SEISMIC HAZARD AND GROUND MOTION FOR LENINGRAD NPP SITE

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ABSTRACT

The paper is part of the project Leningrad NPP In-depth Safety Analysis. The aim of the paper is to develop the seismic hazard curves and the spectral shape for the ground motion at LNPP site.

The input data for the study consists of two earthquake catalogs and two sets of seismic ground motion recordings. The earthquake catalogs are FENCAT and FSU catalog. The first catalog is compiled and maintained by the Institute of Seismology of Helsinki University for Fennoscandian region. The second catalog for the former Soviet – Union territory was compiled by late professor Shebalin from Russian Academy of Sciences. The attenuation data used in the study was collected from two intra-plate, moderate seismicity, pre-cambrian rock regions judged to be similar with target region. These regions were Saguenay region from eastern Canada and Newcastle region from western Australia. The source effects characterization was done with the aid of Richter's a and b parameters calculated on the basis of epicenter locations and magnitudes given in the FENCAT and FSU catalogs. The attenuation relationships presented in tabular form were developed on the basis of the equation form given by Dahle, Bungum and Kvamme. The coefficients in the attenuation relations for 10 different spectral frequencies were calculated by non-linear regression.

The hazard assessment methodology was standard approach utilizing Poisson process assumption of for earthquake occurrence. The investigated region was divided into separate source areas. The seismicity of sources was evaluated in terms of a and b parameters. Attenuation relatioships were determined and the seismic hazard in terms of spectral acceleration frequencies for the site was determined.

The last step of the analysis was the development of synthetic ground motion using the uniform hazard spectral shape developed in the first part of the study. The results of the hazard assessment were presented in the form of the hazard curve in terms peak ground acceleration and in terms of uniform hazard spectral shape for the mean return period of one hundred thousand years. The synthetic ground motion was presented in the form two horizontal and one vertical acceleration time histories fitted to match the uniform hazard response spectrum.

INTRODUCTION

The purpose of the present work is the estimation of seismic hazard on the Leningrad nuclear power plant (NPP) site in Sosnovy Bor. The site is in the southeastern coast of the Gulf of Finland, in northwestern Russia. Regions covered with Vendian and Phanerozoic Sediments surround the southern and eastern Fennoscandian shield [1]. The southeastern edge of the Precambrian Fennoscandian Shield runs through the southern Gulf of Finland. The NPP site is close that edge, south of it. The sedimentary cover is a thin layer (< 1km) on top of Precambrian basement above the general depth of earthquakes. Because there are no registered strong motion acceleration recordings of earthquakes in NW Russian and Finland, the earthquake recordings from Saguenay and Newcastle regions from Canada and Australia were taken as sources of initial data because of their geological and tectonical similarity to the Gulf of Finland region. The probabilistic seismic hazard assessment consists of three parts: 1) source effects, 2) path effects, and 3) site effects. Theoretical bases of determination of seismic hazard, seismicity of the Gulf of Finland region, initial data on earthquakes and techniques of their processing, are considered below.

REGIONAL SEISMICITY IN FENNOSCANDIA

Because earthquakes of the Gulf of Finland region tend to occur in the Precambrian basement, it can be concluded that the seismicity of region is mainly of the same origin as in Finland. Finland is situated on the Fennoscandian shield. According to the fault plane solutions of earthquakes, the push from the North Atlantic Ridge in the NW-SE direction seems to be the major stress related to the seismicity of Finland and of the Gulf of Finland region as well. Other factors of the stress field, such as glacial rebound and local seismotectonics, are more local. Earthquake recurrence rates in Fennoscandia are very low if compared with plate boundary regions worldwide. Nonetheless, Fennoscandia is an active seismic region, albeit at low earthquake recurrence rates and with relatively low magnitudes. The earthquake catalogue for Northern Europe (FENCAT), maintained by the Institute of Seismology of the University of Helsinki, was used in this study [2]. This catalogue encompasses the whole of Fennoscandia and adjacent areas inside a window of about 55-80°N and 10°W-45°E. The catalogue includes all documented earthquakes in the region since 1375. Although instrumental earthquake observations started in Finland in the 1920's, local short period recordings started in 1956 [3]. The events in Finland and in Fennoscandia have been predominantly instrumentally located since the mid 1960's [2]. The instrumental magnitudes are based on the Richter's classical local magnitude scale, M_L, modified for the Fennoscandian region. The uncertainty of macroseismic magnitudes is assumed to be 10% at best [2]. The surroundings of the Gulf of Finland have been inhabited throughout the period of observed seismicity in the study area. This means that the Gulf of Finland region comprises an area with a quite accurate record of its historical earthquakes. Later, the higher density of seismic stations has improved the detection capability and location accuracy of earthquakes in southern Finland in comparison to the northern Baltic and Russia. However, the overall seismicity of the Gulf area is rather well known. Figure 1 shows that the closest active belts of seismicity are the Swedish coast from the Bothnian Sea to the Bothnian Bay, western Lapland and the northern Bothnian Bay-Kuusamo region. Southern Finland, northern Baltic and northwestern Russia are characterised by relatively low seismicity. However, two NW-SE oriented belts of relatively high seismic activity run through the region [4]. The northern zone of higher activity runs from the southern Bothnian Bay towards Ladoga (B-L). The other active belt (Å-P-P) runs from the Åland archipelago to southeastern Estonia, where it extends to from Paldis to Pskov. The zones are distinguished from their surroundings particularly by the occurrence of relatively large earthquakes (Figure 2). However, the period of pronounced seismic activity from 1920 to 1941 brings out the same seismic belts in southern Finland, but elsewhere as well.

