RE-EVALUATION OF SEISMIC HAZARD AT LOVIISA AND OLKILUOTO NPP SITES

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Abstract

There are four operating nuclear power plant (NPP) units in Finland. The power company TVO Ltd has two operating 840 MWe BWR units and one 1600 MWe EPR unit under construction at the Olkiluoto site on the south-western coast of Finland. Fortum Ltd power company has two 500 MWe VVER 440 units at the Loviisa site on the southern coast of Finland. In addition to this, Fennovoima Ltd plans to build a 1200 MWe VVER unit at the Hanhikivi site on the Gulf of Bothnia of Finland.

The purpose of this paper is to describe how the seismic hazard was re-evaluated at the Loviisa nuclear power plant site using a probabilistic approach. Similar procedure was applied for the Olkiluoto site as well. Epistemic uncertainties were incorporated to hazard evaluation by a logic tree that comprised five levels: seismic source area model, seismicity parameters β and λ, maximum magnitude and ground motion prediction equations levels. There were totally 144 branches in the logic tree.

Moment-magnitude-based homogenized catalogue of earthquakes, the seismic source area model and the seismicity parameters are presented by Korja and others [1]. 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 data for ground motion prediction because of their geological and tectonic similarity to Nordic countries. Ground motion prediction equations according to Dahle [2] were used with minor modifications [6]. The hazard analysis was conducted utilizing EZ-FRISK software developed by Risk Engineering Inc [3]. Hazard curves were developed for mean, median (50%), 5%, and 95% fractiles for peak ground acceleration for 10^{-4} to 10^{-8} annual frequencies of exceedance by Saari and Malm [4]. The median spectral accelerations were determined for 0.3 Hz, 1.0 Hz, 5.0 Hz, 10.0 Hz, 25.0 Hz, 50.0 Hz and 97.0 Hz for annual frequency of exceedance of 10^{-5} by Malm and Kaisko [5]. Only horizontal direction was analysed in the studies.

Key Words: probabilistic seismic hazard assessment, ground motion predictions equation, logic tree, seismic hazard curve, ground motion response spectra

1. INTRODUCTION

Finland is located on the Fennoscandian shield, which is known as an area of low seismic activity. The largest earthquake in the vicinity of the Finnish nuclear power plant sites is the magnitude 4.9 event in Estonian coast near the island of Osmussaar in 1976. In the historical period, eight earthquakes with magnitude higher than 4.5 have been observed in Finland.

During 2016 - 2017 the re-evaluation of probabilistic seismic hazard assessment (PSHA) for Loviisa and Olkiluoto was conducted by Fortum and TVO power companies. The agencies participating in the study were ÅF-Consult Ltd, Institute of Seismology, University of Helsinki, the Department of Earth Sciences at the Uppsala University and the Geological Surveys of Finland, Sweden and Estonia. This paper describes the main results and procedures of the PSHA for the Olkiluoto and Loviisa sites. The logic tree used [4 & 5], the seismic hazard curves [4] and the ground response spectra [5] computed for the Loviisa NPP site are presented.

The preparation of input data for the task was as follows. Korja and others [1] were responsible for the definition of the study area that was a rectangle framing two circles having 300 km radii around both NPP sites. They gathered the moment-magnitude-based homogenized catalogue of earthquakes occurred within the study area and defined, based on geophysical, geodetic and geological data, the study area division into seismic source areas 1 - 11 and defined the seismicity parameters for these 11 seismic source areas. The information presented in [1] is the latest scientific knowledge of the subject contributed by the organisations which participated in the study. ÅF-Consult Ltd constructed the logic tree, defined maximum magnitudes and weights of all the branches of the logic tree [4 & 5]. Fortum Power and Heat Ltd was responsible for formulating the ground motion prediction equations (GMPE) and provided the attenuation tables [6]. Finally, ÅF-Consult Ltd computed hazard curves and uniform hazard ground response spectra based on the source area information [1] and ground motion attenuation tables [6]. The hazard calculations were carried out with the aid of EZ-FRISK software [3] developed by Risk Engineering Inc. Guidelines given in IAEA Specific Safety Guide No. SSG-9 [7] were followed.

