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THE SEISMIC SITE HAZARD ASSESSMENT FOR OL3 NPP IN FINLAND

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ABSTRACT

The purpose of the present work is the estimation of seismic hazard in the territory of the nuclear power plant OL3 in Olkiluoto.

Because there are no registered strong motion acceleration recordings of earthquakes in 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 Fennoscandia.

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. The decision three approach is used in the treatment of uncertainties in this study.

The hazard analysis was carried out with the aid of Fortran Computer Program for Seismic Risk Analysis SEISRISK II developed by USGS. The resulting raw site hazard depicting the distribution of the seismic hazard was given in the form 32 curves equipped with appropriate weights.

The end result of the analysis was given in the form of median, mean, 95% - fractile and 5% - fractile curves for horizontal peak ground acceleration amplitudes of 0.001g, 0.005g, 0.01g, 0.05g, 0.07g, 0.1g, 0.2g, 0.3g and 0.4g and for corresponding non-exceedance probabilities.

Keywords: site hazard, mean return period, decision three, peak ground acceleration.

1. INTRODUCTION

The purpose of the present work is the estimation of seismic hazard in the territory of the nuclear power plant Olkiluoto3 in Eurajoki. Because there are no registered strong motion acceleration recordings of earthquakes in 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 Fennoscandia.

The probabilistic seismic hazard assessment consists of three parts: 1) source effects, 2) path effects, 3) site effects. The site effects phase of the study is not relevant to this study because the prospective target sites are located on solid bedrock. Theoretical bases of determination of seismic hazard, questions of seismicity of a southern part of Finland, initial data on earthquakes and techniques of their processing, are considered below.

2. REGIONAL SEISMICITY IN FENNOSCANDIA

Finland is situated on the Baltic shield, which is the one of the seismically quietest areas in the world. 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.

Other factors of the stress field, such as glacial rebound and local seismo-tectonics, 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 [i].

This catalogue encompasses the whole of Fennoscandia and adjacent areas inside a window of about 55-80^{o}N and 10^{o}W-45^{o}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 [ii]. The events in Finland and in Fennoscandia have been predominantly instrumentally located since the mid 1960's [i].

The instrumental magnitudes are based on the Richter's classical local magnitude scale, ML, modified for the Fennoscandian region. The uncertainty of macro-seismic magnitudes is assumed to be 10% at best [i]. Figure 2-1 shows that southern Finland, which is the target area of this study, is characterized by relatively low seismicity.

The most active belts of seismicity close to it are the Swedish coast from the Bothnian Sea to the Bothnian Bay, western Lapland and the northern Bothnian Bay-Kuusamo region. Southern Finland and areas south and east of it are characterized generally by a lower seismic activity. However, two NW-SE oriented belts of relatively high seismic activity run through the region [iii]. 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. However, the period of pronounced seismic activity from 1920 to 1941 brings out the same seismic belts in southern Finland, but elsewhere as well.

Both of the seismically active belts of southern Finland are characterized by long NW-SE oriented fracture zones [iii] and [iv].

The more prominent seismo-tectonic zone in eastern coast of Sweden is associated with considerable (300-400 m) vertical displacements along the eastern coast of Sweden [vii] and [v]. This zone, over 200 km west of Olkiluoto, separates the inland Precambrian bedrock from the offshore Phanerozoic sedimentary rocks.

The study utilizes a similar size of subset of FENCAT for both of the nuclear power plant sites. The seismic characteristics of Finland and examinations of attenuation (Chapter 5) suggest that areas within a distance of 500 km from the nuclear power plant sites are considered large enough to include all significant seismic events.

Within 500 km of the sites, most of the earthquakes are small ($M<5.0$) and well below the threshold of engineering concern. Only one event, which occurred in 1894 ($M=5.1$) in central Sweden can be classified as a moderate ($M\geq5.0$) earthquake.

The highest intensity at the Olkiluoto site is only IV (MSK-64 intensity scale) [ii and vii]. MSK-64 intensity IV is partially described as: felt indoors by many people, outdoors by few, some awakened, vibration is like that due to the passing of a heavily loaded truck; Windows, doors and dishes rattle; Noticeable in standing motor cars [vi]. In the Loviisa site the maximum observed intensity is higher: VI.

Within a distance of 500 km from Olkiluoto, a clear majority (72%) of the seismic events has occurred in Sweden [vii]. The areas in southern Sweden (Telemark-Vänern region) and the eastern coast of Sweden are well known belts of higher seismicity (see e.g. [i]).

These belts are outside the Loviisa data set. Both of the data sets include a small part of the northern Bothnian Bay-Kuusamo seismic belt in the north.