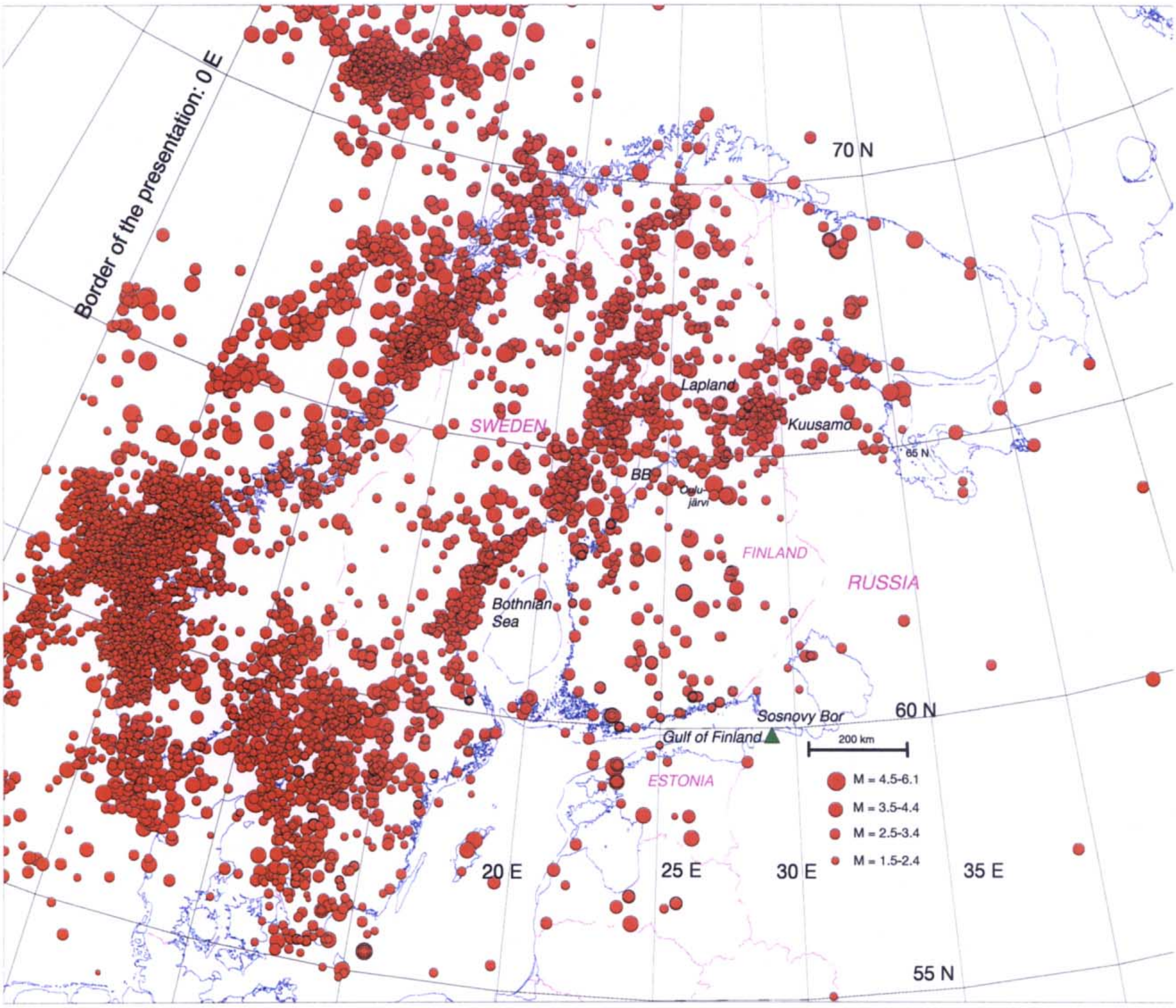

Figure 1 Distribution of the earthquake epicenters in northern Europe (1375-1998) according to FENCAT.