2. Ground Motion Prediction Equations

The GMPEs used previously in the PSHA for the Loviisa NPP site were presented by Varpasuo and others [12]. For the revised PSHA also the GMPEs were recomputed by Leppänen and Varpasuo [6].

The Loviisa and Olkiluoto NPPs are resting on solid Precambrian bedrock. The bedrock at the sites lies near ground surface and approximation for shear wave velocity is over 3000 m/s and thus the site effects are not of importance for the sites. Therefore the v_{s30} velocity was disregarded in the analysis. This also allows one to assume fixed base assumption in seismic analysis of plant buildings [8]. When selecting the GMPEs the following four requirements were seen important [12]:

1. The GMPE should be applicable to intraplate areas
2. The GMPE should be applicable to bedrock conditions as described above
3. The GMPE should be applicable to earthquakes having moderate seismicity and source depths typical to Fennoscandia
4. The GMPE should be applicable to all frequencies such that the ground response spectra, not only the PGA, could be examined.

Based on these requirements and after careful comparisons of available models, the so-called Dahle attenuation model [2] with minor modifications was selected. The final GMPE model was a mix of the so-called Dahle model and a model that is described e.g. in the EZ-FRISK Attenuation equation references [9] and by McGuire [10]. The used GMPE has the following form:

$$ln(y) = c_1 + c_2 M + c_3 ln\left(1/\sqrt{R^2+h^2}\right) + c_4\sqrt{R^2+h^2} \quad \text{for } R < R_0 \qquad (2\text{-}1)$$

$$ln(y) = c_1 + c_2M + c_3ln(R) \quad \text{for } R > R_0 \qquad (2\text{-}2)$$

In the equations above y is ground acceleration (in g-unit), M is earthquake magnitude, R is epicentral distance (km), h is focal depth (km) and c_1, c_2, c_3 and c_4 are coefficients. R_0 was chosen to be 100 km by Varpasuo and others [12]. Coefficient c_2 was determined according to the study by Ahorner [11]. Coefficients c_1, c_3 and c_4 were determined by non-linear regression analysis based on strong motion acceleration recordings from areas that were estimated to have similar features compared to southern Finland. Coefficients c_1 and c_3 at $R > 100$ km do not equal to the values of c_1 and c_3 at $R < 100$ km but were chosen such that the Equations 2-1 and 2-2 are continuous and differentiable at $R = 100$ km [12].

There exist no relevant strong motion acceleration recordings available from Fennoscandia. After screening of available data, longitudinal and transversal recordings from Newcastle region from Australia and Saguenay region from Canada were estimated to be representative for southern Finland [12]. The chosen regions are of moderate seismicity, represent intraplate areas and were seen to form envelope for expected moderate earthquakes for the region to be studied. Used data sets were recorded on the bedrock. In the case of Saguenay, the bedrock is of Precambrian formations and in the case of Newcastle, the rock formations are of sedimentary rocks. The magnitude value for the Saguenay event from November 25 1988 is $M_S = 5.8$ (Surface wave magnitude) and the focal depth is $h = 29$ km. The magnitude value for the Ellalong event from August 6 1994 is $M_L = 5.3$ (Local magnitude scale) and the focal depth is $h = 1.4$ km. The Saguenay and Ellalong recordings were supplemented by two events, namely Miramichi event from March 31 1982 and Kelunji event from December 28 1989, leading to 36 acceleration recordings in both horizontal directions of which 26 were from Saguenay region and 10 from Newcastle region.