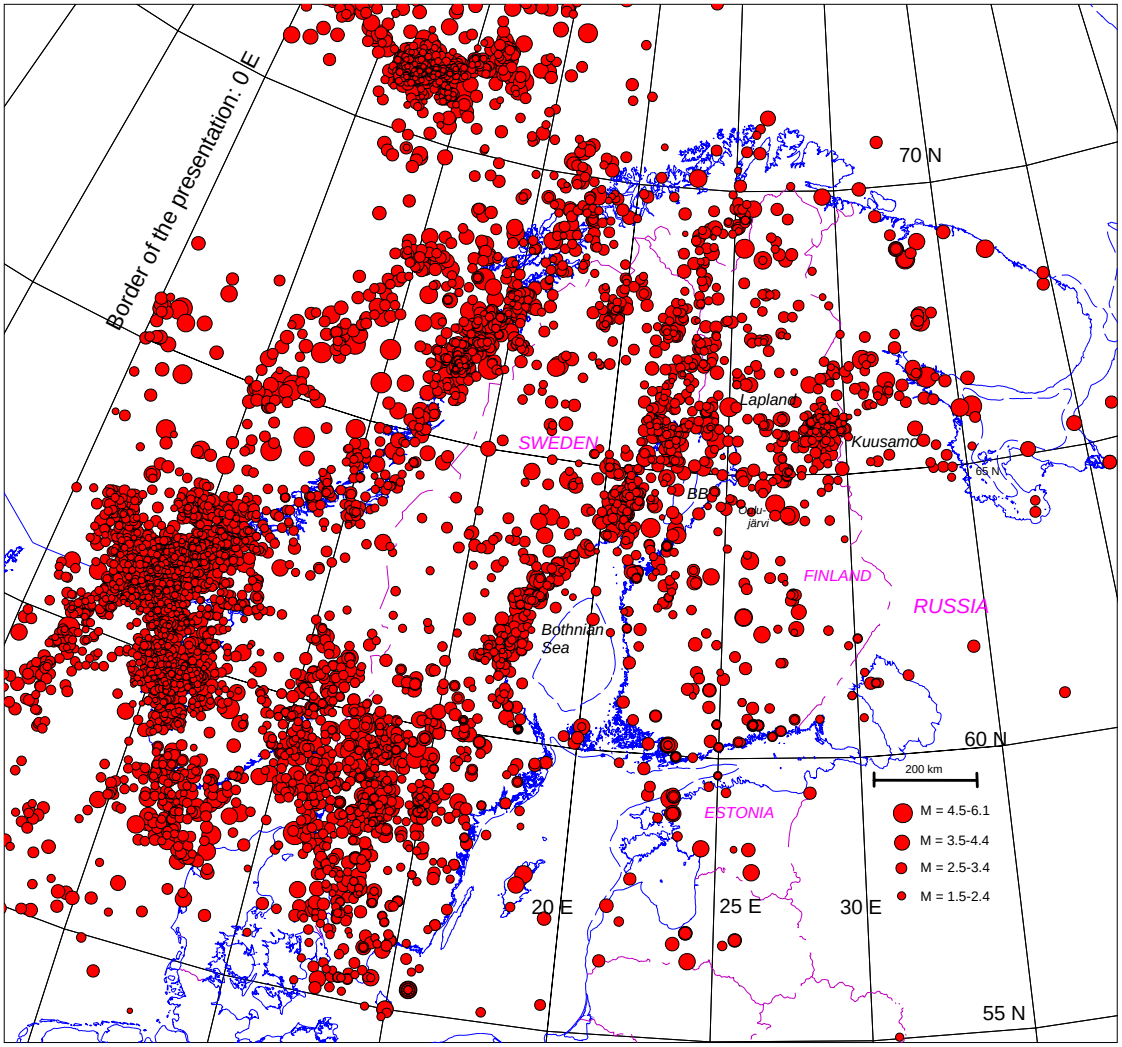

Figure 2-1. Distribution of the earthquake epicenters in northern Europe since 1375 according to FENCAT.

3. SEISMICITY PARAMETERS

Intra-plate earthquakes tend to occur on old zones of crustal weakness reactivated by present stress field. Given the low earthquake recurrence rates and small magnitudes of the Fennoscandian shield region, the earthquake data is not likely to be complete and completeness varies geographically. Local high gain seismic recording stations would be needed to record the small events that characterize most of the regional seismicity.

Since 1750, the number of felt earthquakes in each decade fluctuates but shows a certain continuity of reporting. The beginning of systematic macro-seismic mapping in the 1880'sand the installation of regional seismic network since 1950's are clearly seen in the histogram. The utilization of digital instruments in 1980's caused the latest stepwise increase of the number of observations [viii]. The same facts can be distinguished in the Loviisa data set (Figure 3-1).

Presumably mainly due to the Second World War, there are no reported earthquake observations in Finland from 1942 - 1951. This period is disregarded in calculations of annual seismic activity.

Owing to the long recurrence interval, the current and future seismic hazard assessments will rely strongly on historical seismicity data. The Finnish earthquake data is considered satisfactory after 1880 (see [ii]). This time window is applied to the magnitude range 2<M<4. However, for larger events (M>4.0) this period is coincided too short in relation to the recurrence time of events.

