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Sensitivity study of seismic hazard prediction in Finland (SENSEI)

Simon Burck, Jan-Erik Holmberg, Mari Lahtinen, Olli Okko, Jorma Sandberg, Pekka Välikangas

stuk
SÄTEILYTURVAKESKUS
STRÅLSÄKERHETSCENTRALEN
RADIATION AND NUCLEAR SAFETY AUTHORITY

Nuclear Reactor Regulation
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Abstract

This report is a summary of earthquake hazard sensitivity assessments for Finnish nuclear power plant sites. In this research project, the impact of the input data parameters and modelling method choices of probabilistic earthquake risk assessments on the earthquake risk of Finnish nuclear power plant sites were studied. The latest hazard assessments of the three current and planned nuclear plant sites in Finland were used as reference data. The purpose was not to re-assess old estimates, but to find out which reasons have caused uncertainty and variation between hazard estimates.

There were three parties in the project: The national radiation authority of Finland (STUK), a domestic calculation group responsible for making calculation models and calculations, and a foreign independent expert group. The calculation group had experience in making the previous risk assessments for the licensees and the expert group had experience with the latest calculation methods and an independent perspective on the previous assessments. The calculation team made comparative calculations using new software and attenuation functions also known as ground motion prediction equations (GMPEs). As a rule, the previously used seismic source area zonations were used, but special interest was focused on the seismicity of the rapakivi area near Loviisa. The earthquake catalogue used, was the seismological catalogue maintained by the University of Helsinki.

In probabilistic earthquake risk assessments, the Gutenberg-Richter parameters describing seismicity and the applicable GMPE and its fitting to earthquake observations were identified as the most significant parameters causing uncertainties. The reason for this is the absence of strong and even medium-sized earthquakes in Finland, which leads to the parameters being fitted to the very few observations or the use of experience gained elsewhere, which is not necessarily suitable for Finland's hard bedrock conditions. Smaller uncertainties are caused by the maximum and minimum earthquake magnitude values used in the hazard assessment. Topics that can be excluded from assessments in Finland are, for example, soil liquefaction, soil modelling and local soil-induced vibration amplification, since so far, all nuclear facilities are built on bedrock. This assumption may change if small modular reactors (SMR) are built in new plant locations and new foundation conditions.

Some expert recommendations for further research in Finland are the creation of a national hazard map to help in the siting of new facilities and the use of the GMPE NGA-East and/or the development of the national GMPE to better reflect local earthquake observations.

Keywords: Seismic hazard, PSHA, sensitivity study

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Tiivistelmä

Tämä raportti on yhteenveto maanjäristyshasardiarvion herkkyystarkasteluista suomalaisille ydinvoimalaitospaikoille. Tutkimusprojektissa selvitettiin todennäköisyyspohjaisten maanjäristyshasardiarvioiden lähtötietoparametrien ja mallinnustapavalintojen vaikutusta suomalaisten ydinvoimalaitospaikkojen maanjäristyshasardiin. Lähtötietoina käytettiin kolmen suomalaisen nykyisen ja suunnitellun ydinlaitospaikan viimeisimpiä hasardiarvioita. Tarkoituksena ei ollut arvioida vanhoja arviota vaan selvittää, mitkä syyt ovat aiheuttaneet epävarmuuksia ja vaihtelua hasardiarvioiden välille.

Projektissa oli kolme osapuolta: STUK, kotimainen laskentaryhmä mallien ja hasardilaskentojen tekemistä varten ja ulkomainen itsenäinen asiantuntijaryhmä. Laskentaryhmällä oli kokemusta aikaisempien hasardiarvioiden tekemisestä ja asiantuntijaryhmällä oli kokemusta uusimmista laskentamenetelmistä ja aikaisemmista arvioista täysin riippumaton näkökulma. Laskentaryhmä teki vertailevat laskennat käyttäen uusia ohjelmistoja ja vaimennusfunktioita (GMPE). Seismiset lähdealuejaot olivat pääsääntöisesti samoja kuin aikaisemmissa hasardiarvioissa, mutta Loviisan rapakivialueen seismisyyteen kohdistettiin erityistä mielenkiintoa. Käytetty maajäristysluettelo eli seismologinen katalogi on Helsingin yliopiston ylläpitämä.

Todennäköisyyspohjaisissa maanjäristyshasardiarvioissa merkittävimmiksi epävarmuuksia aiheuttaviksi parametreiksi tunnistettiin seismisyyttä kuvaavat Gutenberg-Richter parametrit ja käytettävä GMPE ja sen sovittaminen maanjäristyshavaintoihin. Syynä tähän on voimakkaiden ja jopa keskisuurten maanjäristysten puuttuminen Suomesta, joten parametrit on sovitettava vähäisten havaintojen perustella tai käytettävä muualta saatua kokemusta, joka ei välttämättä sovellu sellaisinaan Suomen kovaan kallioperään. Pienempiä epävarmuuksia aiheuttavat hasardiarviossa käytettävät maanjäristysmagnitudien maksimi ja minimi raja-arvot. Suomessa arvioista poisrajattavia asioita ovat mm. maaperän nesteytyminen, maaperän mallintaminen ja paikallinen maaperän aiheuttama värähtelyn voimistuminen, koska toistaiseksi kaikki ydinlaitokset on rakennettu peruskalliolle. Tämä tilanne voi muuttua, jos pieniä modulaarisia (SMR) laitoksia rakennetaan uusille laitospaikoille ja uusiin geologisiin olosuhteisiin.

Asiantuntijaryhmän suosituksia jatkotutkimuksille Suomessa ovat kansallisen hasardikartan tekeminen uusien laitosten sijoittamisen avuksi sekä NGA-East GMPE:n käyttäminen ja/tai kansallisen GMPE:n kehittäminen vastaamaan paremmin paikallisia maanjäristyshavaintoja.

Avainsanat: Maanjäristyshasardi, PSHA, herkkyystarkastelu

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Sammanfattning

Denna rapport sammanfattar känslighetsstudier av seismiska hasardanalyser för finska kärnkraftverk. Forskningsprojektet undersökte effekten av indataparametrarna från probabilistiska jordbävningshasarduppskattningar och valet av modelleringsmetoder på jordbävningsrisken på finska kärnkraftsanläggningsplatser. De senaste hasard-uppskattningarna av de tre nuvarande och planerade kärnkraftsanläggningsplatserna i Finland användes som referenser. Syftet var inte att utvärdera tidigare uppskattningar, utan att ta reda på vilka bedömningar som orsakat osäkerheter och variationer mellan hasarduppskattningar.

Projektet hade tre parter: STUK, en inhemsk beräkningsgrupp för modelleringen och hasardberäkningar och en utländsk oberoende expertgrupp. Beräkningsgruppen hade deltagit i de tidigare seismiska hasardanalyserna medan expertgruppen hade erfarenhet av de senaste beräkningsmetoderna och hade ett helt oberoende perspektiv mot tidigare uppskattningar. Beräkningsgruppen gjorde jämförande beräkningar med hjälp av nya program och dämpningsfunktioner (GMPE). Som regel användes tidigare seismiska zonindelningar, men rapakivi-området nära Lovisa var av särskilt intresse i känslighetsstudier. Den av beräkningsgruppen använda jordbävningskatalogen upprätthålls av Helsingfors universitet.

Gutenberg-Richter-parametrar som beskriver seismiciteten och den tillämpade GMPE och dess anpassning till jordbävningsdata identifierades som de viktigaste parametrarna som orsakar osäkerheter i sannolikhetsbedömningar av jordbävningsrisk. Anledningen till detta är frånvaron av stora och även medelstora jordbävningar i Finland. Därför måste parametrarna uppskattas på basis av få observationer eller av jordbävningsdata från andra håll i världen, vilket inte nödvändigtvis är lämpligt för den hårda berggrunden i Finland. De högsta och lägsta gränsvärdena för jordbävningsstorlekar som används som parametrar i hasarduppskattningar har mindre betydelse. Saker som kan uteslutas från hasarduppskattningar i Finland är t.ex. jordförvätskning, jordmodellering och lokal markinducerad vibrationsförstärkning, eftersom hittills alla kärnkraftsanläggningar har byggts på berggrund. Denna bedömning stämmer inte nödvändigtvis om småskaliga modulära (SMR) anläggningar byggs på nya områden som kan ha annorlunda geologiska förhållanden.

Jordbävningsexperter rekommenderar ytterligare forskning i Finland för att framta en nationell hasardkarta som stödjer placeringar av nya anläggningar och tillämpning av NGA-East GMPE eller utveckling av en finsk GMPE som bättre skulle motsvara lokala jordbävningsdata.

Nyckelord: Seismisk hasard, PSHA, känslighetsstudie

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Executive Summary

Four nuclear power plant (NPP) units have been in operation in Finland since the late 1970’s or early 1980’s: two PWR (VVER-440) units in Loviisa and two BWR units in Olkiluoto. These plants were not originally designed against earthquakes. Their seismic safety has been analysed afterwards in seismic PRAs, which were initiated in the 1980’s. STUK issued its first seismic safety related regulatory guide YVL 2.6 in 1988 and it was primarily meant to be followed in the design of new build NPPs. Due to low seismicity, there are no seismic design requirements for buildings and facilities other than nuclear facilities in Finland. Therefore, there has been only limited interest in seismic hazard analysis outside the nuclear energy field.