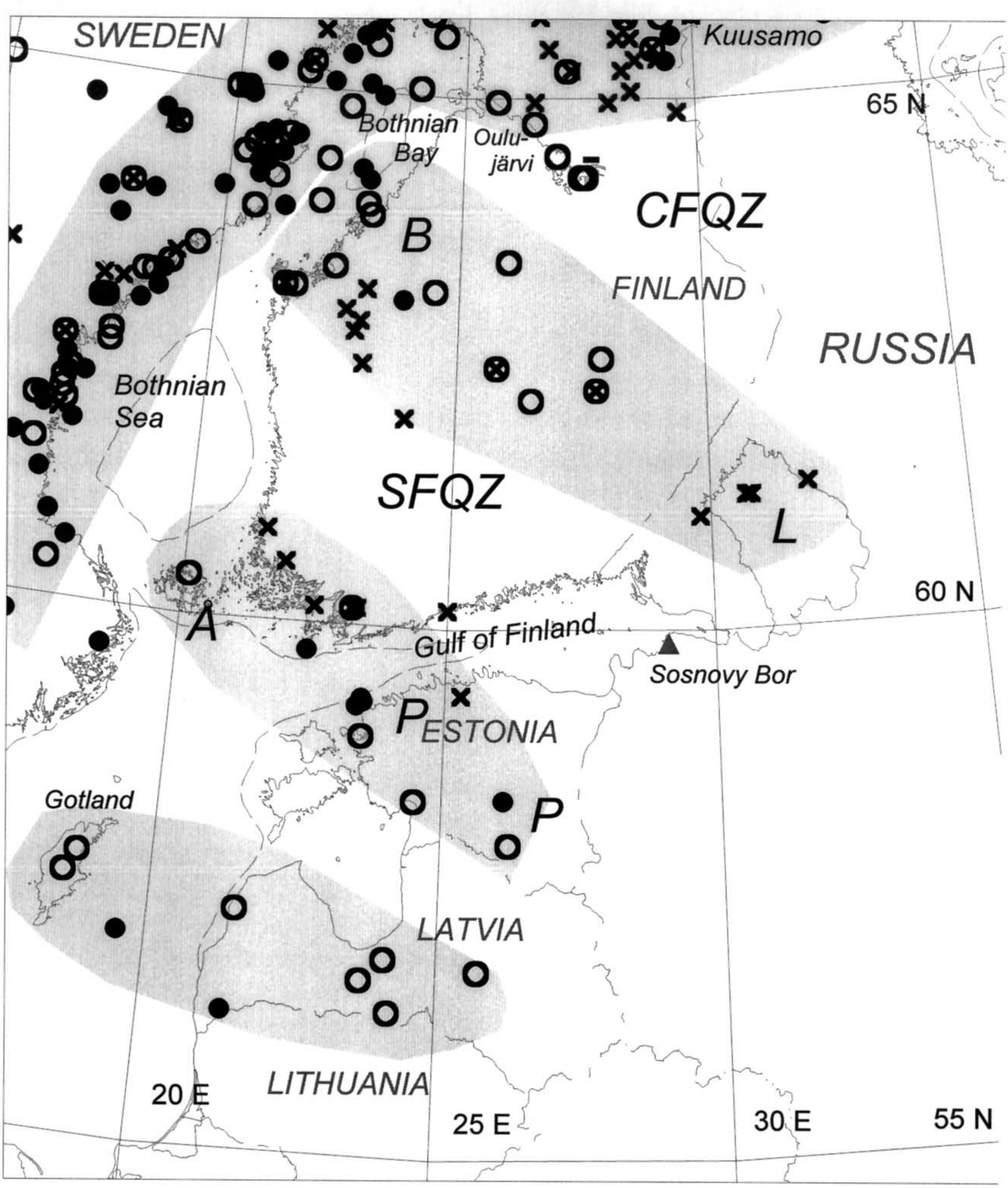

Figure 2 Belts of higher seismic activity (shaded areas). Historical events (1375-1964) with magnitude M ³ 3.5 and instrumentally located (1965-1998) events with magnitude M ³ 3.0 are shown by open and filled black circles, respectively. Crosses denote earthquakes during the period of increased seismic activity 1920-1941. B-L Southern Bothnian Bay - Ladoga Zone, Å-P-P = Åland Archipelago- Paldis-Pskov Zone, CFQZ= Central Finland Quiet Zone, SFQZ = Southern Finland Quiet Zone.

The outlines of the seismic belts applied in this study are presented in Figure 2. Both of the seismically active belts of southern Finland are characterised by long NW-SE oriented fracture zones [4].and [5}. The more prominent seismotectonic zone in eastern coast of Sweden is associated with considerable (300-400 m) vertical displacements along the eastern coast of Sweden [6]. This zone separates the inland Precambrian bedrock from the offshore Phanerozoic sedimentary rocks. In addition to these zones, relatively large events have occurred in the belt from Gotland to Latvia.

QUANTFICATION OF SOURCE ZONE SEISMICITY

The data of seismicity of the territory around Sosnovy Bor with radius 500 km are investigated. This source area is divided into six source zones. As mentioned before, the maximum magnitude applied in the analysis is from FSU-CATALOG [7], if the estimate is larger in that catalog than in FENCAT. The seismic activity parameters in Table 1 are based on FENCAT.

The annual event rates are used directly for seismic hazard analysis, as well the greatest magnitudes registered in the used catalogues for each source zone. Each zone was divided into sub-zones, each of which in its turn represents the quadrilateral area. The vertices of these quadrilateral areas are given with global longitudinal and latitudinal coordinates. These coordinates formed the geometrical initial data for the analysis done by the program SEISRISK III [8] and EZ-FRISK [9].

Table 1 Seismicity parameters for the source zones of the Sosnovy Bor region.

Subset	l	ε	a_{rel}	M_{max} ($M_{max,FSU}$)
1. Russian platform (background)	0.768*	1.340*	1.340	2.9 (-)
2. Å-P-P Zone	0.731	1.097	0.658	4.9(4.3)