During the historical era, the interpretation is more accurate on land than in the water areas, when relatively small earthquakes are concerned. However, there is a relatively long history of dense population in southern

Finland, Estonia and Central Sweden, especially in the coastal areas. It has been shown [iii] that the radius of perceptivity of 100 km of a Finnish earthquake is related to magnitude of the order of M = 3.8 - 4.0. Therefore it can be concluded, that it is very unlikely, that continental or submarine events larger than M=4.0 have remained undetected for the last two or three centuries. Based on the above judgment, the earthquake catalogue is considered quite representative for magnitudes M> 4.0, since 1750.

In addition to the magnitude frequency distributions based on source area delineation, alternative distributions are calculated. With the scarce data in FENCAT it is not possible to establish statistically reliable parameters for every target area. Therefore the magnitude-frequency distribution of the entire Loviisa data set is scaled to represent the regional seismic belts in proportion to the surface area. These distributions are applied in areas of insufficient statistics and as a branch in the decision tree. In eastern Sweden the results presented by Kijko et al. [viii] are used as a reference distribution. The seismicity parameters within the target areas are presented in Table 3-1.

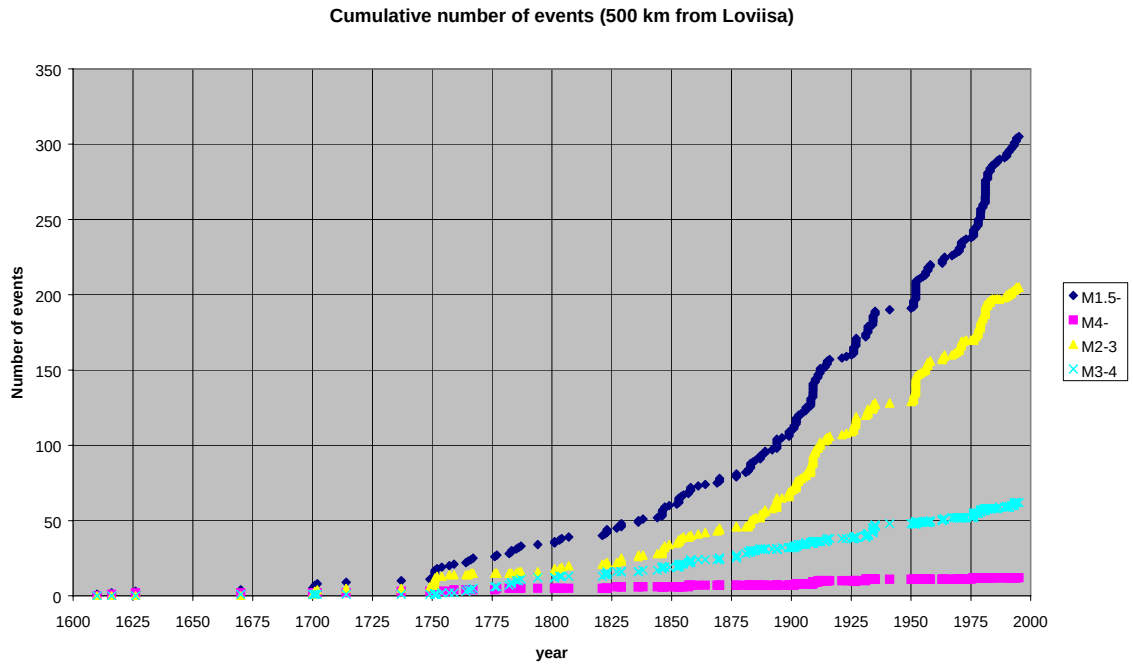

Figure 3-1. Cumulative number of seismic events of the Loviisa data set in four groups: M ≥ 1.5, M = 2 - 3, M = 3 - 4 and M ≥ 4.

Table 3-1. Seismicity parameters for regional source areas

n	**Subregion**	b_n	a_n
1	Central Finland Quiet Zone (CFQZ) + Southern Kuusamo	0.829 ± 0.035	1.121 ± 0.099
2	Southern Bothnian Bay- Ladoga Zone (B-L)	0.782 ± 0.028	1.459 ± 0.090
3	Åland Archipelago - Paldis - Pskov Zone (Å-P-P)	0.731 ± 0.033	1.097 ± 0.101
4	Southern Finland Quiet Zone (SFQZ)	1.166 ± 0.066	2.065 ± 0.179
5	Eastern Sweden	1.173 ± 0.059	3.460 ± 0.213
6	Gulf of Bothnia, Swedish coast (comparison values for the decision tree)	1.26 ± 0.06	3.40 ± 0.2
7	Regional seismicity	0.818 ± 0.016	2.003 ± 0.052

4. DIVISION OF THE SOURCE AREA TO SOURCE ZONES

4.1 Source area delineation for the Olkiluoto site

The data of seismicity of territory around Olkiluoto with radius 500km are investigated. This source area is divided into six source zones presented in Figure 4-1and Table 4-1.

