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Design basis earthquake of the Ignalina Nuclear Power Plant

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Assessment of the seismic potential and related risk level of low seismicity areas is a highly complex problem. The Ignalina NPP, located in the East European Craton, was originally built for the lowest seismic risk conditions. Throughout two decades of operating the plant attempts were taken to reinforce the plant in the face of a possibly higher seismic risk. The seismic potential of the Baltic basin is seemingly underestimated, as evidenced by the recent Kaliningrad earthquakes (2004, M = 5.0). The Design Basis Earthquake was re-evaluated for the Ignalina NPP site. The deterministic approach was applied instead of probabilistic methods due to scarceness of seismic records. The Design Basis Earthquake of the site is estimated as $M_L = 5.6$ ($I_o = 7.5$) and the hypocentral depth of 10 km, based on the fact of presence of a neotectonically active large-scale shear zone close to the nuclear power plant. This tectonic feature is compatible to other fault zones identified within the radius of 150 km, which show historical earthquake activity. The free-field ground response spectra were calculated using the attenuation relationship derived from Japanese near-field seismic records. The site-specific amplification effects were taken into consideration. The estimated design peak ground acceleration is 0.166 *g*. It is higher than the minimum limit (0.1*g*) recommended by the IAEA guidelines for the SL-2 ground motion hazard level. The maximum spectral acceleration is defined within the frequency range 7–10 Hz. The in-structure response spectra were calculated for different levels of the Unit 2 Reactor Building. They differ considerably from previous estimates by a higher load in the high-frequency range, whereas much lower values are estimated for the low-frequency range.

Key words: Design basis earthquake, Ignalina NPP, seismic amplification, seismic safety, free-field spectra.

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INTRODUCTION

Seismic safety issues generally consider derivation of the Design Basis parameters (i.e. seismic input) and the seismic capacity of structures (IAEA, 2003). The results of the reassessment of other East European NPP sites indicate that the original design basis ground motion parameters have been underestimated, sometimes by a considerable margin (Gurpinar, Godoy, 1998). Furthermore, the re-evaluation of the nuclear facilities is a common praxis even in well-studied regions as more data are accumulated in the course of the plant operation (McGuire et al., 2001; Campbell et al., 1998). The Ignalina NPP is located in the East European Craton which was considered as an aseismic region at the time of the construction of the plant. However, systematic seismotectonic studies of the Baltic region and adjacent areas indicated a higher seismic potential and urged the re-evaluation of the seismic safety of the Ignalina NPP. Several attempts were undertaken to re-assess the Design Basis Earthquake during the past decade. The issues of seismic stability of the Ignalina NPP systems and elements have been developed in the past decade (*e.g.*, INPP/B-2.2 seismic upgrading of safety-related equipment; Walkdown visit on Ignalina NPP Units 1 and 2. ISMES Report issued March 24, 1995; ISMES Report INPP/equipment. Walk-down visit Nov.-94. Final Report 24.03.95; Ignalina NPP Safety Analysis Report, code ПТОаб-0345-1B1, 1996; Safety Analysis Report of Ignalina Nuclear Power Plant Review. Official summary. Report RISKAUDIT No 74, code ПТОот-0345-189, 1997; etc.).

The estimation of the seismic potential of cratonic areas is a highly complex problem, as the applicability of techniques developed for seismically active areas to the areas that have no or limited seismic records is still under discussion. On the other hand, the geological knowledge on cratonic regions is rather high. Based on these specific features, an appropriate approach has to be chosen in estimating the seismic hazard level for a site.

The geological stability and the ground motion parameters should be assessed according to specific site conditions and in compliance with criteria and methods valid for new facilities, *e.g.*, criteria established by the IAEA Safety Guide 50-SG-S1 (IAEA, 1991) according to which the review level earthquake corresponds to the SL–2 level directly related to ultimate safety requirements, i.e. a level of extreme ground motion that shall have a very low probability of being exceeded during the plant lifetime and represents the maximum level to be used for design and re-evaluation purposes.

GEOLOGICAL SETTING AND FAULT TECTONICS OF THE BALTIC REGION

The Ignalina NPP is situated in the western part of the East European Craton. The Palaeoproterozoic high-grade metamorphic and igneous rocks are covered by 0.5–5 km thick Phanerozoic sediments of the pericratonic Baltic sedimentary basin. The Ignalina NPP is situated in the eastern periphery of the basin; the thickness of the sedimentary cover is 0.7 km. The Prequaternary succession is topped by Quaternary glacial deposits. The basin shows only weak faulting related to several phases of increased tectonic activity in the late Early Palaeozoic (Caledonian stage) and late Late Palaeozoic (Variscan stage), though minor fault activity is recognised also during other stages of the basin development (Stirpeika, 1999; Brangulis, Kanevs, 2002). The densest network of platform faults is identified in middle Latvia (Fig.1). The amplitudes of faults of the sedimentary cover are commonly less than 50 m. Only the largest-scale faults show amplitudes up to 200–650 m. The rheological modelling indicates that the most intense faulting is related to the weakest lithosphere (middle Latvia, west Lithuania, the Baltic Sea), while the eastern less-faulted part of the Baltic basin is characterised by a very strong lithosphere (Šliaupa, Ershov, 2000). The neotectonic activity of some faults is well documented by deformations of the Baltic Sea terraces and river long–profiles, hydrogeochemical anomalies, etc. The Holocene amplitudes of the vertical movements of some faults attain 5 m (Šliaupa et al., 2005). The recent fault activity reaching up to 1–2 mm/a is identified by geodetic levelling (Zakarevičius, 1999) and GPS data (Zakarevičius et al., 2005).

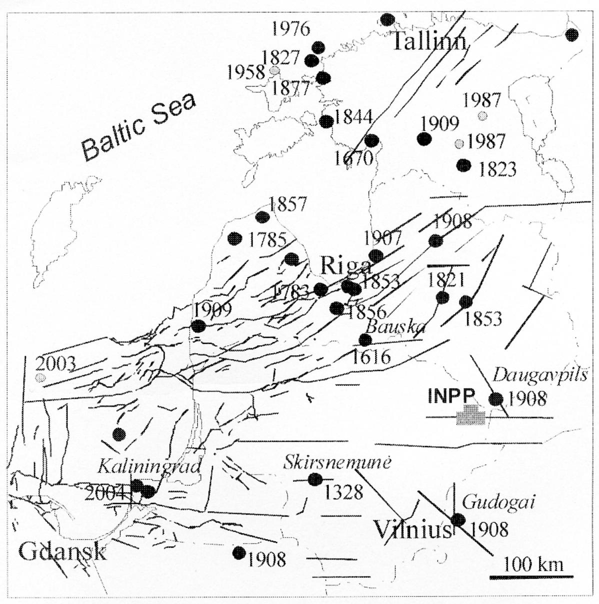

Fig. 1. Major faults defined in the sedimentary cover and earthquakes I_0= 6–7 (black dots, year) of the Baltic region. Seismic events mentioned in the text are labelled. Some important recent lower intensity seismic events are indicated (grey dots, year). Location of The Ignalina NPP is indicated
1 pav. Pagrindiniai Baltijos regiono lūžiai ir žemės drebėjimai I_0 = 6–7 (juodi taškai žymi metus). Pažymėti kai kurie svarbūs silpnesni seisminiai įvykiai (pilki taškai žymi metus). Nurodyti tekste minimų drebėjimų pavadinimai. Pažymėta Ignalinos AE vieta

APPROACH

Deterministic (DSHA) and probabilistic seismic hazard analyses (PSHA) are incompatible methods commonly used in seismic risk studies. DSHA is based on the geological features of the site (Bommer, 2002; Krinitzsky, 2003), whereas PSHA is focused on earthquake statistics and numerical calculations (*e.g.*, Cornell, 1968; Kijko, Öncel, 2000; Musson, Henni, 2001; Sokolov et al., 2001). DSHA is more reliable than PSHA, because it considers the actual geological features and is more transparent. DSHA evaluates earthquake hazards reliably based on geology regardless of time and has no need for time-based probability.