Following the approach presented by Varpasuo and others [12], for each 36 acceleration recordings response spectra for 5% damping ratio was calculated by Leppänen and Varpasuo [6]. From each of these 36 spectra the spectral accelerations for eight frequencies 0.3, 1.0, 5.0, 10.0, 25.0, 50.0, 70.0 and 97.0 Hz were extracted for closer investigation. They were used in determination of the aforementioned coefficients c_1, c_3 and c_4 in Equations 2-1 and 2-2 for the mentioned eight frequencies and 36 recordings using non-linear regression analysis. Finally, four GMPEs were formed for each of these eight frequencies and they are called Saguenay longitudinal and transversal GMPEs and Newcastle longitudinal and transversal GMPEs respectively in the logic tree.

Figure 2-1 shows one example on 36 time-history recordings taken from the Saguenay dataset. It has been recorded at the site 1 located 114 km from the earthquakes epicentrum. Example of attenuation curves have been shown in Figure 2-2 for Saguenay longitudinal motion calculated for 97.0 Hz. The magnitudes for which attenuation tables and curves were computed were M = 2.5, 3,0, 3.5, 4.0, 4.5, 5.0, 5.8, 6.5 and 7.0. M =5.8 is the magnitude of Saguenay event in this plot i.e. the magnitude for which the attenuation Equations 2-1 and 2-2 have been fitted. Magnitudes $M = 6.5$ and $M = 7.0$ have not been considered earlier in seismic hazard assessments for Loviisa and Olkiluoto NPP sites. Totally 32 attenuation curve bundles and corresponding attenuation tables as shown in Figure 3-2 were presented by Leppänen and Varpasuo [6] for the analysis for determination of seismic hazard.

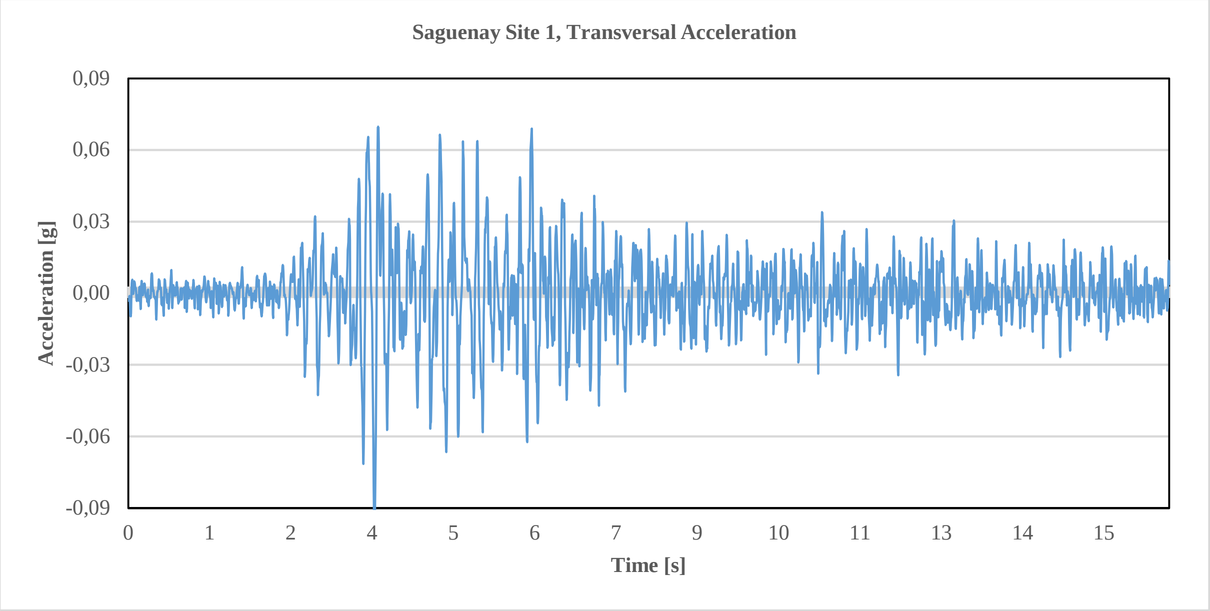

FIG. 2-1. Saguenay event transversal (north-south) component time history recorded at the site 1 [17]