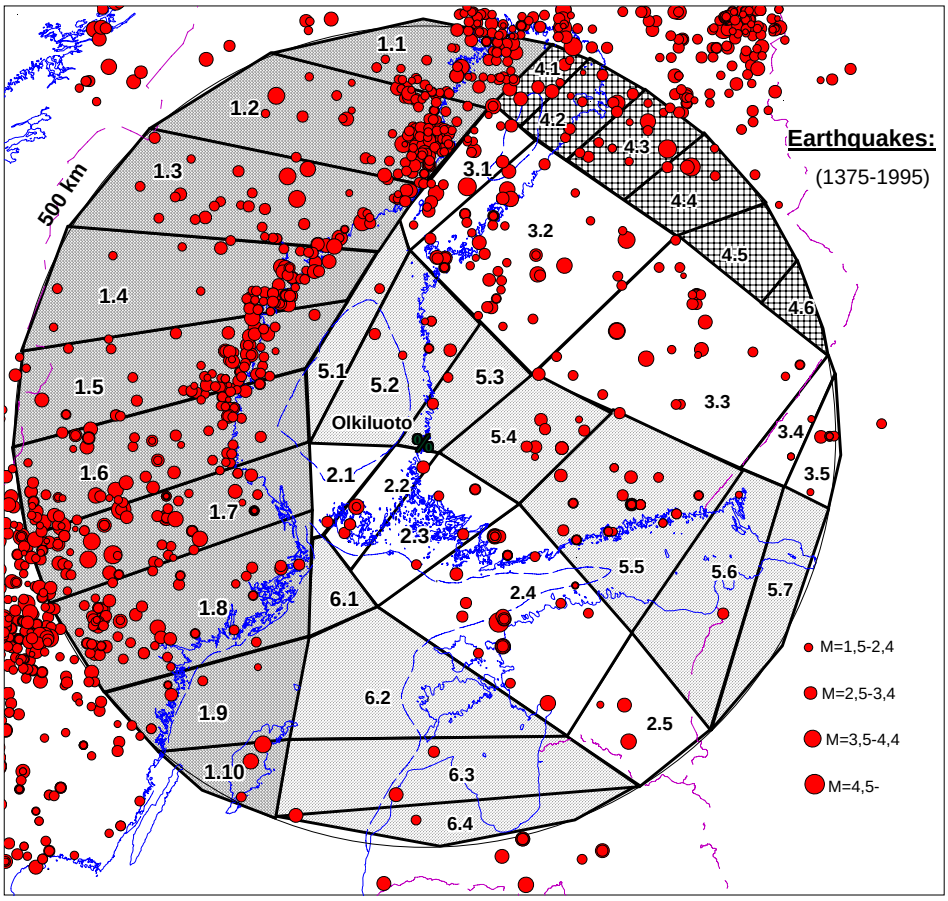

Figure 4-1. The source zone division for Olkiluoto site embedded on the Fennoscandian epicentral for time window 1375-1995 and for magnitudes greater than 1.5. Schematic model for the program SEISRISK III [ix]

Table 4-1. Seismicity parameters for the source zones of the Olkiluoto data set

Source zone	b	a	a_{rel}	M_{max}
1. Eastern Sweden	1.173	3.460	3.642[1)]	5.1
2. Å-P-P Zone	0.731	1.097	1.073	4.9
3. B-L Zone	0.782	1.459	1.192	4.6
4. Bothnian Bay - S. Kuusamo	0.829	1.121	0.810	4.7
5.SFQZ	1.166	2.065	1.230	3.2
6. Latvia	0.818*	1.033*	1.033	3.3

4.2 Attenuation of ground acceleration

The prediction of seismic ground motions in prospective target sites is an essential ingredient in any probabilistic seismic hazard assessment. Its importance is even greater in procedures whose aim is the assessment of the probability of exceedance of ground motion in terms of response spectra for seismic load definition purposes. In opposite to the traditional approach, where a standard normalized design spectrum is anchored to peak ground acceleration at the high frequency asymptote of the spectrum, the uniform risk spectra approach is adopted in this study. This way of estimating response spectra has the advantage of yielding results of equal exceedance probability for all frequencies. In spite of the fact that this method of uniform hazard risk spectra has been available for a long time and that peak ground acceleration for long time has been known to be insufficient to estimate the damage potential and to characterize the seismic load for buildings and structures, the amount of published attenuation equations for other frequencies than peak ground acceleration is scarce. This is true even for plate margin areas and even more so of course for intraplate areas. There are different ways in which strong-motion attenuation relationships can be established:

- Methods, assuming that there is a relationship between intensity and the ground motion parameter to be estimated.
- Methods that are based either on attenuation relationships developed for parallel regions, on relationships developed for parallel regions but adjusted to accommodate local information like source scaling and inelastic attenuation, or on relationships developed from theory, calibrated by available information in terms of local strong-motion data.
- Methods utilizing stochastic models based on random vibration theory in simulating time series or peak parameters such as amplitudes.
- Methods based on conventional regression analysis of observed strong-motion data from the area within which the predictions are intended to be applied.