Current STUK regulations and guides require seismic design of nuclear installations in accordance with international IAEA and WENRA requirements. Seismic design requirements have been taken into account in Olkiluoto unit 3 (OL3), which is at late commissioning stage at the end of 2022, and in Fennovoima Hanhikivi unit 1 (FH1), which was in the construction license application stage, but has since rescinded its license application. STUK regulations include exceptions and transitional provisions on seismic design requirements for installations built before the requirements were introduced. However, the regulations and latest guides shall be applied to operating units to the extent justified considering their technical solutions according to the principle of continuous improvement stated in the Finnish Nuclear Energy Act.

At present, nuclear safety verification of the old units against earthquakes is based on probabilistic seismic hazard analysis (PSHA) and seismic risk analysis (seismic PRA/PSA). Starting from the late 1980’s to this day several safety improvements have been implemented and the current seismic safety level has been considered adequate. However, seismic margins of the first four NPP units are smaller than for seismically designed units and, in some cases, difficult to estimate. Moderate changes in the seismic hazard curve estimates may have relatively large effects on core damage frequency estimates.

The evaluation of seismic safety of nuclear installations is based on deterministic and probabilistic considerations. In both approaches, epistemic uncertainty and aleatory variability shall be considered. Since Finland is located in seismically quiescent Fennoscandia, the assessment of uncertainties (especially epistemic uncertainties) in the seismic hazard can become crucial from the safety demonstration point of view. The fundamental challenge, which the SENSEI project strived to explore, is to find practical and justifiable approaches to account for epistemic uncertainties in the vicinity of the nuclear site.

PSHA challenges in Finland

There is only a small amount of relevant seismic measurements from the seismic measuring network, which was established relatively late, in the 1960’s. The situation is slowly improving as the awareness of the risks to society due to natural hazards is increasing. In the historic macroseismic observations and reporting there are uncertainties in locations and intensities affected by sparse population and differences in collecting and preserving the historic information. The Fennoscandian earthquake catalogue (FENCAT) contains seismic observations and analyses of earthquakes since

1375. The catalogue is continuously maintained by the Institute of Seismology of the Helsinki University.

The lack of strong-motion events in Finland results in challenges to estimate or extrapolate the seismicity parameters from small magnitude events. Moreover, the local measurement data are too limited in number and in magnitude for the determination of ground motion prediction equations (GMPEs) needed in the hazard analyses. The applicability of reported international GMPEs has been previously considered questionable in the Finnish conditions with very hard rock. It is important to use suitable GMPEs for local conditions. The GMPEs used in Finnish PSHAs (for Loviisa and Olkiluoto NPPs) were based on calibrating GMPE equations with a few high-magnitude earthquakes recorded in similar geological conditions in Canada and Australia, or a combination of reported GMPEs and GMPEs calibrated with local measurements for Hanhikivi NPP. The SENSEI project included a review of different GMPEs that have become available since the previous assessments and some comparisons to examine their suitability in Finnish conditions.

SENSEI project – Seismic sensitivity studies

Several PSHAs have been carried out by the licensees in the past 30 years. During this time there have been some differences in the assumptions and methodologies leading to fluctuations in the assessed seismic hazards, in particular in the estimated peak ground acceleration (PGA) values and in the shape of the ground response spectrum. The applications for new reactors to be located at an old nuclear site (OL3) and a totally new site (FH1) introduced the need to review and harmonise the seismic safety assessments for all the NPP sites. These assessments are reviewed in Chapters 1 and 2. To support the review of PSHAs, STUK contracted the SENSEI sensitivity study in such a manner that the sensitivity cases were defined by an international expert group (USA, Germany, Spain) and calculations were carried out by a group of Finnish experts as explained in Chapter 3. This arrangement was adopted to combine international expertise with expertise on Finnish seismology and geology and local data bases. The effect of different selections of input data on the results was studied. The primary goal was to understand sensitivities between parametrial assumptions — not to find final answers to what input data would be the most justified. The work was based on the seismicity models and PSHA analyses of the licensees.

In Finland the licensees have the responsibility of determining the hazard and the role of the regulator is to review it. The purpose of the project was to support the review. Therefore, this study was conducted using the same methods as the licensees and varying the input data instead of using internationally established methods for PSHA, such as SSHAC, which is based on the formal procedure with several expert groups as described in the standard ANSI/ANS-2.29-2008. Several issues which have come up in the SENSEI project have already been discussed with licensees and included in STUK's requests for clarification.

The main topics and variations of input parameters are described in Chapter 3 and the calculated results in Chapter 4. The input parameters covered by the sensitivity studies included seismic source area delineations, depth distribution, seismic parameters of general seismicity (Gutenberg-Richter equation parameters a, b), Maximum and

Minimum Magnitudes for hazard integration, and Ground Motion Prediction Equations (GMPEs).

Seismic source areas and seismicity in Finland

For the PSHA calculations, seismicity is analysed within the seismic source areas, i.e., areas where seismicity features can be considered uniform. The delineation of the uniform areas containing enough information for statistical analysis is a challenge for seismologists. Site-specific seismic source areas models have been delineated for the NPP sites mainly according to seismicity because seismicity does not correlate well with main geological features in Finland. There has not been a general seismic source area model for the whole country, which makes the comparisons between the NPP sites difficult and laborious. Several source area models can be utilised in a logic tree. The evolution of the seismic source area models for NPP sites is described in Chapters 1.1 and 3.2. One of the most recent seismic area delineations is presented in Fig. 1.

In particular, the Wiborg rapakivi area (2.12 in Fig. 1) in south-eastern Finland is quite exceptional. It is the host area of Loviisa NPP, and swarms of small and shallow earthquakes up to M 3 have been occurring in the area - most of them near the NPP site. The consistency of the earthquake catalogue for the rapakivi area was also addressed. During the sensitivity calculations, special attention was focused on these particularities by splitting the rapakivi area into smaller source areas. One of the remaining questions was if the frequency of stronger and deeper earthquakes can be extrapolated from swarms of small, shallow earthquakes. It is also known that the rapakivi batholith is shallow, and in earlier PSHA studies it has not been considered an independent seismic source area for potential strong-motion events.

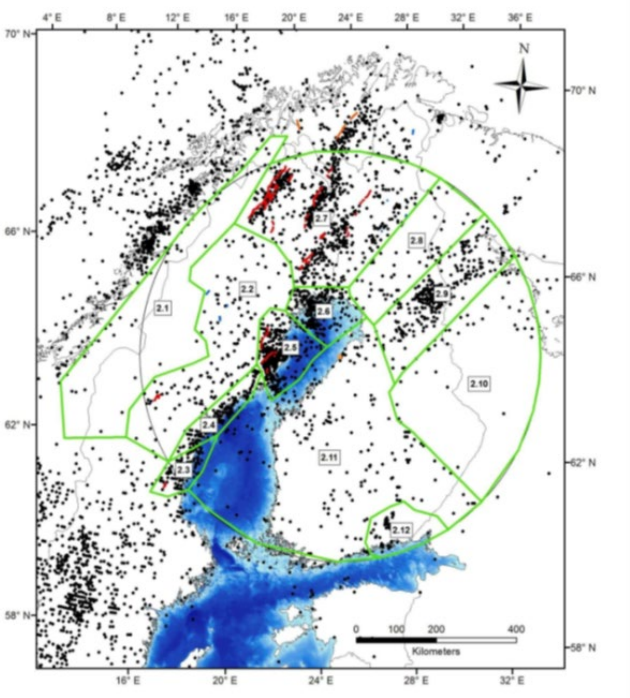


Fig. 1. An example of seismic source areas delineated for the Hanhikivi site PSHA-studies according to the earthquake occurrence in Fennoscandia (Korja & Kosonen 2015). Post-glacial faults in Northern Fennoscandia are marked with red in map.

The estimation of seismicity parameters for the seismic source areas introduces major uncertainties into the sensitivity analysis. The parameters λ and β, or a and b, of the Gutenberg-Richter model describing the annual number of earthquakes above a given magnitude have significant effect on the hazard prediction. The annual occurrence rate is also affected by the possible inhomogeneity during the observation period in the seismic catalogue FENCAT. Most of the recent recordings in Fennoscandia contain low magnitude earthquakes; whereas, in the historic observations there is a threshold for perceivable events which is affected also by the depth of the earthquake. The lack of significant seismic events complicates the estimation or extrapolation of the annual exceedance frequency estimation of the high magnitude events.

On the European scale the seismicity parameters in Fennoscandia are estimated using recordings beyond the Finnish territory. In the SENSEI-project the parameters were assessed for the local seismic source areas as delineated and described in Institute of Seismology's reports. Due to lack of detailed information on the catalogue, the topic was not investigated thoroughly. However, the delineation of the source areas was assessed for the NPP sites. Particularly in Loviisa, the calculated hazard increased remarkably when the size of the host source area of the NPP was decreased by splitting the SSA to account for the uneven distribution of the recorded earthquakes. In addition, the hazards estimated for the shallow earthquakes near Loviisa and Olkiluoto NPPs are higher compared to the hazard due to deeper observed earthquakes in the north, i.e., close to the Hanhikivi site.