The seismotectonic data of the Baltic region are very poor because of (i) low seismic activity and (ii) an insufficient seismological monitoring system. On the other hand, the geological knowledge is rather good owing to extensive geological and geophysical surveys held during the past decades. Furthermore, a detailed geological mapping was performed in the Ignalina NPP area (Marcinkevičius et al., 1995 – unpublished report). Accordingly, the deterministic approach is preferred in the seismic hazard assessment of the site. It is essentially supported by the recent Kaliningrad earthquake (2004 09 21), the magnitude of which exceeded the previous maximum seismic potential estimates of the Baltic region (Aronov et al., 2005).

In accordance with modern practice, seismic load specification is most suitably expressed in the form of Ground Response Spectra from which the synthetic time-histories of ground motions are derived. The assessment of the seismic load is performed in two steps: (1) estimation of the seismogenic potential of the area, and (2) derivation of the site-specific Ground Response Spectra. By using the deterministic approach the most credible maximum earthquake is obtained with respect to depth and magnitude. Furthermore, the safety margin should be incorporated to account for inevitable uncertainties regarding seismological and geological data.

The far-field seismic impact is too low to have any importance for the Ignalina NPP safety. Only near-field effects are considered in the seismic risk assessment. Therefore, only records from near-field events are consistently used to determine such relationships for different rock and soil properties. Methods based on scaling of spectra from records of ground motions generated by strong distant earthquakes bear systematic inconsistencies that may lead to considerable mistakes in derivation of near-field seismic loads.

SEISMIC ACTIVITY IN THE BALTIC REGION

The knowledge of the seismic activity of Lithuania and adjacent countries is based mainly on historical records (Avotinia et al., 1988; Ilginytė, 1998). Scandinavian seismic networks, and a few available Baltic seismic stations provide only scarce information, the consistency of which is debated (Pačėsa, 2003).

Commonly, the territory of the Baltic region is considered to be of very low seismic activity. However, available data indicate that quite strong earthquakes took place in a past. The oldest historical record dates back to 1303, when a strong earthquake shook Prussia (Kaliningrad District) and destroyed most of timber houses. The Chronicles by Petri de Dusburg reports strong shaking of the medieval castle in central Lithuania (Skirsnemune) in 1328, so that terrified inhabitants were “about to throw themselves down the castle walls”. The castle was abandoned in 1329. Since 1616, about 40 strong earthquakes were recorded in the Baltic region (Doss, 1909; Avotinia et al., 1988).

The seismic activity is distributed unevenly in the Baltic and adjacent regions (Garetski et al., 1997). The most distinct earthquake cluster is identified in central Latvia characterized by most intense faulting along the largest–scale Liepaja–Saldus fault zone crossing the country from the east to the west (Fig.1). The closest seismic event took place in the Daugavpils area 35 km to the north–east from the Ignalina NPP on 29 December 1908. The intensity of the earthquake was I_o= 6–7 (noise resembling gun-shot, apertures on the surface 3–4 inches wide, and fractures in building walls); the calculated M_L = 4.6 and the hypocentral depth is 10 km. The epicentre is spatially related to the fault trending NW–SE, the neotectonic activity of which is suggested by its control on the flow direction of the Daugava River. Furthermore, the epicentre is located in the central part of the recent uplift attaining 4 mm/a, which is the highest value registered in the Baltic region (Zakarevičius, 1999). The Ignalina NPP is situated on the southwestern flank of this recent uplift.

The other strong earthquakes took place in Gudogai (30.12.1908), Koknese (21.02.1821), and Bauska (30.06.1616) areas at a distance of 100–150 km from the Ignalina NPP. The hypocentral depths range from 3 km to 20 km, M_L = 3.4 (Koknese), M_L = 4.5 (Gudogai), M_L = 4.8 (Bauska), I_o = 7 (fractures in buildings, apertures in the field, land-slides, difficulty to stay afoot, animals tumbling down) (Avotinia et al., 1988). The Bauska earthquake is related to the W–E striking fault 300 km long (Fig. 1), the offset of Palaeozoic layers attains 50 m. The Gudogai earthquake marks the intersection of two-large scale fault zones striking NW–SE (more than 400 km long) and N–S (250 km long). These faults do not show any significant offset of Prequaternary layers (a few dozens of meters only). The fault control of the Koknese earthquake remains unclear.

The most recent strong seismic events are the Osmussaare (NW Estonia, 1974) and Kaliningrad earthquakes. They are located at a distance of about 350 km from the Ignalina NPP. The Osmussaare earthquake M_L = 4.75 is related to the NNW–SSE trending fault well expressed on the bottom relief of the Baltic Sea. The Kaliningrad earthquake (21. 09. 2004) is the strongest seismic event instrumentally registered in the Baltic region, M_L = 5.0 + 0.3, depth 10–18 km. The main earthquake was preceded by earthquake M_L = 4.4 two hours before and was followed by a small earthquake M_L = 3.4 five minutes later. The earthquakes were induced by right-lateral strike-sleep along the South Kaliningrad fault striking WNW–ESE (Pačėsa et al., 2005).

The seismic activity of faults is related to a stressed state of the lithosphere. West Lithuania is affected by a NW–SE horizontal compression, whereas the main horizontal stress in the eastern part of the country is oriented NE–SW (Sim et al., 1995; Šliaupa, Zakarevičius, 2000).

Based on these data, the maximum seismic potential of the Baltic region is estimated at no less than M_L = 5.0, I_o = 7, the average focal depth being about 10 km. It should be noted that only some earthquakes are related to well-defined faults, whereas a number of seismic events have no clear fault control. It is compatible with other cratonic areas, such as the Canadian shield, where most of strong earthquakes in east Canada have no faulting expression on the surface (*e.g.*, Saguenay earthquake 1988). Accordingly, the concept of area sources (USNRC, 1997) is favoured for the Baltic region instead of the commonly used concept of seismogenic zones and dispersed seismicity, because there is a considerable uncertainty about the underlying causes of earthquakes. In other words, no particular tectonic structure is considered as an individual seismic source, instead assuming that a seismic event of the maximum magnitude and a certain hypocentral depth may take place randomly in the area. The seismotectonic conditions (character of faults, geology of the basement and sedimentary cover, soil, etc.) of the Baltic region vary relatively little across the territory. Furthermore, the frequency of the earthquake occurrence, which varies in different areas of the Baltic region, does not correlate with the maximum recorded earthquake intensities. As mentioned above, most abundant earthquakes are reported from the most faulted central Latvia, whereas only a few earthquakes were registered in the Kaliningrad District where the strongest earthquake took place. Furthermore, the afore-mentioned Gudogai and Daugavpils earthquakes are related to the least faulted area of the Baltic basin. Their magnitudes are compatible to those of middle Latvia.

DESIGN BASIS EARTHQUAKE OF THE IGNALINA NPP

Previous estimates

Several attempts were undertaken in a past to estimate the maximum credible earthquake of Ignalina NPP site. The plant was build for minimum seismic activity region conditions (Medvedev, 1968). However, the inventory of historical records persuaded that the seismic potential was considerably underestimated. The commission assigned by the Academy of Sciences of the USSR reassessed the seismic potential of the Ignalina area in 1988 (Conclusions on evaluation of seismic conditions of Ignalina NPP site. Governmental Commission. Moscow, 1988 – unpublished report). Based on historical earthquakes and site-specific soil conditions the maximum credible earthquake was evaluated I_o = 6 and the design basis earthquake was assessed I_o = 7 (according to USSR regulations a safety margin +1 was assumed). The maximum probable earthquake was estimated as M_{max} = 4.6 and the focal depth of 10 km.

The seismic microzoning was performed in Ignalina NPP area in 1988 (Report on tool investigation in order to perform seismic microzoning of the Ignalina NPP site, PNIIIS 1988, code TACпд-0045-54422 – unpublished report). The authors of the report provided similar estimates of the design basis earthquake I_o = 7, Peak Ground Acceleration PGA = 0.1*g* (T_{max} = 2.5–6.5 Hz) for Unit 1, and I_o = 6 and PGA = 0,06*g* (*g* is a gravitational constant) for Unit 2, the difference is due to different soil conditions. As regards far-field earthquakes, the intensity of ground shaking should not exceed I = 4–5.