The Fennoscandia, where seismicity is moderate, is such area where some kind of semi-empirical approach must be taken in the development of attenuation laws. In earlier earthquake hazard assessments for Fennoscandia, a variety of such approaches have been used. This study concentrates on intra-plate areas that are tectonically stable and geologically more uniform than plate boundary areas. A large number of intra-plate strong-motion acceleration recordings have recently become available from several intra-plate regions including eastern North America, Europe, China and Australia, thus providing the opportunity to derive attenuation models by regression analysis of spectral estimates of ground motion. In the following section the derivation of an intra-plate attenuation relationship is described following the presentation given in reference [x]. The study is restricted on modeling results of response spectral estimates for solid bedrock site conditions. In any statistical analysis of sparse data, it is important to consider critically the selection criteria for choosing the data.

The ground motions were estimated from an attenuation relationships of the following form [x],

$$\begin{aligned} \ln (y) &= c_1 + c_2 M + c_3 \ln ((R+h)^{1/2})^{-1} + c_4 ((R+h)^{1/2}) \quad \text{for } R<R_0 \\ \ln(y) &= c_1 + c_2 M + c_3 \ln ((R + h)^{1/2}) + c_4 ((R+h)^{1/2}) \quad \text{for } R>R_0 \end{aligned} \tag{1}$$

In Equation (1) 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 in described reference [ix]. The R_0 used in Equation 5-6 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, intra-plate 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. In Fennoscandia, the earthquakes occur mainly at depths from 5 km to 20 km. The (80%) majority of the hypocenters are in the depth range of 10-20 km [i]. In spite of the small amount of shallow earthquakes they are important when seismic risk is concerned. Therefore the Newcastle events (depths <5 km) complete essentially the data of Eastern Canada with depths from 10 km to 30 km.

For the determination of coefficients, which are included in Equation (1), the method of optimization described in reference [xi] is used. The method implemented in the algorithm of reference [xi] consists in the nonlinear curve-fitting problem that is solved with the aid of the least-squares method.

The initial data for Saguenay events consist of digitized, three component acceleration registrations for eleven Saguenay events, four Miramichi events and some additional registrations for Nahanni1 and Nahanni2 events. The digital SMA recordings for Newcastle events consist of four three component recordings. These events were converted to g units from SMA recordings by conversion coefficient described in reference [xii]. Synthesized recording for Kelunji earthquake complemented the instrumentally recorded Newcastle events. The Kelunji synthesized recording was amplified to magnitude level of 5.6 from the instrumentally recorded event the magnitude 2.3 by methods described in the reference [xiii].

The processing of these materials were carried out by Microsoft Excel software. First, the acceleration histories were plotted on the basis of the recordings. From these plots we choose the ten-second time windows corresponding maximum acceleration peaks. From these acceleration plots the response spectra for 5% damping were computed with the aid of software from reference [xiv].

The spectral ordinates are calculated for longitudinal and transversal earthquake components. The investigated frequency values were 0.3,1, 2, 5, 7, 10, 15, 20, 25 and 97 Hz. The magnitude value for the Saguenay event was 5.8 and the depth focus was 29 km.

The Kelunji synthesized recording were used for spectral calculations after the scaling of the magnitude to the value of 5.6 and the distance to the value of 10 km. The magnitude scaling was carried out according to the relations given in reference [xv] and the distance scaling according to the relations given in reference [xv]. The Miramichi recordings used for spectral calculations were scaled for same magnitude and same depth value as the recordings of Saguenay event with the aid of relations in the reference [xv]. The Kelunji recordings were used to supplement the four Ellalong recordings that are called together the Newcastle recordings in this report because of their vicinity to town of Newcastle in New South Wales, Australia. The two recordings of the Miramichi event were used to supplement the ten Saguenay recordings that are called Saguenay recordings in this report after the name of the main event. In the following figures the attenuation relations for the logarithm of peak ground acceleration or various spectral accelerations are given as well as the attenuation for the peak ground acceleration acceleration ordinates. The figures are for longitudinal and transversal components of Saguenay and Newcastle event, which for the purposes of this study are regarded as independent recordings. For reliable determination of the coefficient c_2 the magnitude data represented in Saguenay-Newcastle data set was too scarce. For that reason the c_2 coefficient was determined on the basis of reference [xv]. The example of attenuation curves for Saguenay dataset is given next:

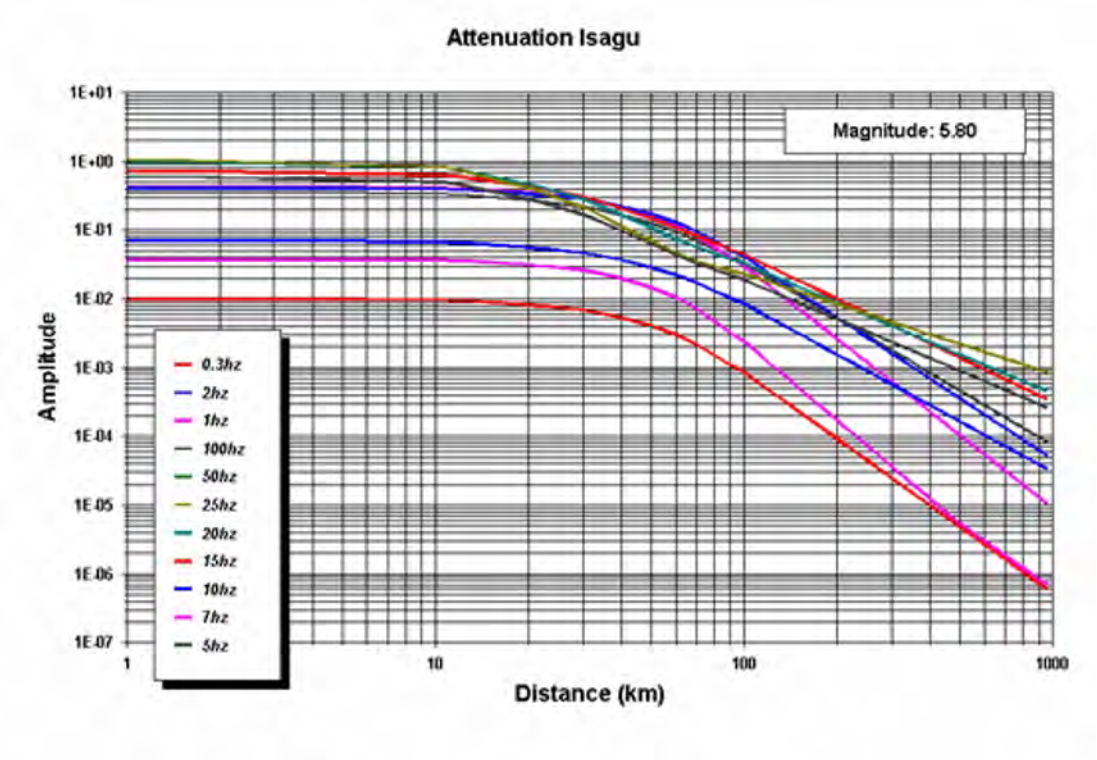

Figure 4-2. Spectral attenuation fit for Saguenay longitudinal component. Damping 5%. Magnitude 5.8.

5. DECISION TREE FOR THE TREATMENT OF 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 [xvi]. The decision three used in the treatment of uncertainties in this study was as follows:

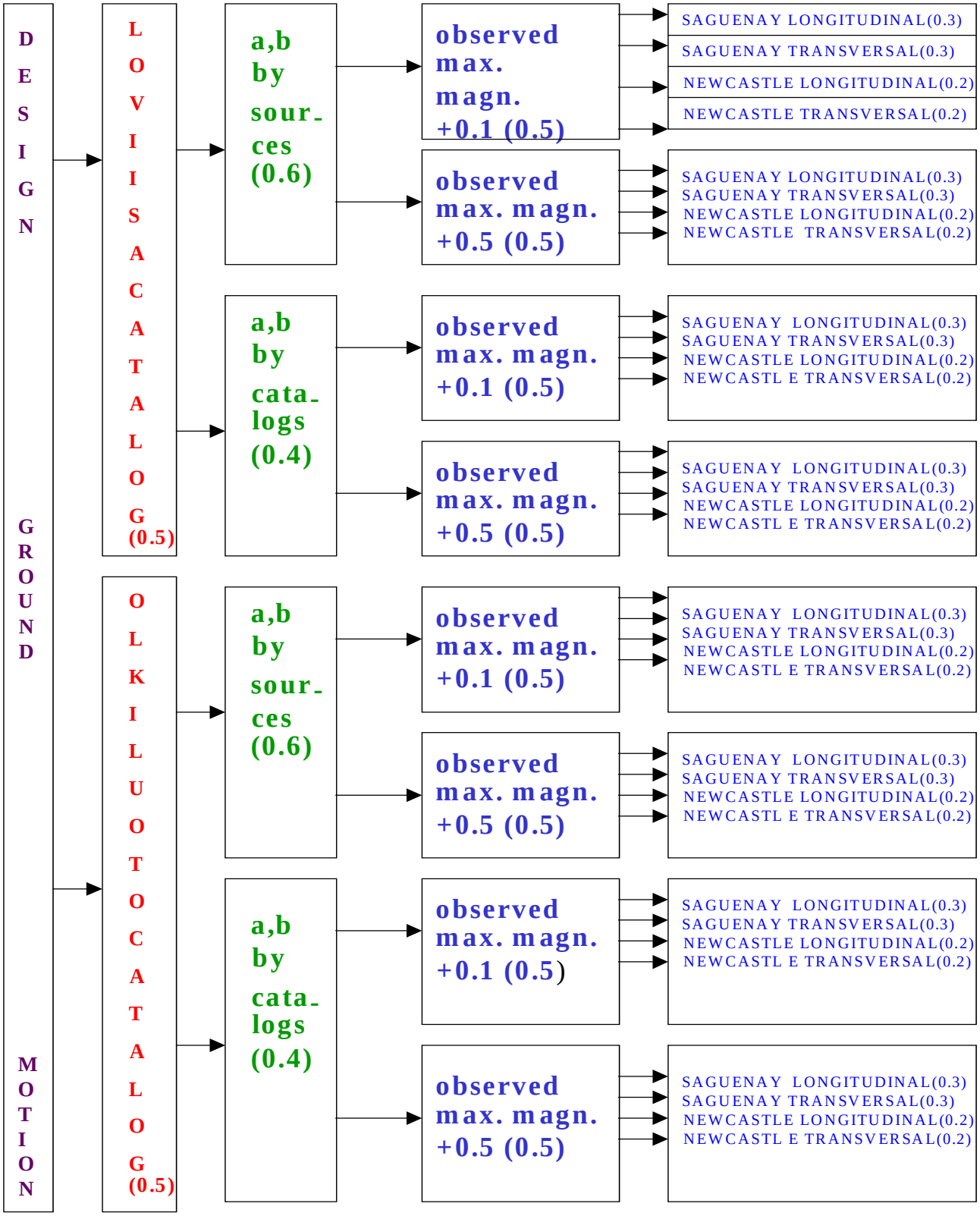

Figure 5-1. Logic three structure for treating uncertainties

In the logic tree the long vertical bar at far left of the diagram summarizes the task at hand, namely, generation of design ground motion for the target window. It branches in two subsequent vertical bars named Loviisa catalog and Olkiluoto catalog. The meaning of these bars are the 500 km radius source regions around both prospective sites. 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 Olkiluoto catalogs have six source areas, which contiguously fill whole source circle drawn around Loviisa, and Olkiluoto 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 vertical 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 areas means that Richter's b parameters are estimated on the basis of events occurring inside each particular source area. Characterization by catalogs means that Richter's b parameters are calculated on the basis of events occurring inside each particular catalog. 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 after the suggestion of reviewers the maximum observed magnitude inside each source area was added by 0.1 magnitude units and 0.5 magnitude units meaning that the maximum possible magnitude was twice as large as the maximum observed or five times as large as the maximum observed. Both these hypotheses were assigned equal weights. Also both catalogs used in the decision tree were assigned equal weights and the weights for hypotheses for Richter parameters were assigned as follows: 0.6 for determination by source areas and 0.4 for determination by respective catalogs. Each box in the fourth level of the decision tree branches to four branches meaning the assumptions concerning the attenuation of earthquake ground motion. The adopted four variants of the attenuation relationships were models evaluated based on Saguenay events longitudinal component recordings, Saguenay transversal component recordings, Newcastle longitudinal and Newcastle transversal recordings, respectively. The weights for Saguenay were 0.3 and for Newcastle 0.2.Each branch end node in logic-tree of Figure 5-1characterize 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.

6. RESULTS

By preparing the initial data according to the previous section, the further analysis was carried out on Fortran Computer Program for Seismic Risk Analysis described in reference [ix]. The resulting raw site hazard curves are given in following figure:

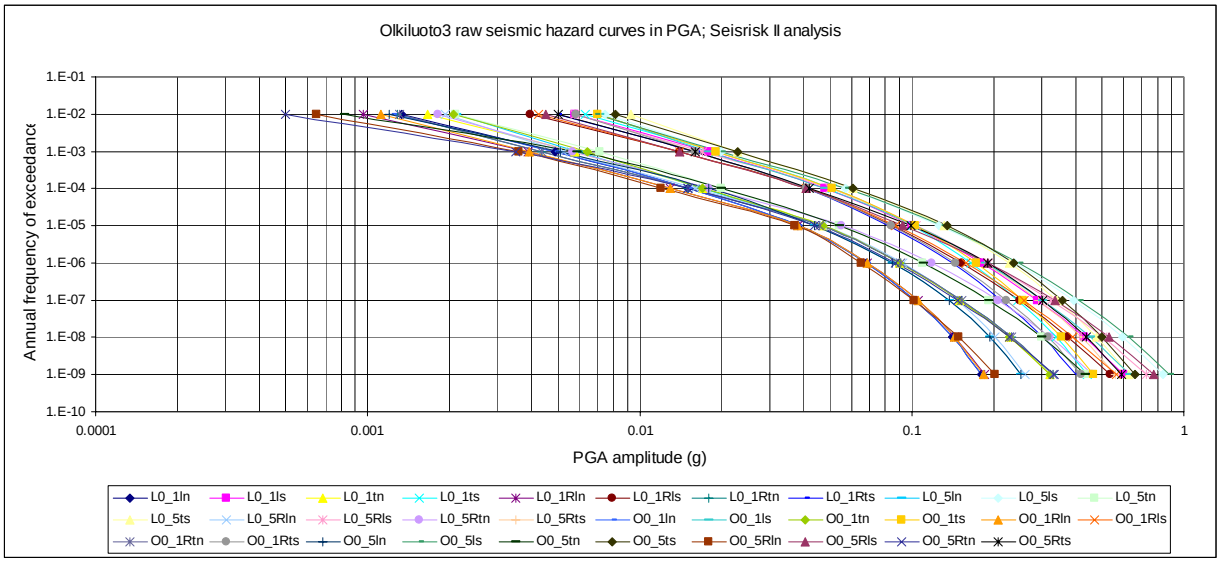

Figure 6-1 Seismic Hazard in PGA for Olkiluoto3 site. Presented are the 32 raw hazard curves forming the hazard distribution at site according to the decision tree presentation of Figure 5-1