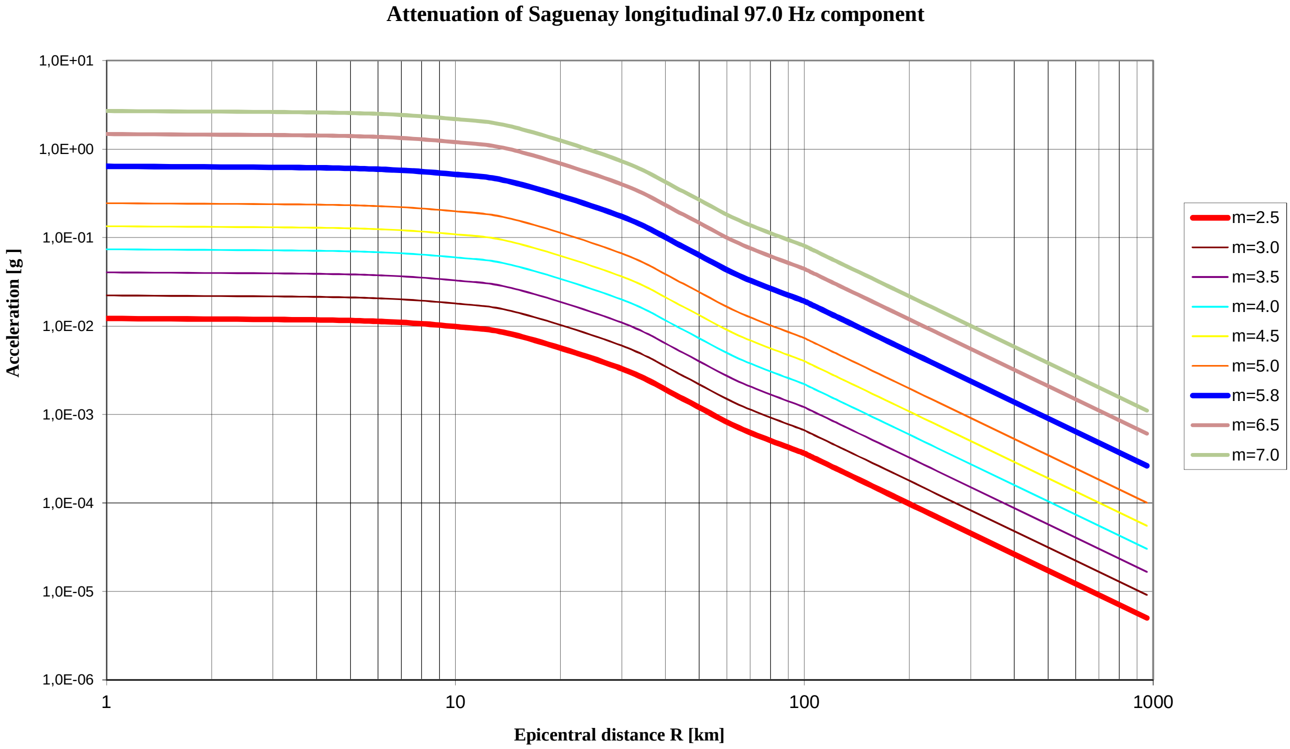

FIG. 2-2. Attenuation curves for Saguenay longitudinal motion for 97.0 Hz component. Figure by Leppänen and Varpasuo [6]

3. Determination of seismic hazard at the Loviisa and Olkiluoto sites

The PSHA at the Loviisa and Olkiluoto sites was conducted using logic tree to represent epistemic uncertainties. Software in the analyses was EZ-FRISK versions 7.62 and 7.65 [3].