In 1991 VNIPIET, the General Designer of the Ignalina NPP, calculated floor accelerograms and floor response spectrum of the main constructions of Ignalina NPP. The Maximal Credible Earthquake was assumed different for calculating different structures and systems, i.e. I_{MCE} = 6.5 to 7 and the maximal acceleration of soil was assumed from 60 to 100 cm/sec^2 (Calculation of floor accelerograms and floor response spectrum, VNIPIET, 91-10335, code TACпд-0045-63714 – unpublished report).

Seismic potential of the Ignalina NPP site

The detailed geological mapping of the Ignalina NPP area, performed after construction of the plant, considerably improved the knowledge of the tectonic conditions of the site (Marcinkevičius, 1995 – unpublished report). The plant was shown to be located close to the intersection of major N–S and W–E striking fault zones. The latter, referred to as the Drūkšiai fault, is an essentially distinct tectonic feature. The intersection of two large-scale faults was likely the reason for the formation of Lake Drūkšiai, the largest lake in Lithuania. The recent activity of faults was proved by geodetic measurements (Zakarevičius, 1999) which showed a relative uplift of the northern flank of the Drūkšiai fault at a rate of about 1 mm/a. Furthermore, high-quality GPS network measurements revealed a horizontal overriding of the northern block onto the southern flank of the Drūkšiai fault (Zakarevičius et al., 2005). In view of these evidences, the Ignalina NPP site is considered to be located above the potential seismic zone (Ilginytė, 1998; Aizberg et al., 1999). The seismotectonic conditions of the Ignalina NPP are compatible with the other seismogenic zones mapped in the Baltic region (and the Daugavpils area in particular) characterised by historical earthquake activity up to I_o = 6–7 and M_L = 4.6. The maximum credible earthquake of the Ignalina NPP site is accordingly estimated at I_{MCE} = 6.5 and M_{MCE} = 4.6, the potential source is being below the plant at a hypocentral depth of 10 km.

Design Basis Earthquake of the Ignalina NPP site

The uncertainty associated with the seismic hazard estimations motivates the application of the seismic margin methodology which focuses on determining earthquake ground motion levels at low probability levels. For the probabilistic approach, a common praxis is estimating PGA for exceedence levels 10^{-4}–10^{-5}. Following IAEA recommendations (IAEA, 2003) and specifically the USSR Standards (PN AE-G-5-006-87) the Design Basis Earthquake of the the Ignalina NPP is estimated at $I_{DBE} = 6.5 + 1 = 7.5$ (which is about 0.15 g in terms of PGA). In terms of the local magnitude, $M_{DBE} = 5.6$ is assumed for the Ignalina NPP site.

SITE-SPECIFIC GROUND RESPONSE SPECTRA OF THE IGNALINA NPP

Soil profile

The rock and soil properties considerably influence the seismic wave propagating from the fault to the surface. Consistent data on the soil seismic properties of the Ignalina NPP site were collected during the aforementioned seismic microzoning survey. S-wave downhole measurements were performed in 20 shallow microzoning wells to the depth of 20 m. P-wave velocities of the whole sedimentary section were obtained from two geological mapping wells drilled into the crystalline basement (730 m) (Marcinkevičius et al., 1995 – unpublished report). For the Unit 2 site, the average S-wave velocity of the uppermost 0–10 m interval of the moraine dominated section is 270 m/s, increasing to 350 m/s in the 10–20 m depth interval. Following the ENV 1998-1-1 (Eurocode 8, 1998) classification, the soil of the Unit 2 site is attributed to the subsoil class B, and to a class D stiff soil according to NEHRP code provisions (BSSC, 1997).

Considering the deeper section layers, S-wave velocities were converted from P-wave measurements. The values of the sedimentary rocks are in the range of 1190 m/s to 2400 m/s (Table 1). The crystalline basement is characterised by an S-wave velocity 3150 m/s, which is lower than most of the Early Precambrian basement rocks due to intense milonitization.

Ground response spectra and synthetic time-histories

Amplitudes of seismic waves increase significantly as they pass through soft soil layers near the earth's surface (*e.g.*, Bard, Bouchon, 1985; Bauer et al., 2001; Ŗafak, 2001; Semblata et al., 2002). This phenomenon, commonly known as site amplification, is a major factor influencing the extent of damage on structures. The increase is due to the low impedance of soil layers near the surface. The soil and rock litholgies have also a great impact on the ground response spectrum shape. A stiff site is characterised by a pronounced peak in the short period range, becoming more complex with a shift of maximum energy towards longer periods in a soft soil site.

Due to the lack of near-field strong earthquake records in the Baltic region, relationships defined in the other regions are applied. In some previous studies, the scaling of far-field (hundreds kilometres) strong motion records (*e.g.*, Carpathian earthquake, M = 8.5) was used in calculating the seismic load for the Ignalina NPP. It bears a systematic error as the dominant frequencies are shifted towards longer periods with an increasing magnitude and distance (Sadigh et al., 1993). In the case of scaling of the Carpathian earthquake, the maximum acceleration was obtained for the frequency 4 Hz.

More consistently, characteristics defined from the near-field records of different geological (soil) conditions can be applied. A comprehensive collection of seismic records from near-field earthquakes is provided from Japan. The Japanese relationships between spectral values and source and wave path parameters were determined by regression analysis of a large number of spectra based on records from sites with outcropping sedimentary rock. In the present study, the regression model presented in (Watabe et al., 1988) was applied for derivation of response spectra for outcropping sedimentary rock:

$$\log pSv(T) = A(T)\cdot M - B(T) - \log X - C(T)\cdot \log Vs - D(T), \qquad (1)$$

where pSv(T) in terms of a period (T) is a pseudo velocity response spectrum (cm/s) with a constant critical damping ratio (5%), A, B, C, D are period-dependent regression coefficients, M is the moment-related magnitude, X is the hypocentral distance (km), Vs is the shear wave velocity (km/s) in the soil.

In this attenuation equation, the magnitude is coupled to the seismic moment M_o, which is the source parameter used in the Japanese and US studies ($M_o = 9.1 + 1.5M$). The moment-magnitude relationship is, however, different in cratonic areas. A region-specific relationship was used for calculating the uniform seismic hazard spectra of the Swedish territory (SKI Report 92:3, 1992). Taking into consideration similar parameters of the earth's crust of Lithuania and Sweden, the latter relationship is more appropriate for the Baltic region. According to this relationship, the magnitude M = 5.6 relates to the seismic moment $M_o = 10^{16.6}$ Nm, which corresponds to the Japanese and USA moment-related magnitude M = 5.0. Accordingly, the latter value was used in the equation to calculate the seismic response spectra of the Ignalina NPP site.

The spectrum derived from Japanese data for sedimentary rock is valid for a shear wave velocity of >700 m/s. The basement rocks are characterised by a shear wave velocity of 2500–3500 m/s, which is close to the Ignalina NPP conditions. The spectral values of S-wave velocities were calculated for different frequencies assuming the outcropping rock of the shear wave velocity to be 700 m/s (Fig.2). The maximum horizontal spectral acceleration (0.32–0.35 *g*) is established for the frequencies 7–10 Hz, the PGA is assessed as 0.13 *g*.