Minimum and Maximum magnitude in PSHA

The magnitude range in the stable continental region is the obvious challenge as most of the observed earthquake are below M 2 and not even felt, and the strongest historical earthquakes are below M 5. EPRI (1989) recommends using M 5 as a minimum magnitude to avoid high PGA values due to near-by low-magnitude earthquakes with no damage potential to well-designed facilities. One issue was to consider how to address NPPs which have not been seismically designed. Therefore, M_{min} was considered in sensitivity calculations (see 3.2.6 and 4.2.5). Values from the catalogue minimum, about M 2, up to M 5 were used in the sensitivity studies. The effect was small below M 4. However, determination of M_{min} suitable for Finnish conditions including the fragility of a specific NPP should be addressed in future research.

Maximum magnitude M_{max} (Gutenberg-Richter relation upper cut-off) was considered. According to current expert opinion, high magnitudes are possible also in stable continental regions where magnitude M 5 is rare. In the early Finnish PSHA studies, a cut-off maximum magnitude (M_{max}) was set for each source area as the observed maximum magnitude plus 0,1 or 0,5 magnitude units. In most current PSHA calculations small weights have been set for higher magnitudes up M 7. In addition, Bayesian methods obtained using prior distributions from all Stable Crustal Regions (SCR's) result in very high maximum magnitudes, up to M 7.77, however this includes data from younger crust areas than Finland. The seismic hazard assessment methods are also developed for seismically more active areas and for significantly softer grounds. This complicates the estimation or extrapolation of the high magnitude events occurrence in Finland.The effect of using high maximum magnitudes in the PSHA in this study for Finnish NPPs was relatively small for the PGA ranges that control design. However, the slope of the hazard curve becomes gentler and thus affects the design extension earthquake assessments.

Ground Motion Prediction Equations

Most of the Ground Motion Prediction Equations (GMPEs) used in earthquake engineering do not handle low-magnitudes or the Fennoscandian geological circumstances. Several modern and recently proposed/published GMPEs were assessed for their suitability in Chapter 3.7.

Based on expert opinions and certain comparisons with uncertainties of Fennoscandian observations, the NGA East GMPEs were used in the SENSEI project (chapters 3.7.1 and 3.7.2). The NGA-East GMPEs have been recently developed for central and eastern United States. However, work on a regional GMPE for Finland is still recommended as the attenuation of seismic energy is lower in Fennoscandia than in the central and eastern United States. This was in line with an M.Sc. thesis based on small-scale study using micro-seismic monitoring records collected at the Olkiluoto repository site.

To study the sensitivity of the selection of a GMPE, an alternative to NGA-East was discussed. A practical choice was Fenno-G16, which was created by part of the calculation team before SENSEI (chapter 3.7.2.2). Fenno-G16 was used also for investigations of minimum magnitudes 2 to 3 where the NGA-East was not applicable due to the narrower magnitude range.

Design extension (beyond design basis) earthquake and seismic PRA

Finnish guides require the determining of a design extension earthquake. Its AFE is not exactly defined, but AFE 10^{-7}/year has been a recommended value, alternative recommendation is about twice the DBE PGA.

In recent PSHA results the accelerations for AFE 10^{-5} – 10^{-6} /year are higher than in older PSHAs. This range is important regarding seismic risk. Some older facilities have systems, structures and components with fairly low fragilities making seismic risk quite sensitive to the changes in the hazard curve. A re-evaluation of certain fragilities is ongoing.

Fig. 2a gives an example on how newer hazard curves are more slowly decreasing than older and how they behave between DBE and DEC PGAs. The effect on the design basis earthquake (AFE 10^{-5}/year) is small, but after that PGA accelerations with new methods are increased (AFE -> 10^{-6} – 10^{-7}/year).

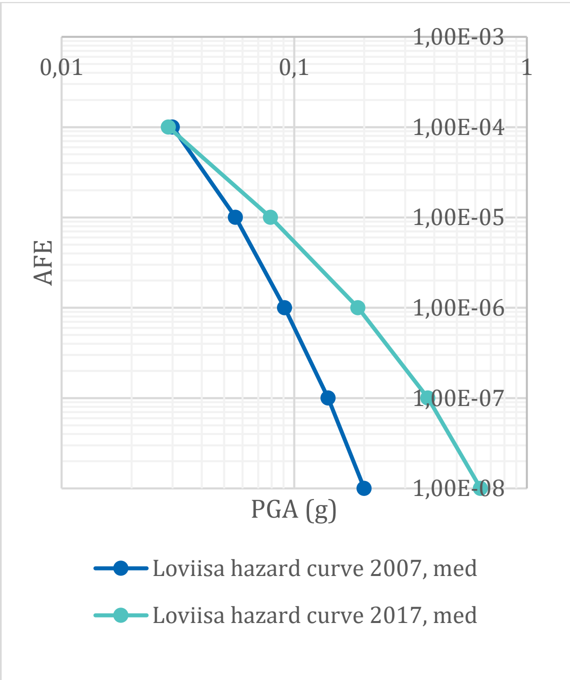


Fig. 2a. Examples of old and new hazard curves, Loviisa median hazard curve 2007 and 2017.

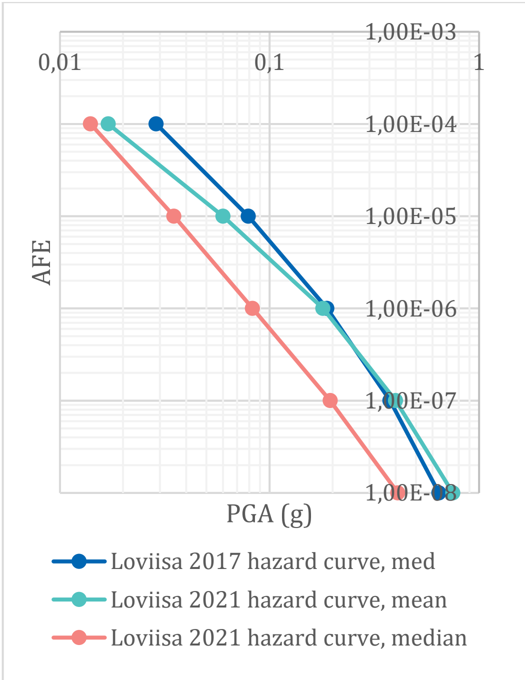


Fig. 2b. Loviisa 2021 mean and median hazard curve compared to the 2017 curve.

A new PSHA has been carried out by Fortum for the Loviisa site in 2021. This study was not considered in the SENSEI project. It gives lower PGA at an AFE of 10^{-5}, but the hazard curve shown in Fig. 2b is even more slowly decreasing than the 2017 hazard curve. The mean hazard curve is considerably higher than the median curve.

<u>High frequency attenuation studies at Olkiluoto (Kappa)</u>

To understand seismic attenuation, the seismic records from the Olkiluoto Repository site were analysed (M.Sc. Thesis, Lauri Rinne). The data is collected to locate and analyse induced micro earthquakes with very short duration (0,2 s) and high frequencies (100 – 500 Hz). The objective of the study was to determine the values of the kappa-parameter describing attenuation of high-frequency vibrations in the vicinity of the recording site.

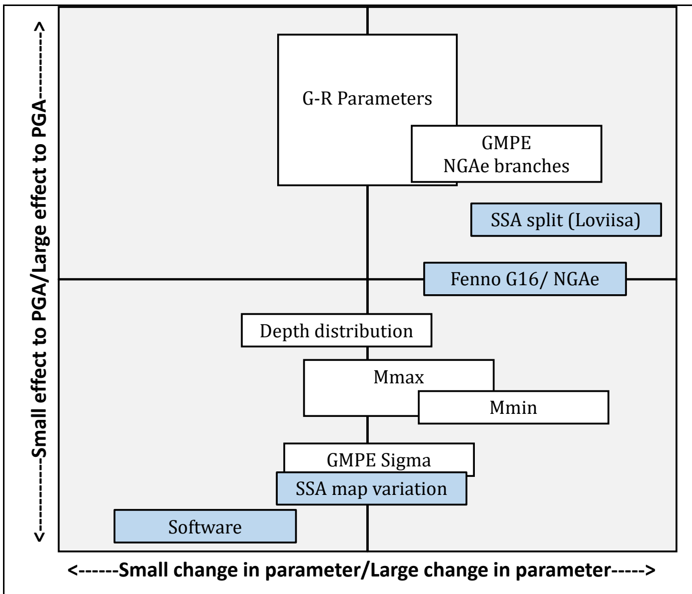
The kappa-values are of the order 0,0025 s, i.e., much lower than the lowest estimates (e.g., 0,006 s for Center and Eastern United States (CEUS) or 0,025 s for the French Alps). This means lower attenuation of high frequency accelerations, which leads to higher amplification at higher frequencies in site spectra. Similarly, the seismic velocities, e.g., V_s are higher (above 3,000 m/s) in Fennoscandia than the highest (2,500 m/s) applied in the CEUS and NGA-East kappa studies.