Seismic hazard curves for acceleration in *g*-unit were determined for mean, 5%, median (50%) and 95% fractiles for 0.3, 1.0, 5.0, 10.0, 25.0, 50.0, 70.0 and 97.0 Hz frequencies for annual frequency of exceedance (AFE) from 10^{-4} to 10^{-8}. From these frequencies 50.0 Hz and 70.0 Hz were not considered in previous analyses [4,15,16]. Hazard response spectra was plotted for both sites using AFE value 10^{-5} and median (50%) fractiles [5].

There were totally five levels and 144 branches in the logic tree. The amount of branches was increased from 32 to 144 compared to the previous analyses [12,16,17]. The basic structure of the tree was similar for both sites but they have different seismicity parameters and different weights relating to maximum magnitudes. The logic tree level representing GMPEs was equivalent for both sites.

Loviisa NPP site logic tree has been shown in Figure 3-1 [5]. Figure 3-2 presents the study area and the seismic source areas 1 – 11 [1], of which the first level of the logic tree is consisted of. Also in the Figure 3-2 the earthquake epicenters since 1375 are presented according to Fennoscandian earthquake catalogue [13] supplemented by observations by Swedish national seismic network and Finnish national seismic network. The Gutenberg-Richter (GR) parameter *b* was computed for each source area 1 - 11 according to the GR – law [14] and presents the second level in the logic tree. Scaled parameter of *b* having value $\beta = b \cdot \ln(10)$ was introduced to EZ-FRISK software. The third level of the logic tree, the seismic activity rate parameter λ, denotes the annual number of earthquakes at least of different magnitude values in all the seismic source areas 1 - 11. Distributions of the *b* and λ parameters follow Bayesian Exponential-Gamma and Bayesian Poisson-Gamma distributions respectively. The weights in the logic tree levels 2 and 3 were defined as 0.16, 0.68 and 0.16 [4]. The definition of the seismic source areas, and the values of the parameters *b* and λ were presented in the study by Korja and others [1]. The depth range for the seismic source areas for the PSHA computation for the Loviisa and Olkiluoto NPP sites was 0 - 35 km.