However, the soil shear wave velocities measured in the Unit 2 site are much lower (270 m/s^2). Therefore, an additional amplification has to be accounted for. It was assessed by comparisons of differences of wave

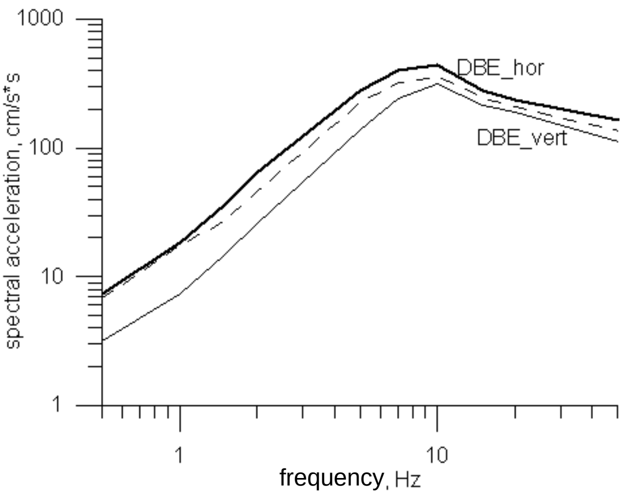

Fig. 2. Free-field response spectra of the INPP Design Basis Earthquake (5% damping, horizontal and vertical motion components). Hatched line shows INPP free-field response spectra calculated for rock conditions (700 m/s)

2 pav. Projektuojamo IAE žemės drebėjimo plyno lauko atsako spektras (5% gesinimas, horizontalių ir vertikalių virpesių komponentės). Brūkšninė linija rodo Ignalinos AE plyno lauko atsako spektrą, apskaičiuotą uolinio pagrindo sąlygoms (700 m/s)

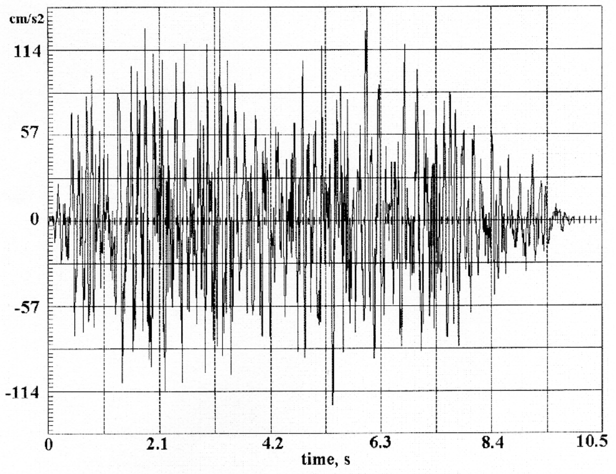

Fig. 3. Synthetic accelerogram (time–history of the horizontal component) of Design Basis Earthquake of INPP site derived from free-field ground response spectrum (Fig. 2). Abscise axis – time (s), ordinate axis – acceleration (cm/s^2)

3 pav. Projektuojamo IAE žemės drebėjimo akselerograma, apskaičiuota iš plyno lauko atsako spektro (3 pav.). Abscisė – laikas (s), ordinatė – pagreitis (cm/s^2)

amplification as presented in US reports (Silva et al., 2000). For soil with shear wave velocities of 200–300 m/s, this additional amplification factor varies between 1.15 and 1.35. The frequency-depended amplification coefficients were accordingly incorporated in the Ignalina NPP Design Basis Earthquake free-field ground response spectrum calculations. The new spectrum shows an increase in ground acceleration compared to the soft rock model (Fig. 2). The maximum values are defined within the 7–10 Hz frequency range (spectral acceleration 0.4–0.45*g*). PGA is as high as 0.166 g. The vertical ground motion spectrum has been derived on the basis of comparisons made in the USA as presented in (Silva et al., 2000) (Fig. 2).

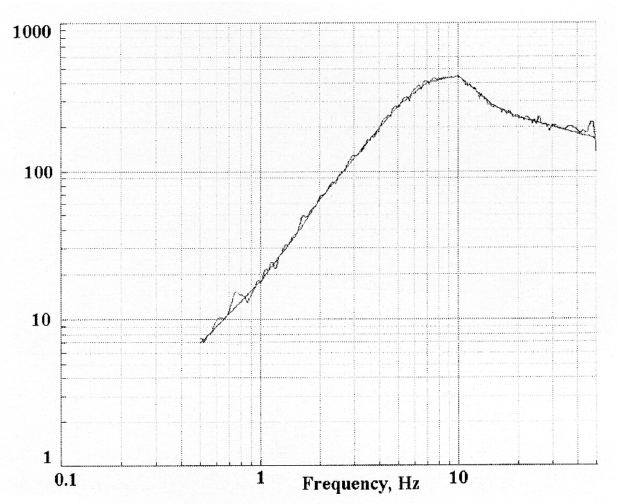

Fig. 4. Comparison of the target response spectra (Fig. 2) and response spectra calculated from the time-history (Fig. 3).

4 pav. Atsako spektro (2 pav.) palyginimas su atsako spektru, apskaičiuotu iš sintetinės akselerogramos (3 pav.)

The same spectral shapes were assumed for two principal horizontal components N–S and W–E. It should be, however, noted that the shape of ground response spectra depends on the fault orientation. Assuming the earthquake generated at the Drūkšiai fault striking west–east, some reduction of the energy can be suggested for the horizontal component W–E compared to the N–S component in a low-frequency range (<3Hz). This effect is still poorly known and therefore was not accounted for in the Ignalina NPP spectra.

The DynaTool program was used to obtain the time signals of ground acceleration (synthetic accelerograms) of the Ignalina NPP site (Fig. 3). The time-histories were derived following ASCE 4-95 and IAE NS-G-1.6 guidelines, the enveloping function was accordingly assumed to be 1+6+3 s. The backward solution indicates the consistency of the method applied (Fig. 4).

COMPARISON OF DESIGN RESPONSE SPECTRA WITH THOSE OF ADJACENT REGIONS

The seismic hazard assessment was performed for nuclear power plants of the neighbour countries. The Swedish nuclear industry and the regulatory agency funded an extensive investigation to develop a characterization of seismic ground motions for probabilistic analyses of nuclear facilities in Sweden. The study (Engelbrektson, 1989; 2000) has produced uniform hazard ground motion spectra for hard rock at annual frequencies of exceedence 10^{-5}, 10^{-6} and 10^{-7}. Due to considerable differences of geological sections of the Baltic basin and Fennoscandian Shield the obtained free-field

Table. **Seismic parameters of geological column of the INPP site**
Lentelė. **IAE geologinio pjūvio seisminės charakteristikos**

Depth m	Density kg/m^3	P-wave m/s	S-wave m/s	Stratigraphy	Lithology
0–10	2150	1080	270	Q	Moraine loam
10–20	2200	1140	380	Q	Moraine loam
20–100	2050	1970	1190	Q	Moraine / sand
100–190	2000	1970	1190	D_2	Sand with clay
190–340	2350	2650	1600	D_2	Marlstone, dolomite
340–490	2450	3810	2310	D_2-S_1-O	Marlst., limestone
490–500	2450	4000	2420	Cm_1	Sandstone
500–580	2400	2430	1470	Cm_1	Clay
580–600	2400	3250	1970	Cm_1	Clay, sandstone
600–655	2400	2530	1530	V_2	Clay, siltstone
655–720	2450	3410	1900	V_2	Sandstone, congl.
>720	2550	5500	3150	PR_1	Basement

ground response spectra are rather different. The Uniform Hazard Spectra calculated for exceedence of 10^{-5} shows a lower PGA, the maximum spectral acceleration values are shifted to the higher frequencies, which is typical of hard-rock sites (SKI Technical Report 92:3, 1992).

By contrast, the Leningrad NPP site situated in the northern periphery of the Moscow sedimentary basin has many similarities to northeast Lithuania. Both sites are located in the East European Craton showing similar litholgical sections. The crystalline basement is part of the same Fennsocandian segment of the earth's crust. In the Leningrad site it is overlain by undeformed sediments 180 m thick (Varpusuo et al., 2001); the sedimentary cover is comprised by Vendian and Cambrian (Blue Clays) terrigens, similar to those of the Ignalina NPP site (Table), it is topped by Quaternary deposits showing shear-wave velocities 180–250 m/s^2. Both regions are characterised by a low seismic activity.

