catalogue of earthquakes), tectonic faults in the Caledonian structural complex of sedimentary cover [11], deep tectonic faults of crystalline basement [12] and lineaments from space sounding [13], data of neotectonic motions [14] and modern motions of the Earth's crust, isostatic anomalies and density of faults of crystalline basement [15,16].

The form of seismic sources is stipulated by the features of the calculation program *CRISIS99* [17], which required their simplification and schematizing, i.e. fragmentation of seismic sources as the simplest geometrical figures.

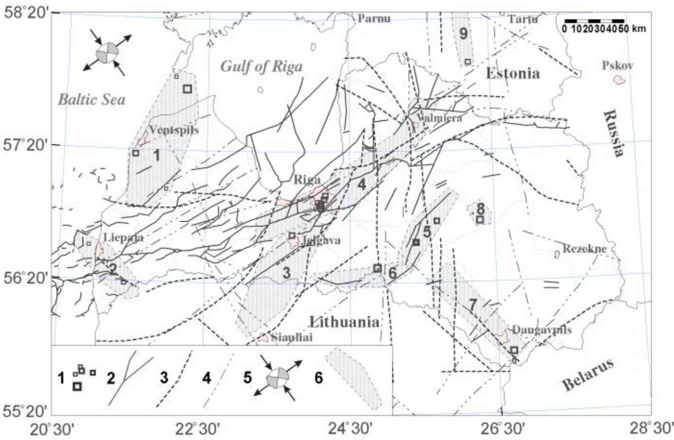

Fig.1. Seismotectonic map of Latvia on basis of the epicenters of earthquakes, faults in a sedimentary cover, deep faults of the Earth's crust and seismic source zones (earthquakes sources). Legend: 1 = epicenters of earthquakes; 2 = tectonic faults in the deposits of Caledonian structural complex of sedimentary cover [11]; 3 = deep tectonic faults of the Earth's crust (by of gravitation and magnetic data) not penetrable into an sedimentary cover; 4 = lineaments from space scanning [13]; 5 = ellipse of deformation with directions of axes of compression and tension; 6 = seismic source zones – earthquakes sources (numbers into source areas are a sequence number).

Eight internal seismic source zones (earthquakes sources) were selected on the territory of Latvia as well as 8 external earthquake sources on an adjoining territory, as a result of seismotectonic analysis. The amount of geological and geophysical information for the territory located outside Latvia was considerably less than for Latvia. Therefore, seismotectonic maps were made only for Latvia. However, the parameters of external seismic sources were appraised and taken into account in calculation of *seismic hazard* on the territory of Latvia.

The main parameters of earthquake sources are maximum magnitude, mean focal depth, seismic activity (number of earthquakes per time unit), and the period of earthquake recurrence. These and other entry parameters were used for calculation of *seismic hazard*.

Seismic activity (*b-value)* was estimated on the basis of the magnitude - frequency relationship.

$$\log N = a - b \times Mw \tag{5}$$

where, N is the number of earthquakes with magnitude Mw, a – the parameter, which determines an initial ordinate, b – the parameter (*b-value*), which determines the angle of slope of line to the horizontal axis, Mw - moment magnitude.

In most seismic source zones of Latvia and the Baltics, the number of earthquakes that happened is negligible. Therefore, two large regions were used for the estimation of parameters: 1) off-shore part and coast of the Baltic Sea and 2) continental part of the Baltic region. These regions are characterized by different parameters of the seismic conditions [18]. Seismicity of the offshore part and coast of the Baltic Sea is conditioned by the activity of neotectonic structures: Gdansk depression, East Gotland and Finnish grabens. The strongest sources for earthquakes in the Baltic region are located along the edges of these structures: Osmussaar in 1976 and Kaliningrad in 2004 [19]. The estimations of *b-value* of every analysed region were appropriated to proper earthquake source, located within the limits of one of the mentioned large regions. For the land part of the Baltic region (formula of 6a), as well as for the off-shore part and coast of the Baltic Sea (formula of 6b), the following magnitude - frequency relationship was obtained:

$$\log N = 2.16 - 0.33Mw \tag{6a}$$

$$\log N = 2.51 - 0.38Mw \tag{6b}$$

The important parameter of seismic sources is the focal depth of hearths of earthquakes. The analysis of distribution of the focal depths of earthquake sources showed that on the East European platform [20] about 44% of earthquakes sources are located at the depths from 4 to 6 km and from 8 to 10 km. However, about 24% earthquakes sources are located at the 0 to 4 km depth in the most overhead layer.