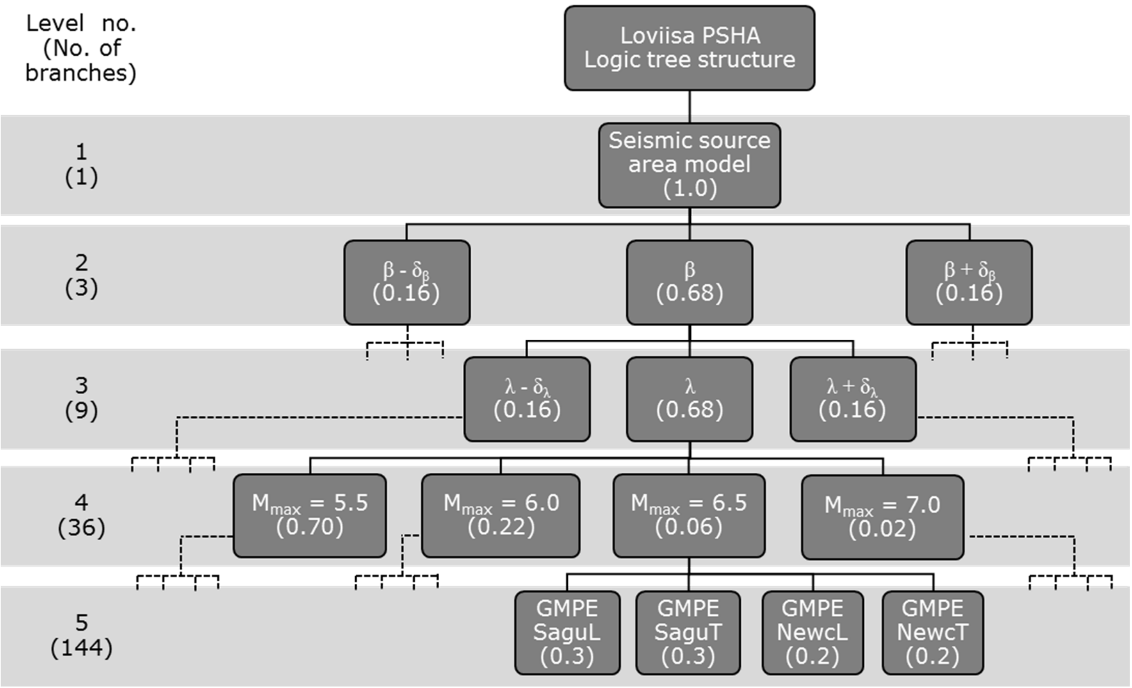

FIG. 3-1. Logic tree used in the PSHA for Loviisa NPP site. Figure by Malm and Kaisko [5]