3. B-L Zone	0.782	1.459	0.806	4.6(4.7)
4. Bothnian Bay -S. Kuusamo	0.829	1.121	-0.035	4.7(5.1)
5.SFQZ	1.166	2.065	0.788	3.2(3.5)
6. Gotland-Latvia	-0.402	-0.282	0.647	3.5(-)

Lack of data: $a=a_{rel}$ and $b = b_{rel}$

ATTENUATION OF GROUND ACCELERATION

An attenuation relationships developed by Dahle and coworkers [10] of the following form was adopted in this study

$$\ln (y) = c_1 + c_2M + c_3\ln ((R+h)^{1/2})^{-1} + c_4((R+h)^{1/2}) \quad \text{for } R<R_0 \qquad (1)$$

$$\ln(y) = c_1 + c_2M + c_3\ln ((R + h)^{1/2}) + c_4((R+h)^{1/2}) \quad \text{for } R>R_0$$

In Equation 1 y is the strong motion parameter of interest; M is earthquake magnitude, R is the distance from the earthquake epicenter to the site; h is the depth of earthquake focus; and c_1, c_2, c_3 and c_4 are regionally dependent coefficients. This form is a mix of the Dahle model and a widely used model that is presented in reference [11]. The R_0 used in reference [10] was chosen to be 100 km.

Attenuation of strong shaking is not only dependent on distance to the source and earthquake magnitude, but is also dependent on the type of earthquake source and of geologic site conditions. In this study, the ground acceleration registrations used for evaluating coefficients c_1, c_2, c_3 and c_4 were selected from those geological and tectonical regions that were judged to be similar to the investigated area. The second principle for choosing these areas was the availability of registrations. By use this procedure the Saguenay region from Eastern Canada and the Newcastle region from Australia were chosen. These are both moderate seismicity, intraplate regions and the registrations were observed on the bedrock. In case of Saguenay, the bedrock was of Precambrian formations, similar to Fennoscandia, but in case of Newcastle the rock formations were sedimentary rocks. This difference in rock formation was the weakness of Newcastle data in respect of its similarity to Fennoscandia, but in other respects also this area was similar to Fennoscandia. The reason for selecting these similar areas as the source of basic data for attenuation is that there are no strong motion acceleration recordings available from Fennoscandia.