The effect of uncertainties on risk analysis results

Assessment of the effect of the identified uncertainties in the PSHA results on the probabilistic seismic risk analysis (seismic PRA) was not an objective of the SENSEI project. However, STUK carried out a “mini-PRA” to give some indicative results on the effects of variations of the hazard curve on seismic risk. The “mini-PRA” is described in Appendix 1.

Indicative summary of sensitivity results

An indicative summary of the sensitivity results is collected in Fig. 3 based on the results in Table 4-1.



Parameters affecting the seismic hazard PGA at an AFE level of 10^{-5}:

- G-R parameters [+σ] effect 100 to 300%
- GMPE [NGAe branches] effect 100%
- SSA map variation [med.-max.] effect 10%
- SSA [Local zone split for Loviisa] effect 80%
- GMPE [Fenno-G16 / NGAe] effect 50%
- Depth distribution [0-35km / 0-13km] 40%
- Mmax [5,5…6,5] effect 15 to 30%
- Mmin [2…4] effect -15%
- GMPE σ [+σ] effect 10%
- Software [OQ / EZFrisk] effect is minor

Fig. 3. An indicative summary of the sensitivity results. The horizontal axis of the chart represents a normalized, to a standard deviation (if possible), change in input parameter and the vertical axis represents the parameters’ effect on the PGA at 10^{-5} AFE. A white background denotes a quantitative input value, and a blue background denotes a qualitative input or choice. (GMPE σ represents the uncertainty of the GMPE’s fitting to measurement data)

The results of the SENSEI project help to understand the quantitative effect of input parameter uncertainties on the results of the PSHA. An important contribution by the international experts was the identification of the input parameters to be varied and the estimation of relevant ranges of variation. The four-field matrix in Fig. 3 illustrates how changes in parameters affect seismic hazard estimation. The field "small change in parameter" and "large effect to PGA" represents highest sensitivity. Such pure cases were not identified, which is a reassuring result. The results do not indicate any completely new significant effects of the input parameter uncertainties on the results. Changes in G-R parameters caused the largest effects. The uncertainty of the G-R parameters depends on the properties of the catalogue, e.g., completeness, declustering and homogenization of the magnitudes.

The results of the sensitivity studies can be used to identify the most important topics for additional research in the field of seismic safety.

General Conclusions and Recommendations of the SENSEI project

An important achievement of the project was promotion of the understanding of modern GMPEs and PSHA calculation procedures in Finland. The main challenges in Fennoscandia are related to the lack of strong-motion seismic events and therefore a weak possibility to calibrate GMPEs that are developed for high magnitudes and the fact that worldwide only few GMPEs are applicable for very hard rock. The maximum possible magnitude has been under debate for years in Fennoscandia, but according to the sensitivity studies, the main sources of uncertainty in Finland have been identified as the Gutenberg-Richter parameters and the epistemic uncertainty of the GMPE, both amplified by data scarcity. The effect of the different input parameters of the sensitivity study on the PGA value and seismic hazard is demonstrated in Figure 2.

In order to have better general understanding of seismicity and seismic hazards in Finland, a national seismic source area map should be developed e.g., in a national research program.

The use of higher maximum magnitudes makes the new hazard curves decrease more slowly than the old ones. The effect on the design basis earthquake (AFE 10^{-5}/year) is small, but at lower AFEs (10^{-6} - 10^{-7}) the PGAs calculated with new methods increase significantly. In addition, differences between mean and median hazard curves tend to increase.

The use of mean hazard instead of median hazard, as currently required in Finland in the definition of DBE, should be discussed. If switched to the more common mean definition, the AFE level should also be adjusted from the current value of 10^{-5}/year. An increase in AFE level should be considered because mean values are usually significantly higher than median values in modern seismic hazard assessments. In this way changing the definition would not result in an increase of the resulting DBE accelerations.

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Terms, definitions, and acronyms

Activity parameters	G-R parameters (β, λ)
Activity rate	Seismic events/year
AFE	Annual frequency of exceedance
AFRY	Engineering and design company, afry.com
Aleatory uncertainty	Internal randomness of phenomena
CAV	Cumulative absolute velocity
CDF	Cumulative density function
CEUS	Central and Eastern United States
DBE	Design basis earthquake
DEC C	Design extension condition C: "an accident caused by a rare external event and which the facility is required to withstand without severe fuel failure" (Nuclear Energy Decree 161/1988)
DiP	Decision in principle, licensing phase of a nuclear power plant
EGF	Endglacial fault
ENSREG	European Nuclear Safety Regulators Group
Epistemic uncertainty	Uncertainty associated with lack of knowledge or data of the phenomena
ESHM	Euro-Mediterranean seismic hazard model (2013)
FENCAT	The Fennoscandian earthquake catalogue
FH1	Fennovoima Hanhikivi site reactor unit 1
FV	Fennovoima Oy
GMPE	Ground motion prediction equations
G-R parameters	Parameters of the Gutenberg-Richter equation: $\log(\lambda_m) = a - b \cdot m$ or $\lambda_m = \exp\{\alpha - \beta \cdot m\}$
Ground response spectrum	The single degree of freedom oscillator's response to vibrations in the bedrock at the site of interest from an earthquake of a certain recurrence rate as given by a hazard study.
Gutenberg-Richter equation	Equation used to describe the magnitude-frequency relationship for a seismic source area
Hazard curve	An earthquake intensity measure, usually PGA, as a function of recurrence rate.
HCLPF	High confidence of low probability of failure
ISUH	Helsinki University Institute of Seismology
LO1, LO2	Loviisa site reactor units 1, 2
M_{max}	Maximum magnitude used in hazard integration in seismic hazard studies
M_{min}	Minimum magnitude used in hazard integration in seismic hazard studies. Alternatively minimum magnitude can refer to the completeness assessment of the catalogue down to a certain magnitude.

M_w	Moment magnitude, a measure of an earthquake's strength based on its seismic moment
NMESE	Non-Mesozoic and younger extended crust (in CEUS)
OL1, OL2, OL3	Olkiluoto site reactor units 1, 2, 3
One-branch calculation	A simplified seismic hazard calculation to study the effects of changing a single parameter
PGA	Peak ground acceleration
PRA	Probabilistic risk assessment
PSHA	Probabilistic seismic hazard analysis
Seismicity parameters	Activity parameters and magnitudes, often for a given SSA
SHARE	Seismic hazards harmonization in Europe www.share-eu.org
SSA	Seismic source area
SSC	Systems, structures, and components
SSHAC	Senior Seismic Hazard Analysis Committee
STUK	Radiation and nuclear safety authority
TVO	Teollisuuden Voima Oyj
UHS	Uniform hazard ground response spectrum
VTT	Technical Research Centre of Finland
WENRA	Western European Nuclear Regulators Association
YVL Guide	STUK's regulatory guide on nuclear safety and security
ÅF	ÅF Consult, currently part of AFRY Oy
δ_β and δ_λ	G-R parameter β and λ uncertainties

1 Introduction

1.1 Background and history

Several seismic hazard analyses have been carried out for the nuclear sites in Finland by the licensees and reviewed by STUK since the 1990s. Preliminary studies were carried out already in the 1980s, but they were not reviewed by STUK. The input data of seismic hazard analyses involve considerable uncertainties, and the choice of input parameters has a significant influence on the results, especially for hazards of very low annual occurrence probabilities typically used for NPP design and risk assessment. The main purpose of the SENSEI (Sensitivity study of seismic hazard prediction in Finland) project organized by STUK was to study the sensitivity of the Finnish seismic hazard models to the selection of input parameters, in a systematic way.

Earthquakes shall be considered in the design of nuclear power plants and other nuclear facilities according to IAEA guidance and national nuclear regulations. However, strong earthquakes are very rare in Finland, and building code for ordinary buildings has no requirements to consider earthquakes specifically. Consequently, in Finland, there has not been much interest in seismic hazard studies and collection of the required observation data outside the nuclear energy field.

For the determination of the seismic design basis, the seismic conditions at the site of the nuclear facility shall be investigated. The seismic hazard is defined as the annual frequency of exceedance of the quantity of interest, usually the peak acceleration at the site. In Finland nuclear facilities are founded directly on bedrock and the acceleration of the site bedrock surface is used. Therefore, the geotechnical site effects e.g. wave propagation and seismic amplification in soil layers and soil-structure interaction have not been of significant interest.

There are well-established international methods and computer programs for seismic hazard studies. The preferred method for the Finnish conditions is Probabilistic Seismic Hazard Analysis (PSHA) (Cornell 1968, IAEA 2016). While the general methods are international, local data, e.g., earthquake observations and geological data, are needed as input.