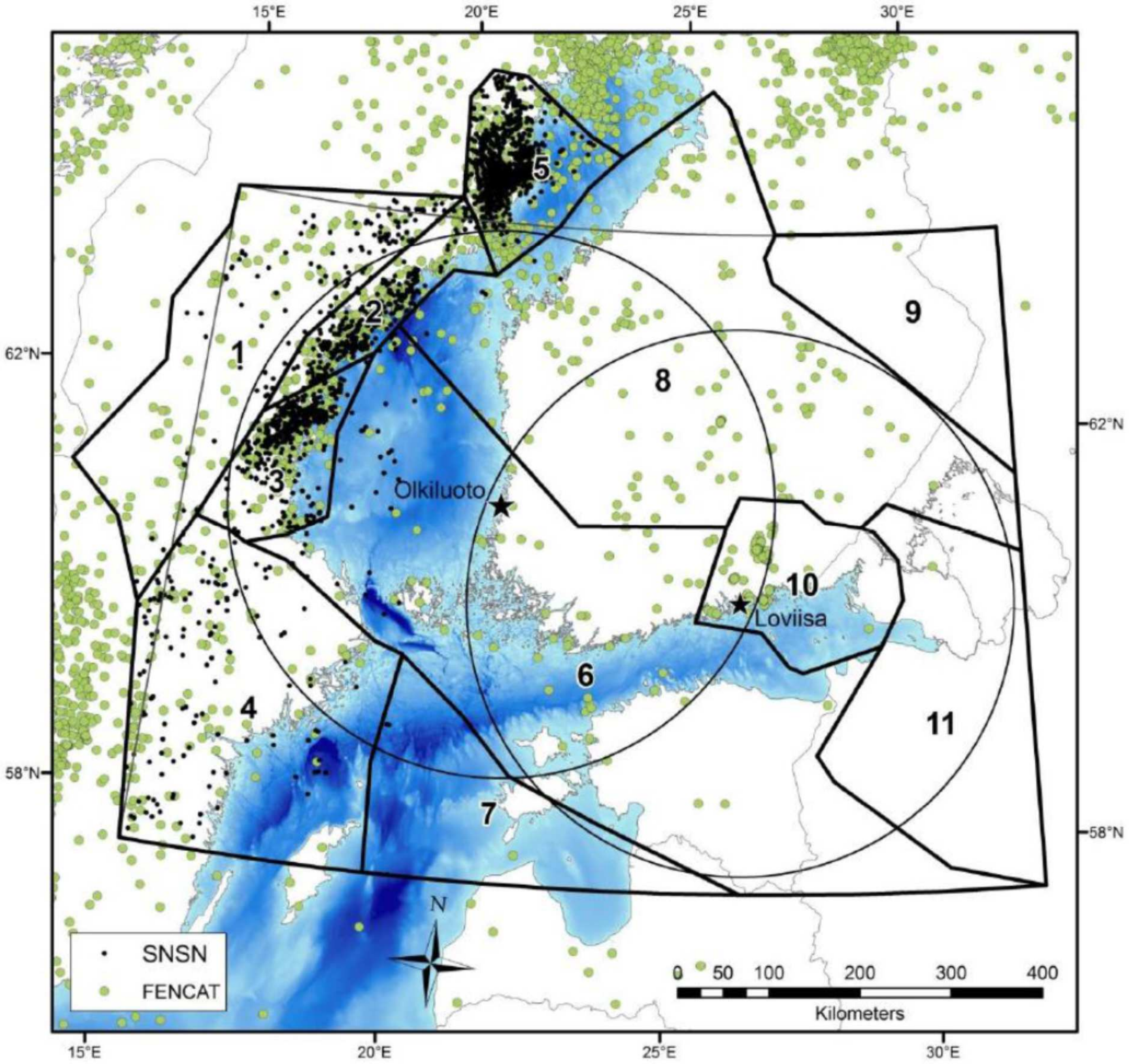

FIG. 3-2. Study area and seismic source areas 1 - 11 for Olkiluoto and Loviisa. The NPP sites are denoted by black stars and the epicenters by green and black dots. Figure by Korja and others [1]

4. Seismic hazard curves and spectra for the Loviisa site

Altogether 144 acceleration values were weighted according to the logic tree for 0.3 Hz, 1.0 Hz, 5.0 Hz, 10.0 Hz, 25.0 Hz, 50.0 Hz, 70.0 Hz and 97.0 Hz frequencies. Ground motion response spectra (GMRS) was determined for median (50%) fractile for AFE value of 10^{-5} [4 & 5]. This has been shown in Figure 4-1 with comparison for GMRS from previous PSHA analysis from 2007 [16]. Hazard curves were plotted for PGA frequency 97.0 Hz for mean, 5%, median (50%) and 95% fractiles for AFE 10^{-4} to 10^{-8}. This has been shown in Figure 4-2.

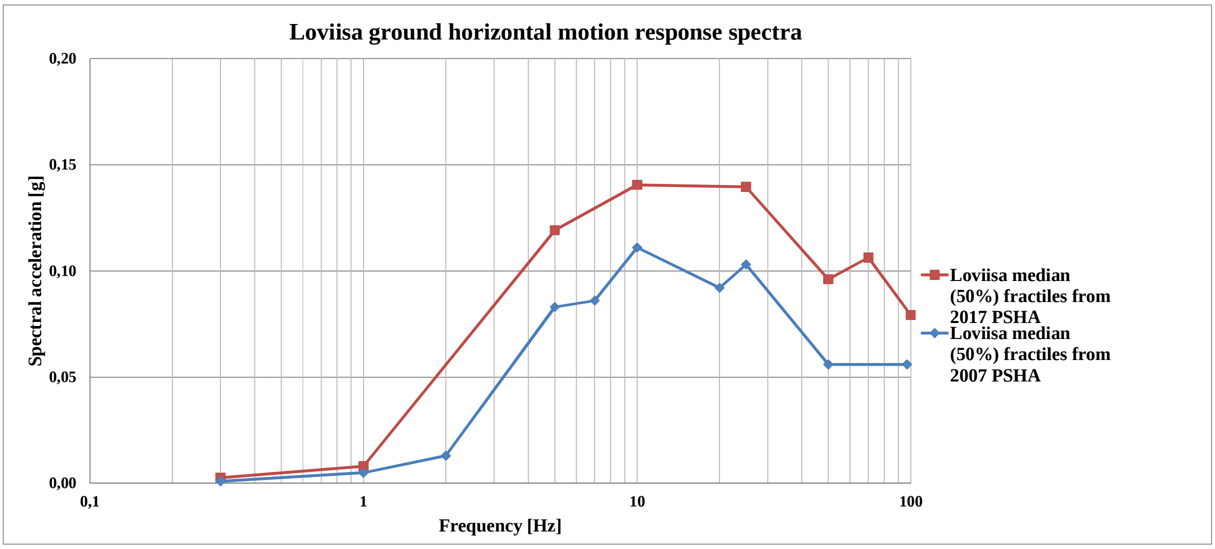

FIG. 4-1. Loviisa NPP GMRS from 2017 [5] and 2007 [16] PSHA analysis for median (50%) fractiles with 5% of critical damping