Table 2 The coefficients c1, c2, c3, c4 and the logarithmic standard deviation of the attenuation model presented in Equation 1 and developed on the basis of Saguenay data set from Eastern Canada

Spectral estimate (m/s^2)	Freq. (Hz)	c_1	c_2	c_3	c_4	$\sigma_{\ln A}$
PSA R_0<100km	0.30	-11.83	1.30	-0.234	-0.03688	0.68
PSA R_0>100km	0.30	0.2262	1.30	-3.217	0.0	0.68
PSA R_0<100km	1.00	-11.69	1.30	-0.679	-0.04827	0.59
PSA R_0>100km	1.00	3.966	1.30	-3.805	0.0	0.59
PSA R_0<100km	2.00	-7.475	1.20	0.4457	-0.02088	0.64
PSA R_0>100km	2.00	-4.520	1.20	-2.451	0.0	0.64
PSA R_0<100km	5.00	-3.941	1.00	0.6711	-0.02049	0.62
PSA R_0>100km	5.00	-0.435	1.00	-2.652	0.0	0.62
PSA R_0<100km	7.00	-6.518	1.00	-0.324	-0.04112	0.54
PSA R_0>100km	7.00	6.910	1.00	-2.652	0.0	0.54
PSA R_0<100km	10.0	-5.965	1.00	-0.070	-0.03213	0.49
PSA R_0>100km	10.0	4.5924	1.00	-2.948	0.0	0.49
PSA R_0<100km	15.0	1.6144	1.20	2.7021	0.008361	0.57
PSA R_0>100km	15.0	-0.167	1.20	-2.149	0.0	0.57
PSA R_0<100km	20.0	8.0727	1.20	4.7478	0.03467	0.72
PSA R_0>100km	20.0	-1.639	1.20	-1.896	0.0	0.72
PSA R_0<100km	25.0	13.780	1.20	6.6452	0.061186	0.72
PSA R_0>100km	25.0	-3.982	1.20	-1.463	0.0	0.72
PGA R_0<100km	97.0	7.9296	1.20	4.8645	0.036029	0.49
PGA R_0>100km	97.0	-2.188	1.20	-1.895	0.0	0.49

The attenuation is used as input for SEISRISK III [8] and EZ-FRISK [12] in table form. The parameter in these attenuation tables is the earthquake magnitude and the argument is the hypocentral distance R. The depth of the source information is included in the Saguenay-Newcastle data set. The source depth vary from 1.4 to 29 km, which covers the range of expected source depths in the Sosnovy Bor earthquake catalog source area circles. The total amount of acceleration records used in the study is 36. This number is considered quite adequate for the purposes of the study. The chosen records were compared to those used in Dahle study [10] and EPRI guidelines [13]. The aim in choosing the available intraplate recordings was not obtain largest possible number but the best possible relevance to the target regions geological and seismological conditions: intraplate, precambrian solid rock and moderate seismicity about the same level as prevailing in the Fennoscandian shield.