1.1.1 Seismic safety of the operating units and new units OL3 and FH1

Earthquakes shall be considered in the design of nuclear facilities according to the Regulation STUK Y/1/2018 Article 14 and the Guide YVL B.7 (STUK 2019). These do not provide the design ground response spectrum for NPPs, and only limited general guidance on the methodology is given. The design basis earthquake ground motion is defined as having a median annual exceedance probability of 10^{-5} and it shall be determined based on site-specific studies. The requirements apply as such to Olkiluoto 3 (OL3) under commissioning at the time of writing and to the planned unit Fennovoima Hanhikivi 1 (FH1). Seismic design requirements have also been applied to the Olkiluoto and Loviisa spent fuel interim storages (KPA storages) and to the Posiva encapsulation plant. The current seismic design requirements have also been applied to plant modifications in the operating Loviisa and Olkiluoto units.

The regulation STUK Y/1/2018 does not require backfitting of the operating units to fulfil the current seismic safety requirements, but seismic safety must be evaluated, and safety improvements have to be made according to the principle of continuous improvement stated in the Nuclear Energy Act (990/1987) Article 7 a.

Earthquakes have been taken into consideration in the design of Loviisa and Olkiluoto final repositories for low and intermediate level nuclear waste and the Olkiluoto final repository for spent nuclear fuel based on the regulatory requirements applicable to final repositories. YVL B.7 is not applied to underground final repositories as their safety issues are different from those of other nuclear facilities.

When the operating units Loviisa 1 and 2 (LO1, LO2) and Olkiluoto 1 and 2 (OL1, OL2) were built in 1970s and early 1980s there were no seismic design requirements for nuclear power plants in Finland. Seismic PRAs have been conducted for the operating units in 1990s and updated later. The seismic safety of the operating units has been evaluated in periodic safety reviews within the PRA framework. The Finnish utilities conduct PRAs for the operating units in-house, but domestic and international consultants have been used to support seismic PRAs and seismic walkdowns especially regarding SSC fragility estimates.

In the early seismic PRAs, several weak points were found in both LO1/LO2 and in OL1/OL2 including support of batteries and anchorage of electric and electronics cabinets. In OL1/OL2 relay chatter and spurious reactor protection signals were identified as a special problem. In Loviisa, potential for damage of large pressure vessels, especially the feedwater tank and steam generators, was identified.

Many of the above problems have been removed or reduced with plant modifications, and in the updated PRAs seismic events make only a small contribution to the total core damage frequency in Loviisa and Olkiluoto. However, the seismic resistance of large tanks, especially the Loviisa feedwater tanks, is still an important issue. The Loviisa seismic PRA has not yet been updated with the latest hazard estimates and Fortum has additional independent PSHA studies under way.

To evaluate seismic safety, it is therefore still important to improve the seismic hazard estimate and the estimates of seismic capacity of critical components. Since the operating units were not seismically designed, the margins for earthquake loads are small and a moderate increase of seismic hazard may result in significant increase of the seismic risk.

1.1.2 Probabilistic seismic hazard analysis

1.1.2.1 Overview of the PSHA procedure

The seismic design basis at a site of a nuclear facility can be determined with PSHA. The method described below is suitable for regions with diffuse seismicity, such as Finland, where earthquakes occur at random locations and cannot be associated with known fault zones (IAEA 2016).

A PSHA includes the following parts:

- Compilation of the seismic catalogue with information on the location, depth, magnitude, and time of earthquakes. The catalogue is compiled based on instrumental and historical observations.

- Compilation of geological and geophysical information on the region.

- Delineation of seismic source areas, i.e., areas where seismic activity can be considered uniform.

- Assembling the catalogue of past earthquake events and defining the magnitude thresholds ($M_{min\text{-}cat}$) above which the catalogue can be considered complete (i.e., for different observation periods).

- Calculation of Gutenberg-Richter equation parameters (G-R parameters a and b) characterizing seismicity of the source areas.

- Estimation of plausible M_{max} for the region or each source area (i.e., either based on the statistics of past observations or geological consideration).

- Choosing the smallest magnitude earthquake ($M_{min\text{-}haz}$) to be included in the hazard calculation. Earthquakes below this magnitude are assumed not to affect NPP safety.

- Estimation of focal depth distribution of the source areas (particularly important for the site region).

- Determination of ground motion prediction equations (GMPE) which predicts the ground motion and associated randomness, e.g., acceleration, at a given distance from an earthquake of a certain magnitude. The GMPEs are determined for peak ground acceleration and for different spectral frequencies. The GMPEs can be determined based on local data, if available, or GMPEs developed for regions with similar geological and seismic conditions can be used.

- Identification of the most important epistemic uncertainties (uncertainties related to incomplete knowledge of seismic phenomena) in the input parameters and design of a logic tree to account for the uncertainties.

- Calculation of the seismic hazard with a PSHA programme.

- Deaggregation (or disaggregation) of the results, showing the contribution of different magnitude and distance intervals to the hazards, is also recommended.

1.1.2.2 The results of the PSHA

The main results of a PSHA study are the hazard curves giving the annual frequency of exceedance (AFE) for each acceleration value. The hazard curve is usually given for the peak ground acceleration (PGA) but it can be given for the spectral frequencies. The hazard curves are usually given for the mean value and for different confidence values, e.g., 5%, 15% (16%), 50% (median), 85% (84%) and 95%.

The hazard curve can be determined separately for the horizontal and vertical components of the ground acceleration. Usually, the curve is determined for the horizontal acceleration and the vertical acceleration is defined as a fraction of the horizontal acceleration. Estimates of the ratio of vertical to horizontal accelerations can be found in international literature and the fraction may depend on the ground conditions, distance of the earthquake sources, frequency, and horizontal PGA level.

Another result of PSHA is a ground response spectrum for each AFE. Ground response spectrum presents the maximum vibrations of single-degree-of-freedom oscillators assumed to be anchored in site bedrock at various natural frequencies and using a particular damping ratio. The ground response spectrum is typically determined for the AFE level corresponding to the design basis earthquake. Confidence levels can also be defined for the ground response spectrum, so that the spectrum represent a uniform hazard level for different frequencies (i.e., uniform hazard spectra / UHS).

1.1.2.3 The uses of the PSHA results

The hazard curve and the ground response spectrum are used for determination of the design basis earthquake (DBE) and design extension earthquake (DEC, beyond design basis earthquake), which form the basis for seismic structural analysis and seismic qualification as described in Guide YVL B.7 (STUK 2019).

The hazard curve and its uncertainties are also used in seismic PRA. The seismic PRA includes the following main steps:

- PSHA: The same PSHA is used for defining design and qualification spectra and seismic PRA.

- Seismic fragility evaluation: Estimation of the conditional probability of failure of important structures and equipment as a function of site PGA. Fragilities are usually expressed as curves defined by the median seismic capacity and uncertainty parameters. The fragilities can be determined based on seismic design analyses. If seismic design analyses are not available, the fragility parameters can be estimated based on previous experience on similar structures and equipment. Additional seismic analyses can be carried out for critical structures and equipment. The ground response spectrum at the design basis AFE determined in PSHA is used in the seismic structural analyses.

- Systems and accident sequence analyses: Identification and modelling of the combinations of structural and equipment failures that could initiate and propagate a seismic core damage sequence.

- Risk quantification: Combination of the result of the seismic hazard, fragility, and system analyses to calculate the frequencies of core damage (level 1 PRA) and radioactive releases (level 2 PRA).

1.1.3 Seismicity and seismic source areas in Finland

Finland is situated on the Fennoscandian shield known for its low or moderate seismicity. On the global seismic hazard map (Fig. 1-1) the southern part of Finland appears as seismically quiescent, whereas some seismicity is observed in the northern part of the country. The stress in the brittle rock mass is assumed to be originating from the Atlantic ridge push and post glacial isostatic uplift. Typically, seismic activity cannot be correlated with the main geological features in Fennoscandia (Fig. 1-2). There are no known rupture zones in the shield, but the palaeoseismic studies have located a few post-glacial fault zones at which minor earthquakes occur in northern Sweden and Finland. Strong earthquakes cannot be excluded in places where little or no seismicity has been observed.