The estimation of the maximally possible magnitude of an earthquake for each particular earthquake source was difficult to perform, since statistics about earthquakes is substantially limited. Within the boundaries of some earthquake sources in Latvia (Bauska, Daugavpils, Jelgava - Kurshenay of sources) only one earthquake is located.

The estimation of maximally possible magnitude of earthquake on the basis of active length of tectonic fault also proved to be inexpedient, due to insufficient information about modern activity of tectonic faults. Maximum magnitude of earthquakes was appraised on the basic of maximally observed magnitude for every earthquake source or by the size of seismotectonic potential. The estimation of the size of seismotectonic potential is based on comparison of different types of the Earth's crust for the set of basic signs of an endogenous situation (parameters of heat flow, Earth's crust thickness, surface topography, isostatic anomalies and depth of the crystalline basement) [21]. If in the limits of even one cell of certain type of the earth's crust an earthquake happened with maximal magnitude, then this value was appropriated to all other cells of this type. For the Baltic region the specified values of seismotectonic potential were used [22].

Attenuation of the energy of seismic waves depends on many factors. Among them such factors as the hypocentral distances (the distance from the earthquake source to the particular point), mechanism of tectonic motion in the earthquake source, characteristics of local ground conditions can be mentioned.

Equation of attenuation of seismic energy for the territory of Europe and the Middle East [23] was used in our research for assessment of attenuation of seismic energy, depending on the mechanism in the earthquake source, type of magnitude, focal depth, and epicentral distance.

Expression allows estimating the *Peak ground acceleration* (PGA) for a 5% critical damping and for periods from 0.05 up to 2.5 sec. In the choice of constants of the expression [23] the mechanism of tectonic motion of strike type (normal fault) [24] was taken into account. The mechanisms of earthquake sources such as strike-slip faulting prevail (50% all earthquakes) in south Sweden [25]. The Kaliningrad earthquake of September 21, 2004 had a similar mechanism of the earthquake source [26].

Attenuation is appraised for hard soils, which are equivalent to the Pre-Quaternary deposits. The table of attenuation of seismic energy was got, foremost depending on the initial value of magnitude and distance from a source up to the point of influence.

b-values were changing from 0.33 for the land part up to 0.38 for the off-shore part. The time range of the earthquakes is equal to 705 years.

As a result of calculations a complete set of maps of *Peak ground acceleration* (PGA) of hard soil was obtained with the 10%, 5%, 1% and 0.5% probability of the possible exceeding of the calculated seismic intensity within 50 years. With the probability of 100% the indicated accelerations (PGA) of hard soil will be exceeded accordingly in 475, 975, 4975 and 9975 years.

The map of the expected PGA is shown on fig. 2 for a recurrences period of 475 years. It is tantamount to 10% probabilities of exceeding the values of PGA indicated on a map within 50 years. With a 10% probability the maximum PGA values can exceed 10 – 13 cm/s^2 in Riga, Cesis, Aizkraukle, Olaine and Sigulda and in their environs.

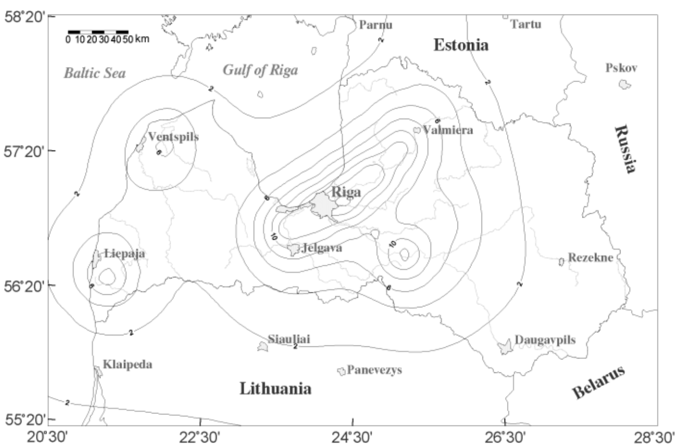

Fig.2. The map of the expected maximal accelerations of PGA with 10% probability of exceeding during 50 years (at a recurrences period of 475 years).

An indicated PGA on the map of zoning of seismic intensity belongs to the geological deposits of A type. Deposits of A type in accordance with LVS EN 1998-1:2005 are characterized as rock or deposits with shear waves velocity more than 800 m/s. These terms on the whole are characteristic for Pre-Quaternary deposits, which on the largest part of the territory of Latvia (about 94%) consist of sandstones, siltstones, clays, dolomite marls, dolomites and gypsums of the Upper and Middle Devon.