DECISION TREE APPROACH FOR QUATIFYING UNCERTAINTIES

The code basis for the ground motion estimation in probabilistic seismic hazard studies stipulates the median spectra for mean return period of 100 000 years [14]. The decision three used in the treatment of uncertainties in this study is presented in Figure 3. The first level of the decision tree includes two equally weighted branches called Sosnovy Bor catalog and Loviisa catalog. The meaning of these bars are the 500 km radius source regions around both prospective sites as described in Chapter 4. These bars are called catalogs because they include that particular subset of the parent catalog FENCAT that is located inside each particular source circle. Each catalog in its turn is divided to source areas. Both Loviisa and Sosnovy Bor catalogs have six source areas, which contiguously fill whole source circle drawn around Loviisa, and Sosnovy Bor sites. The source term seismicity felt at particular site is originated in the source areas. The seismicity of source areas is quantified by Gutenberg-Richter magnitude recurrence relationship determined by two parameters: *a* and *b*. Consequently, the four following branch bars in the decision tree characterize the seismicity of source areas. Two different hypotheses are adopted to characterize the source areas, namely, characterization by areas itself or characterization by respective parent catalogs. Characterization by sources means that Richter's parameters are estimated on the basis of events occurring inside each particular source area. Regional characterization means that Richter's *a* and *b* parameters are calculated on the basis of all events occurred inside each particular catalog. Seismic activity parameters estimated for each of the source areas (weight = 0.6) is considered more reliable than the corresponding regional estimates (weight = 0.4). Next eight branches in the decision tree describe various assumptions concerning the maximum possible magnitude inside each source. The determination of maximum magnitudes attributed to source areas is probably the most difficult and controversial aspect of probabilistic seismic hazard analysis. In this study the maximum observed magnitude $\mathrm{MAX}(M_{FENcAT}, M_{FSU\text{-}CATALOG})$ inside each source area was added by 0.1 magnitude units and 0.5 magnitude units. Both these hypotheses were assigned equal weights. In the fourth level of the decision tree branches to 32 branches meaning the assumptions concerning the attenuation of earthquake ground motion. The adopted four variants of the attenuation relationships were models evaluated based on Canadian events longitudinal component recordings, Canadian transversal component recordings, Australian longitudinal and Australian transversal recordings, respectively. The weights for Canadian data were 0.3 and for Australian data 0.2. Each branch end node in logic-tree characterizes the credible alternative inputs to probabilistic seismic hazard analysis and their likelihoods. The end node likelihood can be calculated by multiplying the branch likelihoods leading to end node. The sum of end node likelihoods as well as branch likelihoods at each level must be one.

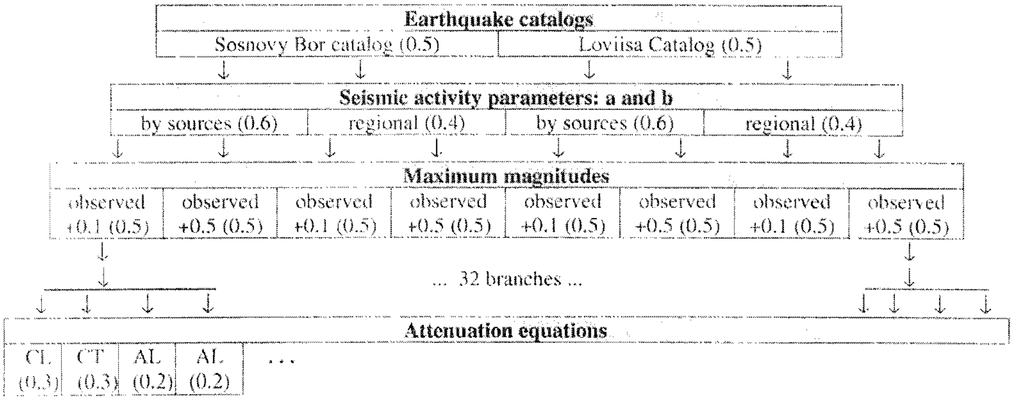

Figure 3 Logic three structure for treating uncertainties. CL = attenuation based on longitudinal recordings from Canada (Saguenay), CT = Canada transversal recordings, AL and AT are corresponding equations from Australia (Newcastle). Weighting coefficients of each branch are in parenthesis.

SITE EFFECTS

The seismic response of the soil structure is a combination of processes on two different scales: The incidence seismic wave operates in the scale of tens or hundreds of kilometers whereas in soil dynamics the scale is of tens or hundreds of meters. In the soil structure, seismic waves can be amplified as they propagate owing to a variety of factors: contrasting impedance between the bedrock and superficial layers due to the conservation of energy; resonance phenomena if the dominant period of the incident wave is close to the fundamental period of the superficial layer; and topographical effects [15]. This modification of ground motion is often called amplification, but also site effect. The flat topography and geological interpretation [1] of the southern coast of the Gulf of Finland indicate that the bedrock is a horizontal plane and the superficial soil layers are horizontally stratified. The lack of topographical effects enables to present the soil characteristics by a column. A given soil column is assumed to be composed of a number of uniform soil layers of arbitrary thickness, each with linear soil properties.

The site effects of the Sosnovy Bor are analyzed with the program CARES [16]. The soil characteristics of the NPP site are presented in Table 3. The total thickness of the soil column is 180 m. The damping ratio used in the analysis is the average of D_p and D_s.

Table 3 Soil characteristics of the Sosnovy Bor site. h= thickness of the layer; Vp and Vs = P- and S-wave velocity; ρ = density; Dp and Ds = damping factors for P- and S-waves; μ=shear modulus.