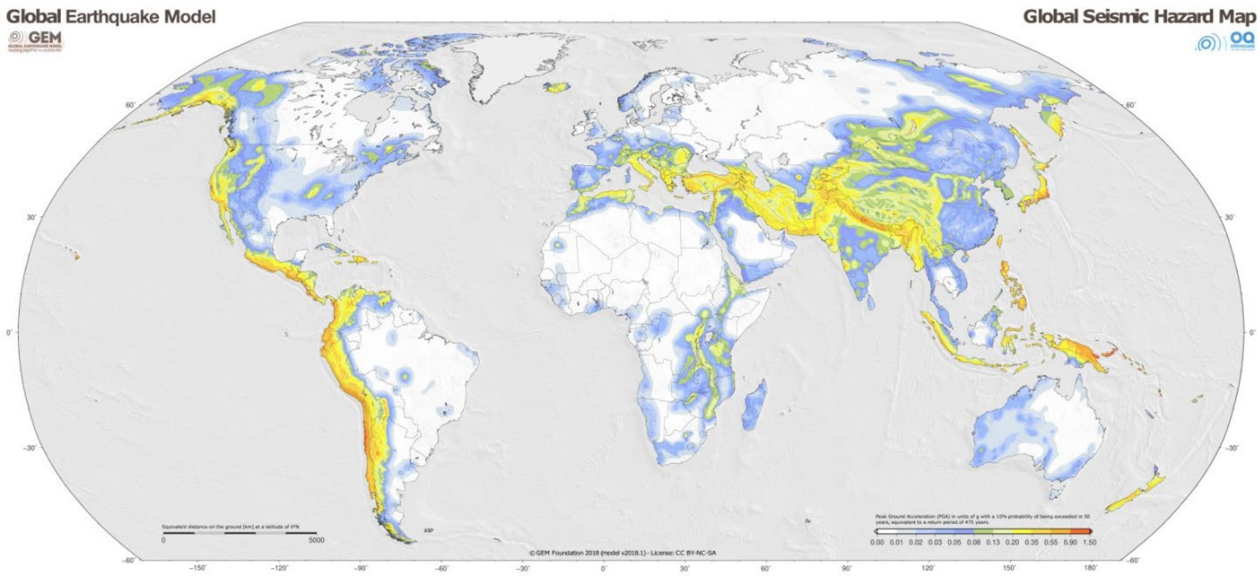


Fig. 1-1. Global seismic hazard map (gfz-potsdam.de)

Seismic records are collected in Northern Europe historically from observations since 1375 and in Finnish territory since 17th century, and more complete instrumental data is available since 1970. The Fennoscandian earthquake catalogue (FENCAT) is maintained by the Institute of Seismology of the University of Helsinki, ISUH (see https://www2.helsinki.fi/en/institute-of-seismology/bulletins). As part of defining the Fennovoima seismic design basis, homogenization work on the records collected in Finland, Estonia, Norway, and Sweden was performed as described by (Saari et al. 2015). Northwest Russian records are under processing for the catalogue. In the harmonisation, anthropogenic e.g., mining induced seismic events, and non-tectonic earthquakes, frost events etc. are excluded from the catalogue. Seismicity is described as homogenised moment magnitude, M_w.

There are roughly ten magnitude $M_w > 2$ earthquakes per year in Finland, but only a few events with magnitudes over M_w 4, the largest have been in the order of 4,5. The historic data contains large uncertainties since the estimates for epicentres and magnitudes of historic earthquakes that occurred in irregularly and sparsely populated areas are only indicative. The seismic patterns are diffuse, but there are in Finland a few areas of enhanced seismic activity. Fennoscandian seismicity is shown in Figure 1-2 together with one of the most recent source areal models (Korja & Kosonen 2015). The Swedish coastline along the Bothnian Bay towards western Lapland (zones 2.5, 2.6 and 2.7 in Fig. 1-2) and Kuusamo-Kandalaksha (zone 2.9) zones exhibit the most prominent seismicity rates. Along the Bothnian Bay the earthquakes are deep, and their focal mechanism is typically strike-slip. The post-glacial faults and their seismicity is present in Lapland zone 2.7. In southern Finland to Northwest Russia there are more oblique and reverse focal mechanisms. The Wiborg rapakivi granite batholith (zone 2.12) has its own seismic character due to the observed shallow low-magnitude earthquake swarms within the batholith. The eastern part (zone 2.10) of the Fennoscandian shield appears to be seismically quiescent. This may be due to lack of observations in the remote area and/or lack of seismicity.

The largest earthquake in Fennoscandia is associated with the Pärvie fault in Sweden and it has been estimated at magnitude 8 ± 0.4 (Lindblom et al. 2015). The largest magnitudes related to the endglacial faults (EGF) in Fennoscandia have been dated to ca. 9 000—11 000 years before present and are associated with the deglaciation of the Weichselian ice sheet. The endglacial earthquakes belong to a different stress regime and are therefore not considered in PSHA for NPP sites.

It has been observed that especially in Sweden the epicentres of some systematic small earthquakes appear to gather along postglacial faults. Currently the most active fault in Sweden is the Burträsk fault, where Lindblom et al. (2015) have reported a remarkable correlation between the present-day seismicity and the EGFs mapped in northern Sweden. The 48 km long Suasselkä fault is the most prominent EGF in the Finnish territory, and Afonin et al. (2017) have recorded some minor seismicity along the Suasselkä fault concluding that the fault is seismically active. These observations suggest that defining seismic fault zones may become an option in the future at least for some parts of Fennoscandia. Post glacial faults are marked with red in Figure 1-2. An important note on the possible methodologies of PSHAs in Fennoscandia is that more information on earthquake locations have been gathered due to improved seismic networks.

For PSHA, the seismic source areas must be defined. It is assumed that the source areas have uniform seismicity. For the hazard assessment, the occurrence of magnitudes is defined by calculating the Gutenberg-Richer parameters for each of the seismic source areas. This has been done at different scales for different purposes and different methods. In the first place, the seismic source areas should be delineated based on uniform geology and seismicity, but these should be large enough to include a sufficient number of earthquakes to give statistical confidence on the calculated parameters. The challenge in Finland is that the main areas with more frequent seismic observations do not correlate well with the main geological features as can be noted in Fig. 1-2 below.

In the European large-scale Finland is considered almost as one homogeneous area, only the northern zones have differentiated for their higher number of occurrences (see the source area models for SHARE (2013) and ESHM (2020)). Currently the seismic hazard and risk in the capital region of Finland are under a new assessment at ISUH. The ESHM maps presented in Fig. 1-3 are used as bases, but more detailed source zones assessment is ongoing in spring 2021.

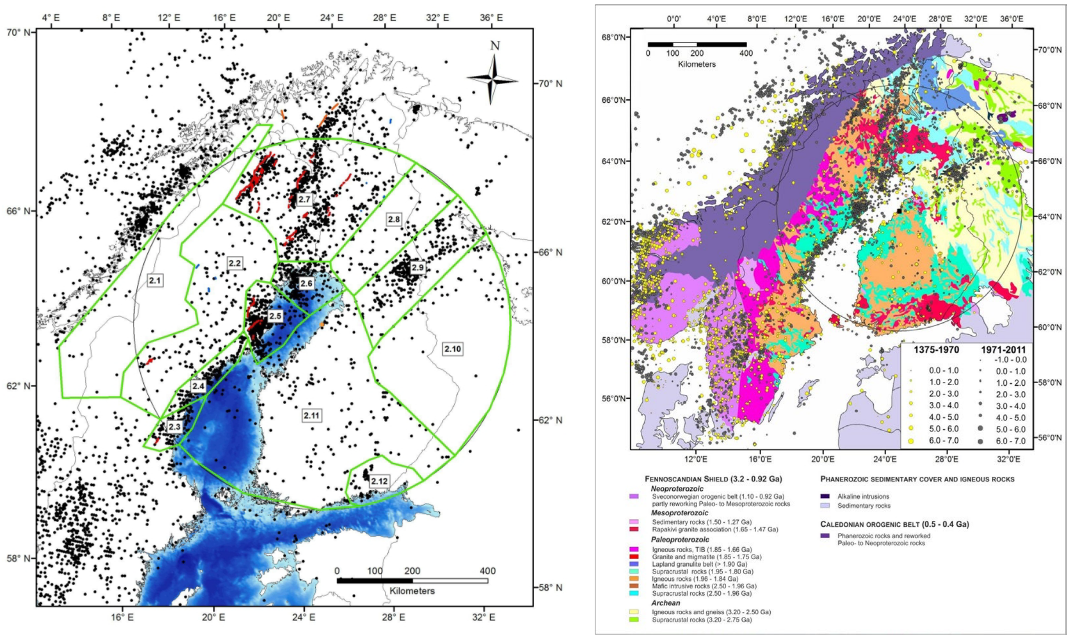


Fig. 1-2. Fennoscandian earthquake map and one of the most current source area models, model 2 for Fennovoima, (Korja & Kosonen 2015). Hanhikivi site in marked by red dot and post glacial faults are marked with red on the left. The geological map and the earthquake observations are on the right.

The major geological units of Fennoscandian shield and observed seismicity are presented in Figure 1-2. All Finnish NPPs are located around the igneous granitic massif in central Finland, and they can be understood to be located on the same large source area, zone 2.11 in Figure 1-2. However, detailed site-specific analyses have been carried out for the individual NPPs. Source area or even sub-source area boundaries are defined according either to seismicity or the geological setting near the Olkiluoto NPP. At the Loviisa NPP, the source area 2.11 can be expected to continue below the rapakivi batholith, although the rapakivi area (source area 2.12) is considered in the most recent assessment to be the main source area for Loviisa. In the recent study Korja & Kosonen (2015) presented a few alternative source area models for the Hanhikivi NPP. The areas with enchased seismic activity are close to the Hanhikivi site, thus the effects of the source area delineations are a research topic on the European and local scale.

For the hazard assessments for the NPPs the seismic zoning has been defined for the individual NPP cases separately and independently. Thus, the numbering of source has been fluctuating between the different studies. Figure 1-4 shows the source area models used in the VNS studies (Varpasuo et al. 2000) for Loviisa and Olkiluoto in 1999 and 2000. The effects of the neighbouring source areas and their border locations have been fluctuating during the hazard assessments. Therefore, the local source zones and their effects to the hazard calculations were assessed during the SENSEI project based on the earlier source zone delineations as the seismicity parameters were available for those zonings.