The approach used of the assessment of seismic hazard in the Leningrad NPP was different from that applied in the Ignalina NPP. The seismic potential was assessed using probabilistic methods. A spectral shape of ground motion was derived from near-field seismic records of east Canada, modified to site-specific soil conditions using the CARES program (Varpusuo et al., 2001). The Design Basis Earthquake PGA of the Leningrad NPP site was calculated to be 0.17 g, which is very close to the value obtained for the Ignalina NPP (0.166 g). The spectral shapes are also rather similar for both sites (Fig. 5). The differences are minor and consider mainly the maximum spectral acceleration at 5 Hz and somewhat lower values (by 5–15 m/s^2) in the low frequency range for the Leningrad NPP site.

The application of the spectral acceleration attenuation of the East European Platform (van Gelder, Varpasuo, 1998) for the calculation of the Ignalina NPP hazard spectra bears considerable inaccuracies (Fig. 5), as it is mainly based on far-field seismic records and lacks soil-specific corrections.

IN-STRUCTURE RESPONSE SPECTRA OF THE IGNALINA NPP UNIT 2 REACTOR BUILDING

The importance of the re-evaluated Design Basis Earthquake is demonstrated by examination of its influence on safety parameters of the NPP structures and systems. Calculation of in-structure response spectra of building in particular is one of the basic steps in seismic safety assessment.

The Ignalina NPP operates RBMK-1500, graphite-moderated, boiling water, multi-channel reactors. The reactor building represents a three-dimensional multi-sectional

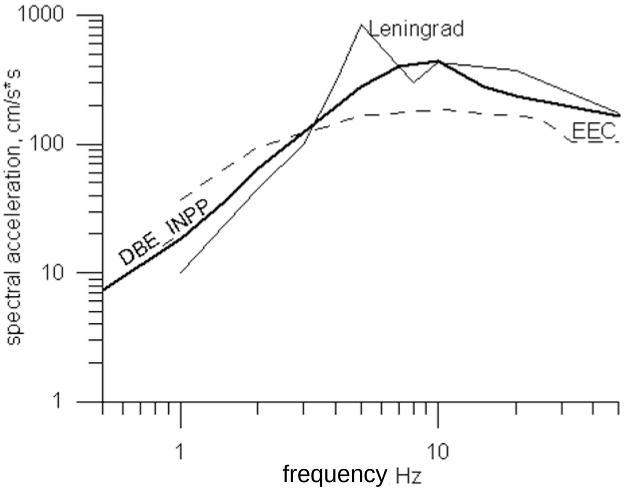

Fig. 5. Free-field ground response spectra of the INPP Design Basis Earthquake compared with free-field response spectra of the Leningrad NPP Design Basis Earthquake. Hatched line shows free-field response spectra calculated using attenuation defined for East European Craton (not corrected for soil conditions of the INPP)

5 pav. Projektuojamo IAE žemės drebėjimo plyno lauko atsako spektras (5% gesinimas, horizontalių virpesių komponentė) ir analogiškas Leningrado AE spektras. Brūkšninė linija rodo spektrą, apskaičiuotą remiantis bendra Rytų Europos platformai seismine priklausomybe (neatsižvelgiant į nuosėdinės dangos geologinio pjūvio vietinę specifiką) thin-walled reinforced concrete structure of a complicated geometry composed of elements of different stiffness. Furthermore, the dynamic behaviour of the structure during the earthquake is heavily affected by the masses of irregularly positioned systems and components. A detailed description of the Ignalina NPP is given by Almenas et al. (1998).

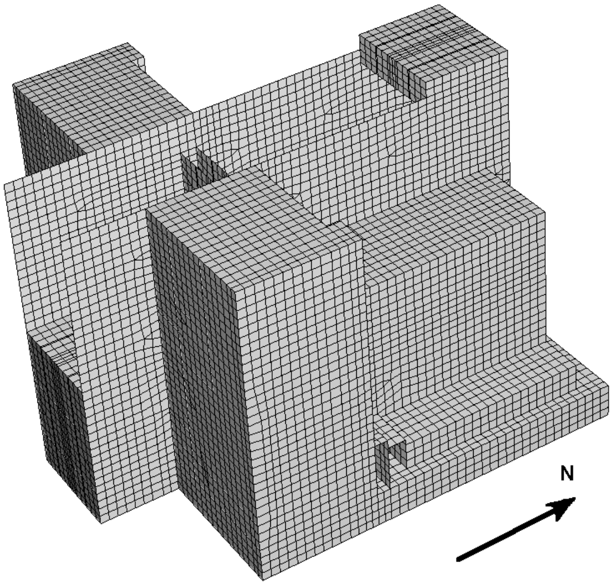

Fig. 6. Finite element model of INPP reactor building

6 pav. Ignalinos AE reaktoriaus pastato baigtinių elementų modelis

Following the advanced engineering analysis procedures, the finite element techniques are employed for the calculation of in-structure response spectra. A three-dimensional finite element model of the Unit 2 reactor building was created using the BRIGADE/Plus code (BRIGADE, 2003). The model comprises the monolithic part only, while the influence of prefabricated structures is evaluated by incorporation of external masses and stiffening of walls. The influence of the neighbouring buildings is neglected. Masses of the wall structures are applied in the form of consistence masses, while masses of equipment are modelled as lumped masses and associated rotational inertia masses. The mass of the water in condensing pools is attached to the walls in the form of lumped masses.

The geometry of the building is described in the Cartesian co-ordinate system *Oxyz*. *Oz* is a vertical axis, while *Ox* is oriented east–west. The structure is supported (grounded) at the level $z = -7.20$ m. The linear four-node shell elements are applied to describe the walls and slabs. To avoid local effects, specific equipments are described by beam elements, while roof the structure represents a rigid constraint. The general (outside) view of the finite element model is shown in Fig. 6.

Numerical analysis comprises calculation of eigenfrequencies using the ABAQUS (ABAQUS, 2003) FE code