DISCUSSION

As a result of the general seismic zoning in 1998 17 seismic sources (earthquakes sources) were discovered on territory of Latvia [1]. In the updated version of the seismic districting of 2007, 8 earthquakes sources were identified on the territory of Latvia. The difference is explained by the use of another method. In 1998 for identification of earthquakes sources three gradations of seismic sources were used: sure sources (6 areas), supposed sources (6 areas) and seismotectonic sources (5 areas) [1]. In some seismic sources, selected in 1998 (Svetupe, Western-Baltic and Sloka), earthquakes were not discovered, yet there were only geological and geophysical pre-conditions of seismicity.

The method that was used in 2007 is based on another approach. Seismic sources (earthquakes sources) were selected in case if earthquakes happened in these areas. Configuration of the earthquakes sources was conditioned by a set of geological, geophysical and geodynamical signs, which characterized these sources, as well as by the features of their geometrical figures consisting of triangles.

Seismic danger of the Baltic region, including the territory of Latvia, in terms of seismic risk, was assessed in a number of researches.

In particular, the research by the Geological Survey of Finland [27] showed that the level of seismic influences does not exceed 4% (39 cm/s^2) of the total value of acceleration on the territories of the Baltic countries. The results of GSHAP project [28] for the whole territory of Europe were used as the basic data for these estimations. The results showed that for the Baltic countries the seismic risk within 50 years would exceed 20 cm/sek^2 - 30 cm/s^2 for stiff site conditions.

Estimation of Baltic seismic risk carried out by Lithuanian experts [29] showed that on a considerable part of the territory of Latvia PGA can exceed 150 cm/s^2 with the probability 10^{-4} (for the recurrences period of 10000 years).

Peak ground acceleration (PGA) can exceed 110 cm/s^2 (Aizkraukle) within the framework of our analysed research with the probability 0.5% (for the period of repetition 9975 years). The difference in estimations can be explained by divergence of *b-value* of seismic activity. According to the Lithuanian researchers, *b-value is* equal to 0.63 [29] across the whole of the Baltic region. Within the framework of analyzed research, *b-value* changes from 0.33 to 0.38, depending on the area – the continental part of the Baltic region or offshore and the Baltic Sea coast.

Similar estimations of the seismic risk obtained for Fennoskandia [30, 31] showed that in Southern Finland, on a small territory of South-eastern Sweden (district of Stockholm, Gotland) within 50 years the PGA would exceed 10 cm/s^2 with the 10% probability. These estimations are actually comparable with the level of PGA, which with the probability 10% can be exceeded in Riga, Cesis, Aizkraukle, Olaine, Sigulda and their environs. On a considerable part of the territory of Sweden, in North-eastern Norway, in Northern and Central Finland the probability of PGA will exceed the accelerations being in the range from 10 up to 25 cm/s^2.

It is necessary to take into account that a sedimentary coveris practically absent on the territory of Scandinavia and the foregoing estimations are given for the soil of A type. Thickness of sedimentary cover in Latvia reaches 250 – 1900 m and it covers the crystalline basement. Its uppermost part is represented by Quaternary deposits, by the most unconsolidated deposits from a few meters up to 310 m thick. The unconsolidated deposits are able to strengthen seismic shakings on the surface as a result of the phenomena of resonances [32]. In particular, that could be seen after the Kaliningrad earthquake of September, 21, 2004 [33]. The level of seismic signal on soil in some places of Latvia considerably excelled its level on crystalline basement.

Conclusions

1. With the probability of 10% within 50 years on hard, Pre-Quaternary deposits of Latvia, PGA can exceed 10-13 cm/s^2 in Sigulda, Riga, Olaine, Aizkraukle, Cesis and their environs.
2. On the surface of Pre-Quaternary deposits of Latvia PGA do not exceed 0.04g (39 cm/s^2). This estimation corresponds to a very low level of *seismic hazard* according to the conditions of LVS EN 1998-1:2005.
3. The total seismic risk includes the estimation of PGA on Pre-Quaternary deposits and the seismic response of the unconsolidated Quaternary deposits for the upper 30-meter layer. For estimation of *seismic hazard* on the surface of soil it is necessary to take into account the amplification of seismic effect from unconsolidated Quaternary deposits and the response spectrum from it.