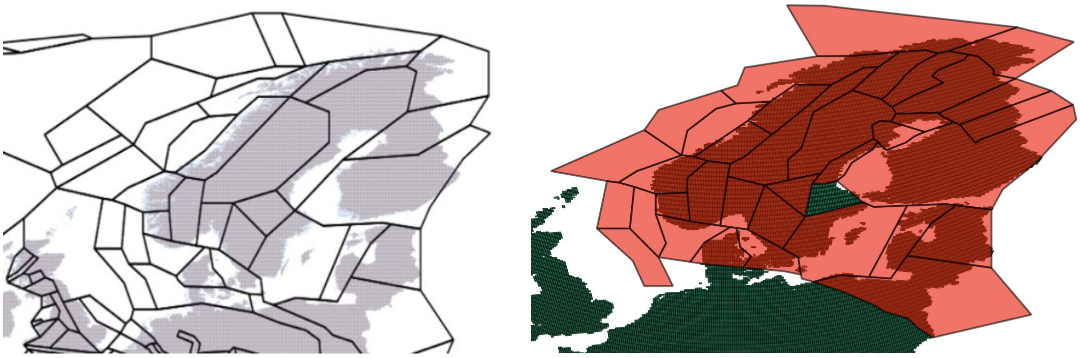


Figure 1-3a. Seismic source areas used in Share project for the Euro-Mediterranean Seismic Hazard Model 2013 (share-eu.org). Figure 1-3b. Preliminary source areas for the European Seismic Hazard Model 2020 (sera-eu.org).

1.1.4 Seismic hazard analyses in Finland

As seismic design is not required in the general building code in Finland, outside the nuclear energy field there has been only limited interest in seismic hazard analysis and the development of the seismic monitoring network to better support seismic hazard studies has earlier not been a focus area.

In low-seismicity regions, such as the Fennoscandian Shield, epistemic uncertainties are extensive. They can be reduced by acquiring more data, improving modelling, and accumulating knowledge over the course of time. However, the rarity of large-magnitude earthquakes in Fennoscandia makes it difficult to acquire empirical observations on damaging earthquakes. For instance, the recent highest observed magnitudes are much lower (in the order of 5) than what has been estimated (of the order of 7-8) in the early post-glacial era. The end-glacial/early post-glacial seismicity occurred in a different stress field, and therefore comparison to the historical era is not very meaningful. Glaciation becomes important for the long-term safety of repositories for spent nuclear fuel but is not relevant to NPP safety. The current predictions for M_{max} consider higher magnitudes than earlier hazard assessments. Even magnitude 7 earthquakes are considered in the logic trees with low weights.

1.1.4.1 Loviisa and Olkiluoto

Early seismic hazard studies were carried out in the 1980’s and 1990’s for the planned new nuclear power plant unit and for seismic PRA of the operating units.

A more extensive study was carried out in the late 1990’s by Fortum Nuclear Engineering for the Olkiluoto and Loviisa sites. The purpose of the study was the determination of the seismic design basis of the fifth NPP unit later realised in Olkiluoto, but the results have also been used in the updates of the seismic PRAs of the Loviisa and Olkiluoto operating units. The original report by Varpasuo, Nikkari and Saari (Varpasuo et al. 2000), known as the VNS study, was first submitted to STUK in 1999 and updated in 2000.

The VNS study was a PSHA study aimed at calculating site-specific uniform hazard ground response spectra (UHS). The study was based on the seismic catalogue for Finland and near region up to 1992. Six seismic source areas were defined based on earthquake observations and geological considerations, Fig 1-4. The cut-off maximum magnitude (M_{max}) was set for each region as the observed maximum magnitude plus 0,1 or 0,5 magnitude units.

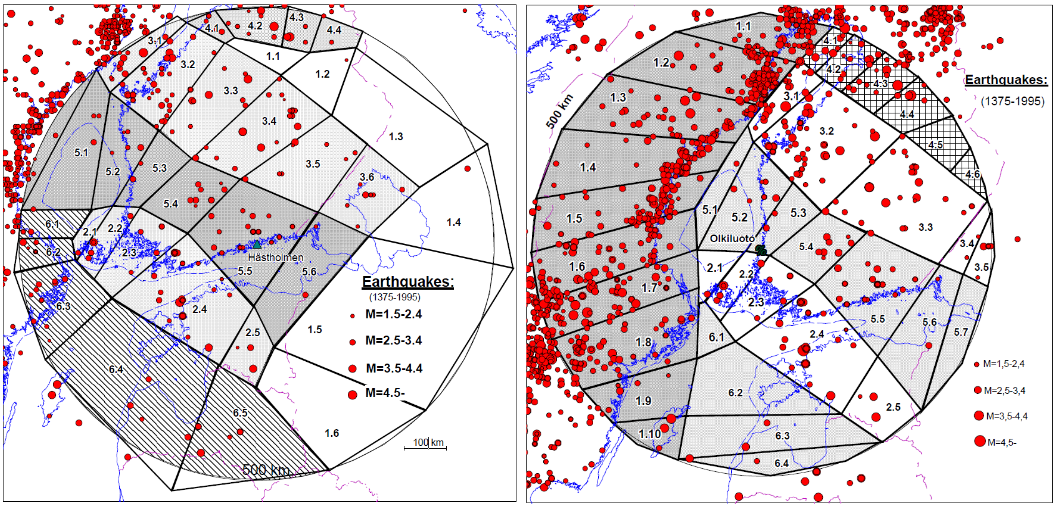


Fig. 1-4 Seismic source areas used in the Varpasuo, Nikkari, Saari study for Loviisa (left) and Olkiluoto (right). The subdivision of the six source areas is for computational purposes only as quadrangular areas must be used in SEISRISK III input.

Because a sufficient number of strong motion recordings of earthquakes is not available in Finland to determine GMPEs based on local data, the question of suitable GMPEs for Finland was addressed in the VNS study. The suitability of published international GMPEs was considered questionable because it was not known if the data used for their determination came from rock conditions comparable to Finland. The approach used in the VNS study was to develop new GMPEs using a modified form of the equations developed for Sweden (Dahle et al. 1990) and measurements from regions with geological properties resembling Finland.

The data used in the development of the VNS GMPEs was from the Saguenay 1988 earthquake in Canada and from the Newcastle 1989 earthquake in Australia. According to the VNS study, the properties of the measuring stations were known. However, the disadvantage of the approach is the small number of events used. The approach drew some criticism already when the study was reviewed in 1999 – 2000, but a clearly better alternative was not pointed out (NORSAR 1999). More criticism has been presented later by several experts in connection with other seismic hazard studies as more international GMPEs for hard rock areas have become available, see e.g. (Bungum and Lindholm 2011).

The main results of the VNS study were the ground response spectrum shape for southern Finland shown in Fig. 1-6 and the AFE 10^{-5} PGA values 0,085 g for Olkiluoto and 0,06 g for Loviisa. The spectrum shape was accepted by STUK in 2001. The calculated PGA values were lower than the minimum value of 0,1 g recommended in the

IAEA NS-G-1.6 (IAEA 2003). A design basis earthquake (DBE) PGA of 0,1 g was applied in Olkiluoto and Loviisa.

The original VNS report did not include the PGA hazard curve, but it was calculated later in 2007 based on the same PSHA model (Varpasuo 2007). The hazard curve is shown in Fig. 1-5.

The Finnish Regulatory Guide YVL B.7 requires that seismic hazard analyses shall be reviewed and updated, if necessary, with about ten-year intervals. The updated PSHAs for Olkiluoto and Loviisa were submitted to STUK in 2016-2019. These studies, which were used as a starting point in the SENSEI project, are described in Chapter 2.

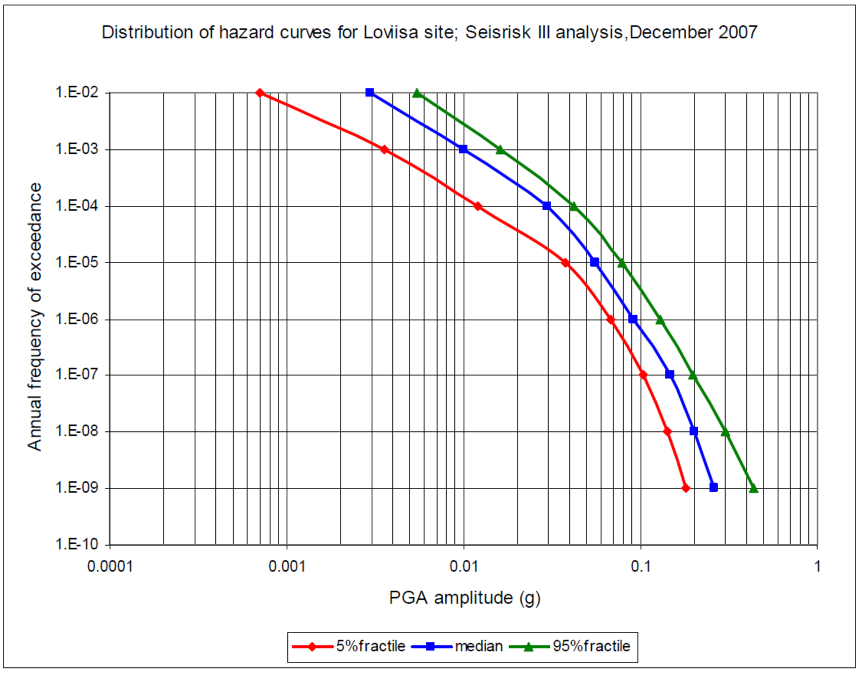


Fig. 1-5 PGA hazard curve with confidence bounds (5%, median, 95%) for the Loviisa site (Varpasuo 2007).