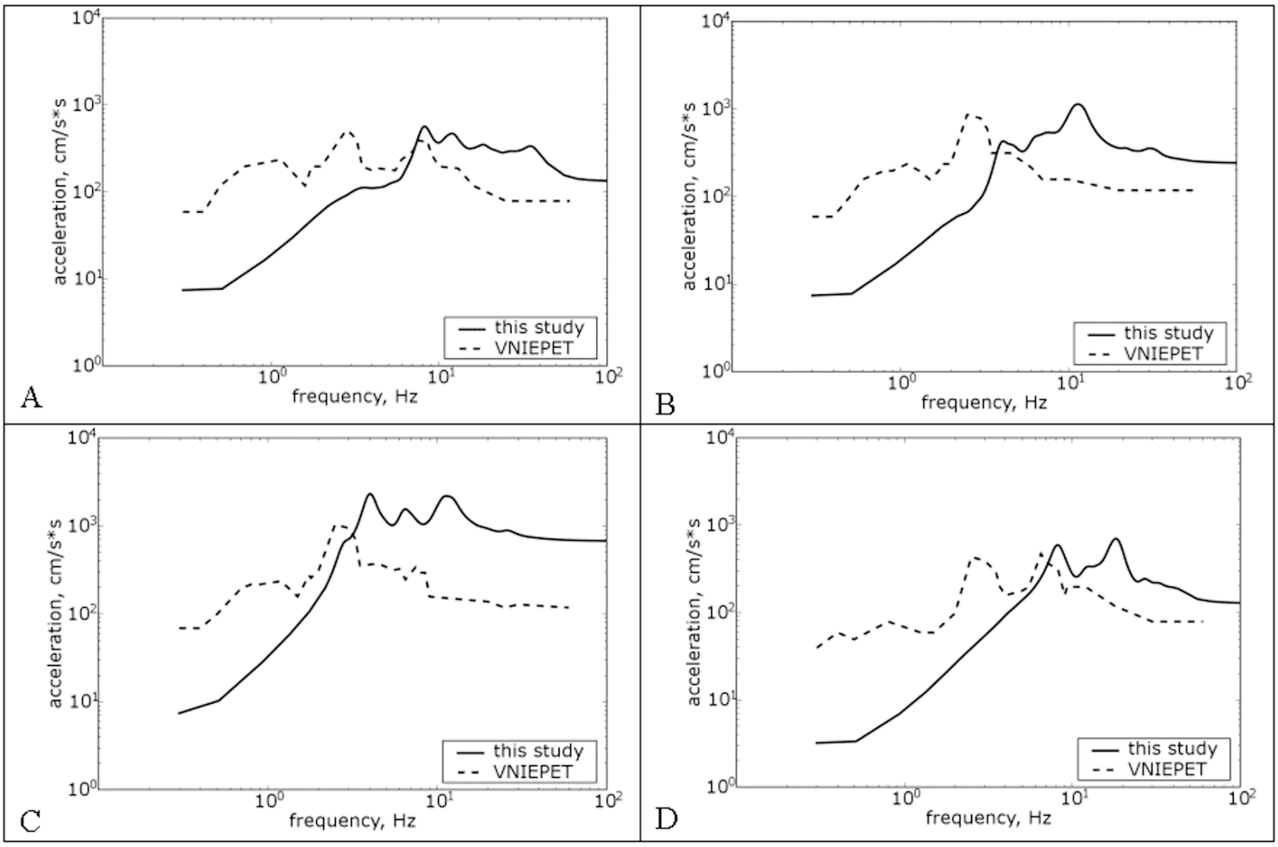

Fig. 7. In-structure acceleration response spectra at various levels *z*: *a* – horizontal ($z = 6.0$ m), *b* – horizontal ($z = 36.0$ m), *c* – horizontal ($z = 53.0$ m), *d* – vertical ($z = 6.0$ m)

7 pav. Konstrukcijų pagreičių atsako spektrai įvairiose *z* lygiuose: *a* – horizontalus ($z = 6{,}0$ m), *b* – horizontalus ($z = 36{,}0$ m), *c* – horizontalus ($z = 53{,}0$ m), *d* – vertikalus ($z = 6{,}0$ m) and calculation of in-structure acceleration spectra at different building levels. The in-structure spectra are obtained by a direct spectra-to-spectra approach using the BRIGADE/Plus code (BRIGADE, 2003). Three reference levels are examined for the sake of comparison. The first level ($z = 6.0$ m) represents the reactor support level, the second level ($z = 36.0$ m) is the support level of the refuelling machine, and the third level ($z = 53.0$ m) represents the level of the roof structure. The in-structure spectra of the horizontal (oriented east–west) and vertical components were calculated for reference levels using a new free-field seismic input. Here a 5% damping was applied.

The horizontal spectra at different levels (Fig. 7A-C) show a systematic increase in the acceleration with an increasing altitude. A comparison of the results indicates an increasing peak horizontal acceleration with an 11% difference at the lower level and up to 123% at the uppermost level. The peaks are shifted towards higher frequencies at the higher levels. A similar tendency is observed for the vertical component spectra (Fig. 7D).

The newly obtained spectra are compared to the spectra calculated in previous studies for a one-dimensional model (Fig.7), which, moreover, used different Design Basis Earthquake characteristics, i.e. $I = 6.5$ and PGA = 0.075 g, as provided by the Russian Design and Scientific-Research Institute for Complex Energetic Technology (VNIEPET, 1991 – unpublished report). The previous synthetic standard input was calculated using the former Soviet Union design rules (Rules and Standards, 1987). Differences of the new and previous models are considerable. A common feature for all levels is a significantly overestimated seismic load in the low-frequency range (<3–8 Hz depending on the level) of the previous model, while the high-frequency range has a reverse tendency towards a significant underestimation.

CONCLUSIONS

The Baltic region is characterized by a higher seismic potential than previously thought. Furthermore, approaches used in previous seismic risk assessment studies of the Ignalina NPP bear some significant inconsistencies, such as scaling of the far-field seismic records, which lead to overestimation of the long-period spectral values.

The most credible earthquake of the site is estimated at $M_L = 4.6$. It is based on the fact of presence of the large-scale Drūkšiai shear zone close to the nuclear power plant. This zone is compatible to the other fault zones identified within the radius of 150 km, showing a historical seismic activity up to M = 4.6–4.8. Taking into consideration the recent Kaliningrad earthquake (M = 5.0 + 0.3) and uncertainties in estimating the seismic source parameters, the safety margin was incorporated. The Design Basis Earthquake of the Ignalina NPP is accordingly assumed to be as high as $M_L = 5.6$. The calculated design peak ground acceleration is 0.166 g. The maximum spectral acceleration 0.4–0.45 g is defined within the 7–10 Hz frequency range. The Design Basis Earthquake characteristics of the Ignalina NPP are close to those estimated for the Leningrad NPP, which has similar geological conditions. The approaches in evaluating the Design Basis Earthquakes are, however, different, proving the consistency of the methodology used in the INPP site.

The re-evaluation of the Design Basis Earthquake has a considerable effect on the safety assessment of the NPP structures and systems. It was examined by 3-D finite-element modelling of in-structure response spectra for the Unit 2 Rector Building. A comparison showed a considerable difference from the previous estimates, with a higher load in the high-frequency range, whereas much lower values were estimated for the low-frequency range. In this case, despite a higher seismic potential assumed in the new model as compared with the previous estimates, the destructive potential for the reactor building is lower.

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References

ABAQUS, 2003. Version 6.4. Analysis User's Manual, ABAQUS, Inc.

Aizberg R., Garetsky R., Aronov A., Karabanov A., Safronov O. 1999. Seismotectonics of Belarus the Baltic region. *Technika roszukiwań geologisznych. Geosynoptika i gotermia.* Kraków. ***38***. 28–37.

Almenas K., Kaliatka A., and Uspuras E. 1998. Ignalina RBMK-1500. A Source Book**,** extended and updated version, Ignalina Safety Analysis Group, Lithuanian Energy Institute, 1998.

Analysis of initial seismological information of The Ignalina NPP microzoning, VNIPIET, 89-01626, code TACпд-0045-55553.

Seismic Analysis of Safety-Related Nuclear Structures and Commentary. ASCE 4–98. American Socienty of Civil Engineers. 2000.

Aronov A. G., Seroglazov R. R., Aronova T. I. 2005. Kaliningrad earthquake of September 21, 2004 and Seismic hazard forecast in the Belorussian-Baltic Region. *Science and Technology for Safe Development of Lifeline Systems*. October 24–25, 2005, Bratislava, Slovak Republic.1–7.

Bard PY, Bouchon M. 1985. The two-dimensional resonance of sediment-filled valleys. *Bull Seismological Society of America.* ***75****(2).* 519–41.

Bauer R. A., Kiefer J., Hester N. 2001. Soil amplification maps for estimating earthquake ground motions in the Central US. *Engineering Geology.* ***62***. 7–17.

Bommer J. J. 2002. Deterministic versus probabilistic seismic hazard assessment: an exaggerated and obstructive dichotomy. *Journal of Earthquake Engineering.* ***6*** *(Special Issue 1)*. 43–73.

Brangulis A., Kanevs S. 2002. Latvijas tektonika. Riga. 50 p (in Latvian).

BRIGADE/Plus. 2003. Version 1.2. User's Manual, Scanscot Technology AB.

BSSC, 1997. NEHRP Recommended Provisions for Seismic Regulation for New Buildings, Part 1 – Provisions. Building Seismic Safety Council, Washington, D.C. 337 p.

Campbell R. D., Hardy G. S., Ravindra M. K., Johnson, J. J., Hoy A. J. 1998. Seismic re-evaluation of nuclear facilities worldwide: overview and status. *Nuclear Engineering and Design.* ***182***. 17–34.

Cornell C. A. 1968. Engineering seismic risk analysis. *Bull Seis Soc Am. 58(5).* 1583–1606.

Doss B. 1909. Die historisch beglaubigten Einsturzbeben und seismischkusischen phenomene der russischen Ostseeprovinzen. *Beitrage fur Geophysic.* ***BX H1***. Leipzig. 1–24.