Layer	h (m)	Vp (m/s)	Vs (m/s)	ρ (g/cm^3)	Dp	Ds	μ (kg/ms^2)
1	2	400	180	1.7	0.55	0.6	5.51E+07
2	4	1100	250	1.8	0.5	0.6	1.13E+08
3	4	1500	350	1.9	0.4	0.5	2.33E+08
4	20	2000	350	2.2	0.15	0.4	2.70E+08
5	30	2200	450	2.3	0.1	0.35	4.66E+08
6	120	2500	650	2.4	0.05	0.005	1.01E+09

The objective of the analysis is to determine the acceleration response spectra at the soil surface, when a specified acceleration time history (accelerogram) is input at the basement (bedrock) of the soil column. The first step of the analysis is to generate an acceleration time history and Fourier components compatible to the design spectrum. The second step deals with seismic waves propagating through the layered soil. Seismic waves are simulated as shear waves traveling vertically through a soil idealized as horizontally bedded layers. The Fourier components of the motion at any depth of the profile can be obtained through a deconvolution/convolution analysis. In this study, the Fourier components of the motion at the surface are calculated. Finally, the acceleration time history and response spectrum at the surface are generated from the results of deconvolution analysis, i.e. from the Fourier components of the surface ground motion.

RESULTS

In the following Figure the unsmoothed free-field acceleration spectra for Sosnovy Bor site corresponding the 100 000 year return period in median is given. Note the strong spectral amplification at 8 Hz correspoding to the resonance frequencies of the soft soil layers on the site

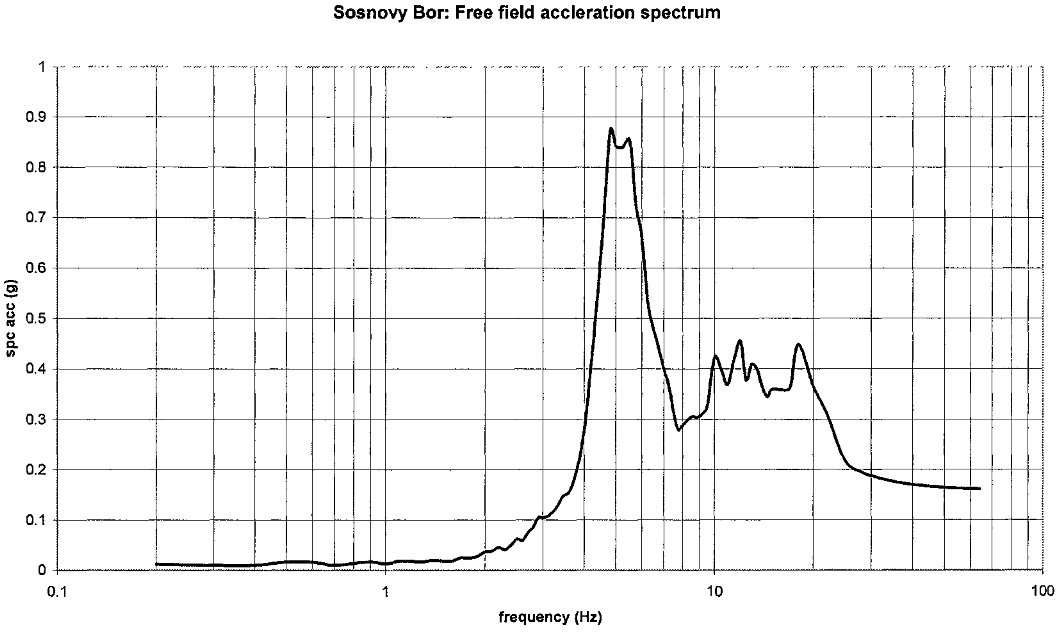

Figure 4 Computed acceleration response spectra at the free field surface (5% damping) cooresponding the 100 000 year return period in median.

CONCLUSION

The seismic hazard and ground motion development for the Leniningrad NPP site at Sosnovy Bor was carried out. The unsmoothed design horizontal acceleration ground response spectrum for the site was generated. The damping coefficient for the spectrum was 5% and the frequency of the earhquake occurence for this spectrum was 10^{-5} in median. The unceratinty in soil charateristics was not yet quantified explicitly. When the site effect uncertainty can be included in the decision tree approach the smooth site specific design spectrum for the ground motion can be developed.

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