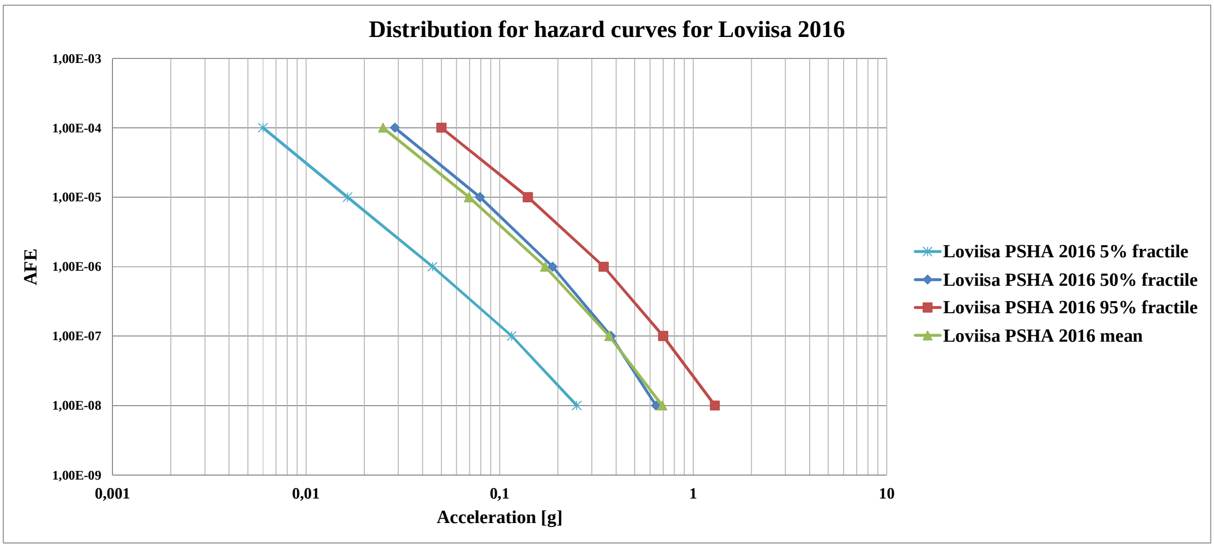

FIG. 4-2. Loviisa NPP PGA hazard curves for mean, 5%, median (50%) and 95% fractiles from 2016 PSHA analysis. Figure by Saari and Malm [4]

5. Conclusions

In the re-evaluation task of the seismic hazard curves for the Loviisa NPP site [4 & 5] four revised alternative attenuation functions [6] were used. One of them was based on longitudinal Saguenay recordings; the other one was based on transversal Saguenay recordings from eastern Canada; the remaining two alternatives were based on longitudinal and transversal recordings from Newcastle area from southeastern Australia. Compared to the previous analyses two new magnitudes, namely 6.5 and 7.0, and two new frequencies, namely 50.0 Hz and 70.0 Hz, were introduced. In addition to this, the amount of branches in the logic tree was increased from 32 to 144 and the seismicity parameters were revised according to the study by Korja and others [1].

The median level PGA for the Loviisa NPP site, in horizontal direction, with 100 000 year recurrence period was 0.048 *g* in the original PSHA from the year 1992 [15], 0.056 *g* in the year 2007 study [16] and 0.079 *g* in the newest analysis [4 & 5]. The reason for the change lie behind the new seismic source area model [1] used in this current analysis. In addition to this new logic tree structure of 144 branches, newly defined seismicity parameters β and λ, newly defined GMPE equations and two new magnitudes 6.5 and 7.0 have contributed to this more conservative result.

Vertical ground response spectra have been assumed to be 2/3 of the horizontal values. It is of interest to figure out vertical hazard curves and vertical ground response spectra using similar procedure as described in this paper.

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