The site hazard with confidence bounds for Olkiluoto site are given in the following figure:

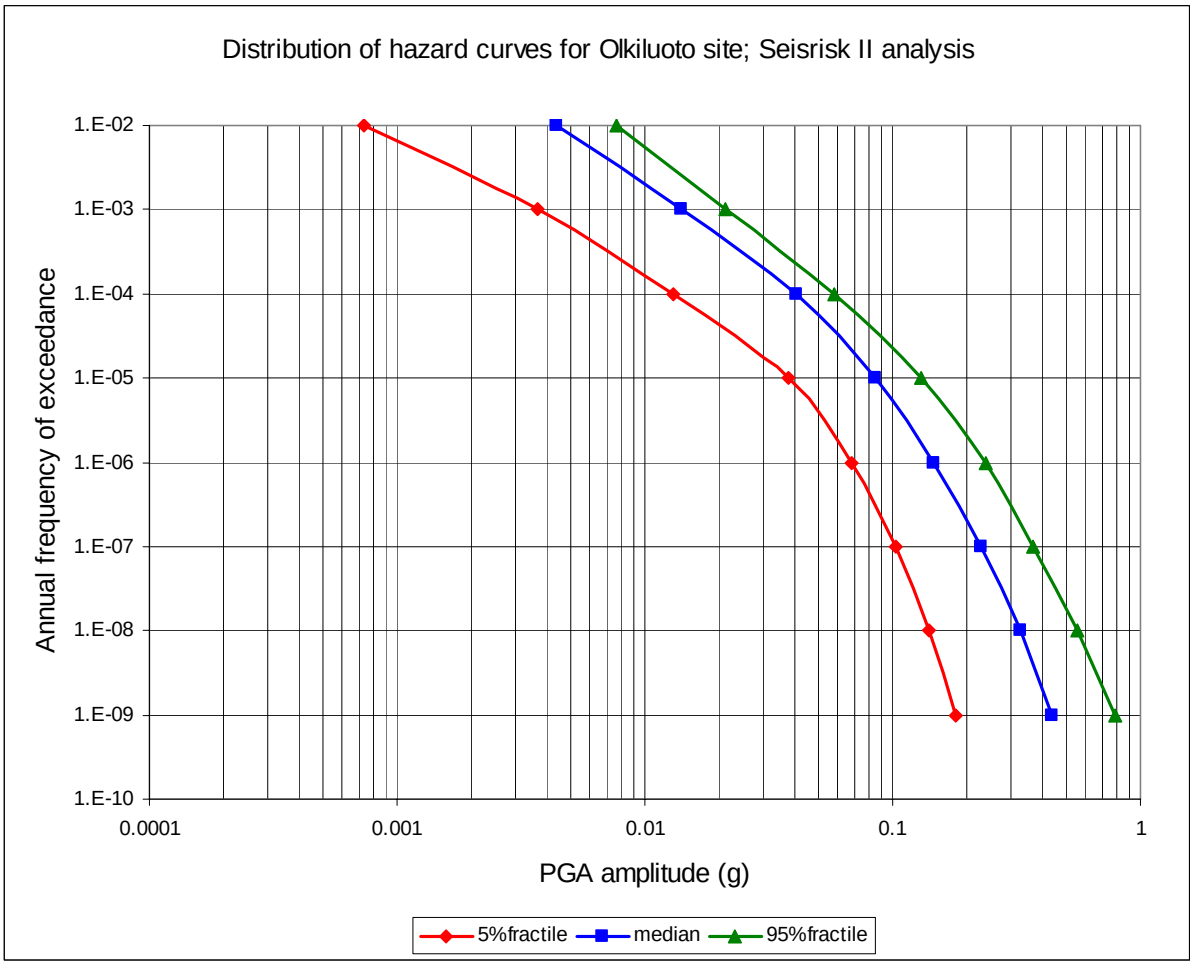

Figure 6-2 Hazard curves with confidence bounds (5%, median, 95%) for Olkiluoto site

7. CONCLUSION

The Olkiluoto site hazard has been developed with the aid of probabilistic seismic hazard assessment methodology. Two different datasets were utilized in the study. The utilized datasets were Loviisa dataset (collected within 500km distance from Loviisa site) and Olkiluoto dataset (collected within 500km distance from Olkiluoto site).

The ground motion attenuation was developed by using the strong motion acceleration records from the areas that were estimated to be similar with the investigated region in seismicity characteristics and in tectonic features.

The obtained median peak ground acceleration value for the 1.E-5 annual frequency of exceedance is 0.085g.

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