Engelbrektson A. 1989. Characterization of Seismic Ground Motions for Probabilistic Safety Analyses of Nuclear Facilities in Sweden. *Transactions of the 10th International SMiRT Conference.* ***K1***. 37–42,

Engelbrektson A. 2000. An approach for probabilistic seismic risk assessment. VBB Report 2107191–1, April 11, 2000.

Eurocode 8. 1998. Design of structures for earthquake resistance.

Garetsky R. G., Aronov A. G., Aizberg R. I., Karabanov A. K., Safronov O. N. 1997. General seismic zoning of the Belarussian-Baltic region. *Doklady Akademii nauk Belarusi.* ***41****(4)*. 98–102.

Grachev A. F. (ed.). 2000. Neotectonics, Geodynamics and Seismicity of Northern Eurasia. United Institute of Physics of the Earth. 487 p.

Grunthal G., Stromyer D. 1996. Rezentes Spannungslfeld und Seismzitat des Baltischen Raumes und angrenzender Gebiete – ein Ausdruck aktueller geodynamischer Prozesse. *Brandenburgische Geowissentschaftliche Beitrage.* 69–76.

Gurpinar A., Godoy A. 1998. Seismic safety of nuclear power plants in eastern Europe. *Nuclear Engineering and Design.* ***182***. 47–58

Idriss I.M. 1990. Response of Soft Soil Sites during Earthquakes. *Proceedings, Memorial Symposium to honor Professor Harry Bolton Seed, Berkeley, California.* ***2***. May.

Ilginytė V. 1998. Seismic activity of Lithuania. *Ph.D. dissertation*. Vilnius. 127 p.

INTERNATIONAL ATOMIC ENERGY AGENCY. 1996. Quality Assurance for Safety in Nuclear Power Plants and Other Nuclear Installations, Safety Series No. 50-C/SG-Q, IAEA,Vienna.

INTERNATIONAL ATOMIC ENERGY AGENCY. 1996. Evaluation of Seismic Hazards for Nuclear Power Plants, Safety Standards Series No. NS-G-3.3, IAEA, Vienna.

INTERNATIONAL ATOMIC ENERGY AGENCY. 2003. Seismic Design and Qualification for Nuclear Power Plants: Safety Guide No. NS-G-1.6, IAEA, Vienna.

INTERNATIONAL ATOMIC ENERGY AGENCY, Consideration of external events in the design of nuclear facilities other than nuclear power plants, with emphasis on earthquakes, IAEA-TECDOC-1347, IAEA, Vienna.

Kijko A., Öncel A. O. 2000. Probabilistic seismic hazard maps for the Japanese islands. *Soil Dynamics and Earthquake Engineering.* ***20***. 485–491.

Krinitzsky E. L. 2003. How to combine deterministic and probabilistic methods for assessing earthquake hazards. *Engineering Geology.* ***70***. 157–163.

Leydecker G., Kopera J.R., 1999. Seismological hazard assessment for a site. in Northern Germany, an area of low seismicity. *Engineering Geology.* ***52***. 293–304.

McGuire R. K., Silva W. J., Kenneally R. 2001. New seismic design spectra for nuclear power plants. *Nuclear Engineering and Design.* ***203***. 249–257.

Musson R.M.W., Henni P.H.O. 2001. Methodological considerations of probabilistic seismic hazard mapping. *Soil Dynamics and Earthquake Engineering.* ***21***. 385–403.

Nikulin V., 1998. Evaluation of some seismic parameters of the Baltic region. *Journal of the State Geological Survey of Latvia.* ***4***. 29–35.

Pačėsa A. 2003. Lietuvos seismologinis monitoringas 2002 metais. *Lietuvos geologijos tarnybos 2002 metų veiklos rezultatai, metinė ataskaita*. Vilnius. 47–49.

Pačėsa A., Šliaupa S., Satkūnas J. 2005. Naujausi žemės drebėjimai Baltijos regione ir Lietuvos seisminis monitoringas. *Geologija.* ***50***. 8–18.

Rules and Standards. 1987. Designing of seismic–resistant nuclear power plants, NP AE G-5-006-87, State Regulatory Body publishers, Moscow.

Schmidt H.-G., Schwarz J., Wuttke F. 1998. Site response studies for low seismicity regions of Central Europe: research strategies in support of code development. *Soil Dynamics and Earthquake Engineering.* ***17***. 459–464.

Seed H. B., Idriss I. M. 1970. Soil Moduli and Damping Factors for Dynamic Response Analysis, Report No. UCB/EERC-70/10, Earthquake Engineering Research Center, University of California, Berkeley, December, 48 p.

Semblata J. F, Duval A. M, Dangla P. 2002. Seismic site effects in a deep alluvial basin: numerical analysis by the boundary element method. *Computers and Geotechnics.* ***29***. 573–585.

Silva W. J., McGuire R., Costantino C. 1999. Comparison of site specific soil UHS and soil motions computed with rock UHS. *Report to the OED-NEA workshop Nov.*

Silva W. J., Youngs R. R., Idriss I. M. 2000. Development of design response spectral shapes for central and eastern USA (CEUS) and western US (WUS) rock site conditions. *Proc.of the OECE-NEA Workshopon Engineering Characterization of Seismic Input Nov.15–17,1999 NEA/CSNI/R(2000)2.*

Sim L., Bryantseva G., Karabanov A. K., Levkov E., Aizberg R. 1995. The Neotectonic stress of Belorus and the Baltic countries. *Technika Poszukiwań Geologicznych.* ***3***. Kraków. 53–56.

SKI Technical Report 92:3. 1992. Characterization of seismic ground motions for probabilistic safety analyses of nuclear facilities in Sweden. *Summary Report.*

Sokolov, V., Loha, C.-H., Wen, K.-L. 2001. Site-dependent design input ground motion estimations for the Taipei area: a probabilistic approach. *Probabilistic Engineering Mechanics*. ***16***. 177–191.

Šliaupa S. 1996. Major neotectonicaly active fault zones in Lithuania. *Litasfera*. ***5***. Minsk. 108–115.

Šliaupa S., Ershov A. 2000. Influence of the lithosphere strength variations to geometry of the Baltic basin. *Geophysical Journal*. ***22(4)***. Kiev. 128.

Šliaupa S. 2002. Impact of last glaciation on stress regime and fault activity of the Baltic region. *Geologija*. ***39***. 20–34.

Šliaupa S., Ilginytė V. 2000. Seismicity in Lithuania: evaluation of external sources. *Defence Technologies from Lithuania*. Vilnius: 34–35.

Šliaupa S. 1996. Major neotectonicaly active fault zones in Lithuania. *Litasfera*. ***5***. Minsk. 108–115.

Šliaupa S., Bitinas A., Zakarevicius A. 2005. Predictive model of the vertical movements of the earth's surface with respect to the land use of the Lithuanian coastal area. *Social Strategies*. ***40***.

Stirpeika A. 1999. Tectonic evolution of the Baltic Syneclise and local structures in the South Baltic region with respect to their petroleum potential. Vilnius. 112p.

Ŗafak E. 2001. Local site effects and dynamic soil behavior. *Soil Dynamics and Earthquake Engineering*. ***21***. 453–458.

USNRC. 1993. Design response spectra for seismic design of nuclear power plants. *Regulatory Guide 1.60, Revision 1, December*.

USNRC, 1997. Identification and characterization of seismic sources and determination of safe shutdown earthquake ground motion. USNRC, Regulatory Guide 1.165, March.

Van Gelder P. H. A. J. M., Varpasuo P. 1998. Bayesian Seismic Hazard Assessment for a Nuclear Power Plant. *Safety and Reliability*. ***2***.1437–1443.

Varpusuo P., Saari J., Nikkary Y. 2001. Seismic hazard and ground motion for Leningrad NPP site. *Transactions, SMiRT 16*, Washington DC. Paper # 1342. 1–8.

Watabe M., Ohkawa L., Jido J., Oguro E., Chiba O., Tohdo M., Hatori T. 1988. Simplified seismic analysis methods in Japan. 1–8.