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Valerijs Ņikuļins. Latvijas seismiskā riska novērtējums. 2007. gada versija
Latvijas seismiskais risks ir novērtēts, pamatojoties uz PSHA (Analysis Hazard Seismic Probabilistic) metodi. Seismotektoniskā analīze ļāva izdalīt 8 seismogēnās zonas Latvijas teritorijā, un tikpat daudz aiz tās robežām, tiešā Latvijas tuvumā. Katrai seismogēnajai zonai ir novērtēti tādi parametri kā seismiskā aktivitāte, zemestrīces cilmvietas dziļums, maksimālā magnitūda u.c. Magnitūdu-biežumu atkarības *b* parametrs ir noteikts diviem lieliem apgabaliem: Baltijas piejūras un krasta zonām (0.38), kā arī Baltijas reģiona kontinentālajai zonai (0.33). Magnitūdas nozīmju atšķirīgi tipi ir pārrēķināti attiecībā pret momenta magnitūdu.
Seismiskā riska novērtējumi Latvijas teritorijā rāda, ka maksimālie grunts (PGA) paātrinājumi ar varbūtību 10%, turpmākajos 50 gados pārsniegs 10 – 13 cm/s^2 Siguldā, Rīgā, Olainē, Aizkrauklē, Cēsīs. Atbilstošais atkārtojamības periods ir 475 gadi. Saņemtie PGA novērtējumi attiecas uz A tipa cietajām gruntīm. Latvijas teritorijā šīm gruntīm atbilst pirmskvartāra nogulumi. Atbilstoši seismiskā riska līmenim, Latvijas esošie pirmskvartāra nogulumi pieskaitāmi ļoti zemai satricinājumu intensitātes kategorijai. Tā ir raksturojama ar PGA nozīmi, kura nepārsniedz 0.04 g (39 cm/s^2). Saskaņā ar EN 1998-1:2004 Eiropas normatīvā dokumenta rekomendācijām, kas ir adaptēts Latvijā 2005.gadā (EN LVS 1998-1:2005 „ Seismiski izturīgu konstrukciju projektēšana. 1.daļa: Vispārīgie noteikumi. Seismiskās iedarbes un noteikumi ēkām”), reakcijas citu tipu grunts (bez A tipa grunts) novērtējumam uz seismiskām iedarbībām ir nepieciešami papildus pētījumi. Kompleksveida seismiskais risks iekļauj pirmskvartāra nogulumu PGA novērtējumu un spektrālo atbalsi no nekonsolidēto kvartāra nogulumu augšēja 30 metru biezā slāņa.

Валерий Никулин. Оценка сейсмического риска в Латвии. Версия 2007 года.
На основе метода PSHA (Analysis Hazard Seismic Probabilistic) оценен сейсмический риск в Латвии. Сейсмотектонический анализ позволил выделить 8 сейсмогенных зон внутри Латвии и столько же за ее пределами. Для каждой сейсмогенной зоны оценены параметры сейсмической активности, глубины гипоцентра землетрясения, максимальной магнитуды и др. Параметр магнитудо-частотной зависимости b определен для двух крупных областей: прибрежной и береговой зоны Балтийского моря (0.38), а также континентальной зоны Балтийского региона (0.33). Различные типы магнитудных значений пересчитаны к моментной магнитуде.
Оценки сейсмического риска Латвии показывают, что максимальные ускорения грунта (PGA) с вероятностью 10% в течение 50 лет превысят 10 – 13 см/с^2 в Сигулде, Риге, Олайне, Айзкраукле, Цесисе. Соответствующий период повторяемости равен 475 годам. Полученные оценки PGA относятся к жестким грунтам A типа. На территории Латвии этим грунтам соответствуют дочетвертичные отложения. По уровню сейсмического риска на дочетвертичных отложениях территория Латвии относится к категории очень низкой сейсмичности. Она характеризуется значениями PGA, не превышающими 0.04 g (39 см/с^2). В соответствии с рекомендациями европейского нормативного документа EN 1998-1:2004, адаптированного в Латвии в 2005 году (EN LVS 1998-1:2005 „8.Eirokodekss. Seismiski izturīgu konstrukciju projektēšana. 1.daļa: Vispārīgie noteikumi. Seismiskās iedarbes un noteikumi ēkām”), для оценки реакции спектрального отклика других типов грунтов (кроме грунта A типа) на сейсмические воздействия, необходимы дополнительные исследования. Комплексный сейсмический риск включает оценку PGA на дочетвертичных отложениях и спектральный отклик неконсолидированных четвертичных отложений верхнего слоя толщиной 30 метров.