Zakarevičius A., Stanionis A., Šliaupa S., Stephenson R. 2005. Crustal deformations of the GPS polygon of the Ignalina NPP: Application of finite element modeling for geodynamic implications.D. Cygas, K.D. Froehner (eds.) *Environmental Engineering, 6th International Conference, Selected Papers*. ***2***. Vilnius. 1041–1047.

Zakarevičius A. 1999. Investigation of the recent movements earths crust in the territory of the Lithuania. *Summary of research report presented for habilitation*. Vilnius: Technika: 35 p.

Авотиня И., Боборыкин А. М., Емельянов А. П., Силдвяе Н. Н. 1988. Каталог исторических землятрясений Беларусии и Прибалтики. 1984 г. Сейсмологических станций "Минск" (Плещеници) и "Нароч". *Сейсмологический бюлетень*. Минск. 126–137.

Медведев С.В. 1968. Сейсмическое районирование СССР. Москва: Наука. 476 с.

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PROJEKTUOJAMAS IGNALINOS AE ŽEMĖS DREBĖJIMAS

Santrauka

Mažo aktyvumo regionų seisminio potencialo įvertinimas yra ypač sudėtinga problema. Kadangi esamos metodologijos remiasi duomenimis, surinktais iš seismiškai aktyvių regionų, šių duomenų pritaikymas mažo aktyvumo rajonams yra diskutuotinas. Be to, seismologinės informacijos trūkumas (pavieniai istoriniai žemės drebėjimai ir reti seisminių įvykių instrumentinio registravimo duomenys) taip pat labai mažina seisminio potencialo įvertinimo patikimumą. Ignalinos AE, esanti Rytų Europos kratone, buvo statyta minimalaus seisminio aktyvumo sąlygoms. Po statybos elektrinė buvo kelis kartus stiprinama siekiant sumažinti seisminę riziką, nes pagal seismotektoninę informaciją, gana pavojingi žemės drebėjimai nėra išimtis ir Baltijos regione. Visgi, kaip rodo neseniai įvykę Kaliningrado žemės drebėjimai (2004 09 21), Baltijos baseino seisminis potencialas nebuvo iki galo įvertintas, ir tai verčia peržiūrėti pavojingiausių objektų seisminį saugumą, pirmiausiai Ignalinos AE. Atsižvelgiant į tai, kad regiono, ir konkrečiai Ignalinos AE ploto, geologinė sandara yra daug geriau žinoma nei turima seismologinė medžiaga, tyrimams pasirinkta deterministinė metodika, skirtingai nuo dažniausiai naudojamos tikimybių metodikos. Kaip rodo detalūs geologiniai ir geofiziniai tyrimai Ignalinos AE rajone, elektrinė yra pastatyta šalia stambios tektoninės zonos, kuri traktuojama kaip seismiškai potenciali struktūra. Atitinkamai prognozuojama artimo žemės drebėjimo galimybė (židinys po elektrine). Projektuojamas žemės drebėjimas įvertintas $M_L = 5,6$ ($I_0 = 7,5$), hipocentrinis gylis – 10 km. Atitinkamai buvo perskaičiuoti plyno lauko virpesių spektrai Ignalinos AE antrojo bloko aikštelei. Skaičiavimai paremti priklausomybėmis, nustatytomis artimiems žemės drebėjimams Japonijoje. Ankstesniuose tyrimuose dažniausiai naudoti tolimų žemės drebėjimų duomenys lėmė reikšmingas klaidas, ypač žemų dažnių intervale, kuris yra labai svarbus pastatų dinaminiam stabilumui. Atsižvelgta ir į specifines Ignalinos AE grunto savybes. Nustatytas grunto 0,166 g virpesių pikas. Tai aukštesnė reikšmė už TATENA rekomenduojamą minimalią 0.1 g apkrovą vertinant elektrinių seisminį saugumą. Maksimalūs spektriniai pagreičiai apskaičiuoti 7–10 Hz intervalui. Ignalinos NPP plyno lauko spektrai buvo palyginti su Leningrado AE projektuojamo žemės drebėjimo spektrais (geologinės sąlygos panašios). Nepaisant žymių metodologinių skirtumų, gautas geras atitikmuo. Remiantis naujais spektrais, apskaičiuotos sintetinės projektuojamo žemės drebėjimo seismogramos.

Remiantis naujai apskaičiuotais projektuojamo žemės drebėjimo plyno lauko spektrais, buvo modeliuoti Ignalinos AE antrojo bloko struktūrų skirtingų aukštų atsako spektrai. Modeliavimui naudotos 3-D baigtinių elementų technologijos. Rezultatų palyginimas rodo reikšmingus skirtumus tarp ankstesnių ir naujų įvertimų. Skirtumai apima tiek virpesių pagreičio piko reikšmes, tiek ir spektrų formą. Pastarosios rodo gerokai mažesnes seismines apkrovas žemų dažnių intervale naujai perskaičiuotuose spektruose, tuo tarpu aukštų dažnių pagreičiai yra didesni.

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Эугениюс Ушпурас

ПРОЕКТНОЕ ЗЕМЛЕТРЯСЕНИЕ ДЛЯ ИГНАЛИНСКОЙ АЭС

Резюме

Оценка сейсмического потенциала для регионов малой сейсмической активности является особенно сложной проблемой, так как имеющаяся методология опирается на данные сейсмически активных регионов, и использование таких данных в сейсмически малоактивных районах представляется спорным. Кроме того, недостаток сейсмологической информации (единичные исторические землетрясения и данные инструментальной регистрации редких сейсмических происшествий) также снижают надежность оценки сейсмического потенциала. Игналинская АЭС, находящаяся на Восточно-Европейском кратоне, была сооружена в условиях минимальной сейсмической активности. Впоследствии электростанция несколько раз укреплялась для снижения сейсмического риска, этого требовала накапливаемая сейсмотектоническая информация, которая показывала, что достаточно опасные землетрясения не исключены и в Балтийском регионе. Все же, как показало недавнее Калининградское землетрясение (21.09.2004), сейсмический потенциал Балтийского бассейна был неоценен, что заставляет пересмотреть сейсмическую безопасность таких объектов, как Игналинская АЭС. Поскольку геологическое строение площади под Игналинской АЭС известно значительно лучше, чем сейсмологические материалы, для исследований выбрана детерминистическая методика, отличающаяся от часто применяемой вероятностной методики. Как показали детальные геологические и геофизические исследования, Игналинская АЭС построена вблизи от крупной тектонической зоны, которая трактуется как сейсмически опасная структура. Прогнозируется возможность близкого землетрясения (очаг под станцией). Проектное землетрясение оценивается следующим образом: M_L = 5,6 (I_o = 7,5), глубина эпицентра – 10 км. Соответственно были рассчитаны колебательные спектры свободного поля площадки второго блока Игналинской АЭС. Расчеты подтверждены зависимостями, установленными по землетрясениям в Японии. Ранее в исследованиях часто использовались данные дальних землетрясений, что предопределяло значительные ошибки, особенно в интервале низких частот, очень важных для динамической стабильности строений. Также рассмотрены специфические свойства грунта Игналинской АЭС. Установлен пик колебания грунта – 0,166 г. Это значение выше рекомендуемой МАГАТЭ минимальной нагрузки 0,1 г, определяющей сейсмическую безопасность станции. Максимальные спектральные ускорения рассчитаны в интервале 7–10 Гц. Спектры свободного поля Игналинской АЭС сравнивались со спектрами проектных землетрясений Ленинградской АЭС, расположенной в аналогичных геологических условиях. Получено хорошее соответствие, несмотря на значительные методологические различия. На основе новых спектров были рассчитаны синтетические сейсмограммы проектного землетрясения.

По новым рассчитанным спектрам свободного поля проектного землетрясения моделировались спектры структур ответа второго блока Игналинской АЭС на различных этажах. Для моделирования использовались технологии 3-D конечных элементов. Сравнение результатов показало значительное различие между старой и новой оценками. Различия касаются и значений пиков колебаний ускорения, и формы спектров. Последние в заново рассчитанном спектре показывают меньшую сейсмическую нагрузку в интервале низких частот и большее ускорение в высоких частотах.