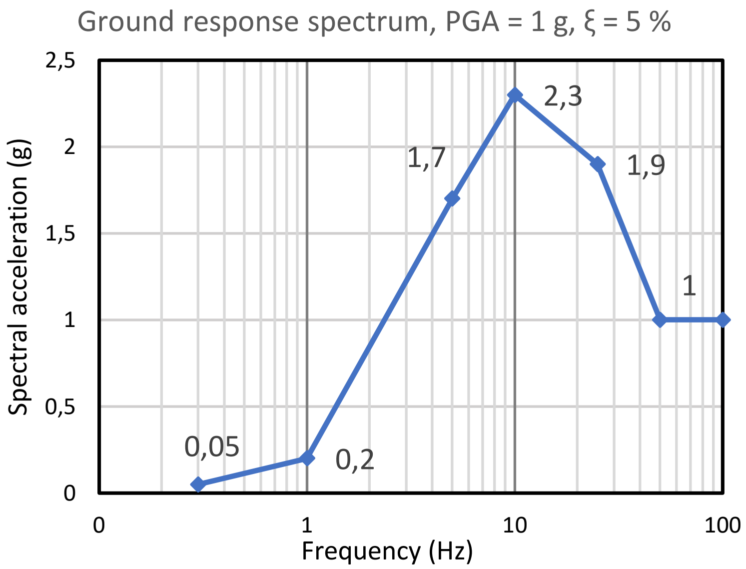


Fig. 1-6. The unnormalized ground response spectrum accepted for Southern Finland in 2001. The spectrum is based on the calculations in, but it has been modified to envelope the uniform hazard spectra for both Loviisa and Olkiluoto (translated from Varpasuo et al. 2000).

1.1.4.2 Fennovoima Hanhikivi 1 NPP under design

A new company Fennovoima Oy (FV) was founded in 2007 for building a nuclear power plant on a green-field site. Fennovoima started immediately preparations for a site selection and a Decision in Principle (DiP) application. According to the Nuclear Energy Act the Decision in Principle is made by the Government and accepted or rejected as such by the Parliament. The application concerned several alternative sites and alternative NPP concepts.

A preliminary evaluation of the suitability of the site shall be done in the DiP phase. Detailed site evaluation and determination of site-specific design basis values shall be carried out for the construction license application. Fennovoima contracted preliminary seismic hazard studies for three alternative sites: Hanhikivi in Pyhäjoki, Karsikko in Simo and Gäddbergsö in Ruotsinpyhtää municipality which was later annexed to Loviisa. Hanhikivi and Karsikko sites are situated on the coast of the Bay of Bothnia in Northern Finland which was not covered by previous seismic hazard studies. Extensive seismic source areas were used in the preliminary study and only PGA values were considered (Mäntyniemi 2008).

For the review of the DiP application STUK contracted ÅF-Consult (presently AFRY) and ISUH to carry out an independent study for the northern sites (Saari et al. 2009). It was decided that the study should be based on the same methods, GMPEs and logic tree as the VNS study to give comparable results. The source areas for northern Finland were developed in the study along the same lines as in the VNS study, Fig. 1-7. According to the STUK study, the PGA with AFE 10^{-5} at Hanhikivi was 0,085 g which is the same as calculated for Olkiluoto. However, there was a local minimum of PGA at Hanhikivi, and the spatial variation was very large in the region. At a distance of about 60 km to the south the value was doubled and 60 km to the north-west it was tripled. At the Karsikko site 120 km from Hanhikivi the PGA value was 0,27 g. The calculated ground response spectra were less peaked but enveloped by the Olkiluoto spectrum. The Gäddbergsö site in Loviisa was rejected by Fennovoima during the DiP process.

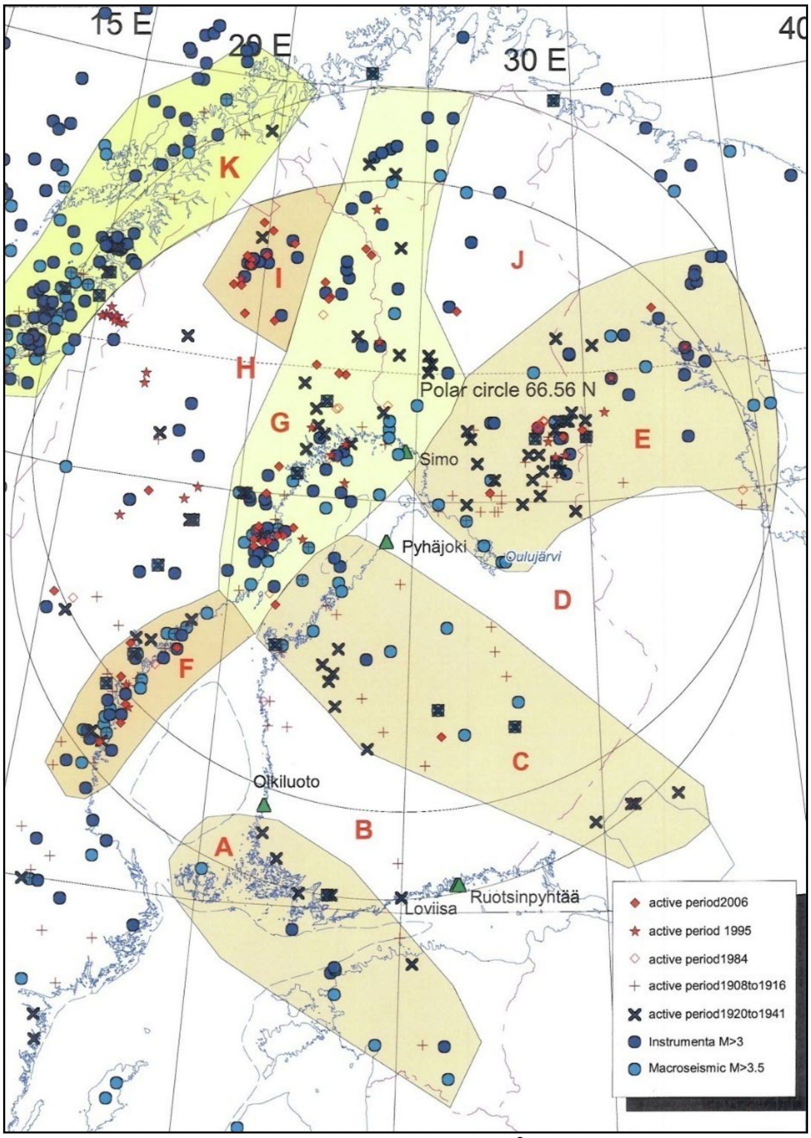


Fig. 1-7 Seismic source areas used in the ÅF study in 2009 (Saari et al. 2009). The source areas in Southern Finland are essentially the same as in the VNS study for Loviisa and Olkiluoto.

After the DiP was made in 2010 Fennovoima contracted additional seismic hazard analyses from ÅF-Consult (Saari and Malm 2010). The computational methods and seismic source areas were the same as in the ÅF study contracted by STUK in 2009 but two alternative GMPEs were used (Atkinson-Boore (2006), Toro et al. (1997)). The four cases (ISUH, ÅF/STUK with VNS GMPE, ÅF/Fennovoima with Atkinson-Boore GMPE and ÅF/Fennovoima with Toro GMPE) were used by Fennovoima for determining the design basis earthquake PGA (Matikainen 2010). The weighted average of the four results and its standard deviation was calculated for Hanhikivi and Karsikko with weights determined by an expert group. For Hanhikivi the PGA values were in the range 0,09 g – 0,16 g, the weighted average PGA was 0,13 g and weighted standard deviation 0,015 g. The design basis PGA for Hanhikivi was set conservatively as 0,2 g (Puttonen 2010a and Matikainen 2010).

For the Karsikko site, which was later rejected as Hanhikivi was chosen as the preferred site, the range of calculated PGA was 0,23 g – 0,44 g. The weighted average PGA was 0,295 g, weighted standard deviation 0,047 g and the proposed design basis PGA was 0,35 g. (Puttonen 2010b and Matikainen 2010)

Fennovoima also contracted a report on the ground response spectrum shape (Puttonen 2010a). The suggested spectrum was based on the Eurocode 8 Type 2 spectrum (CEN 2004) for hard rock, but it was broadened to higher frequencies (fig. 1-8). The spectrum was very conservative and covered all calculated ground response spectra.

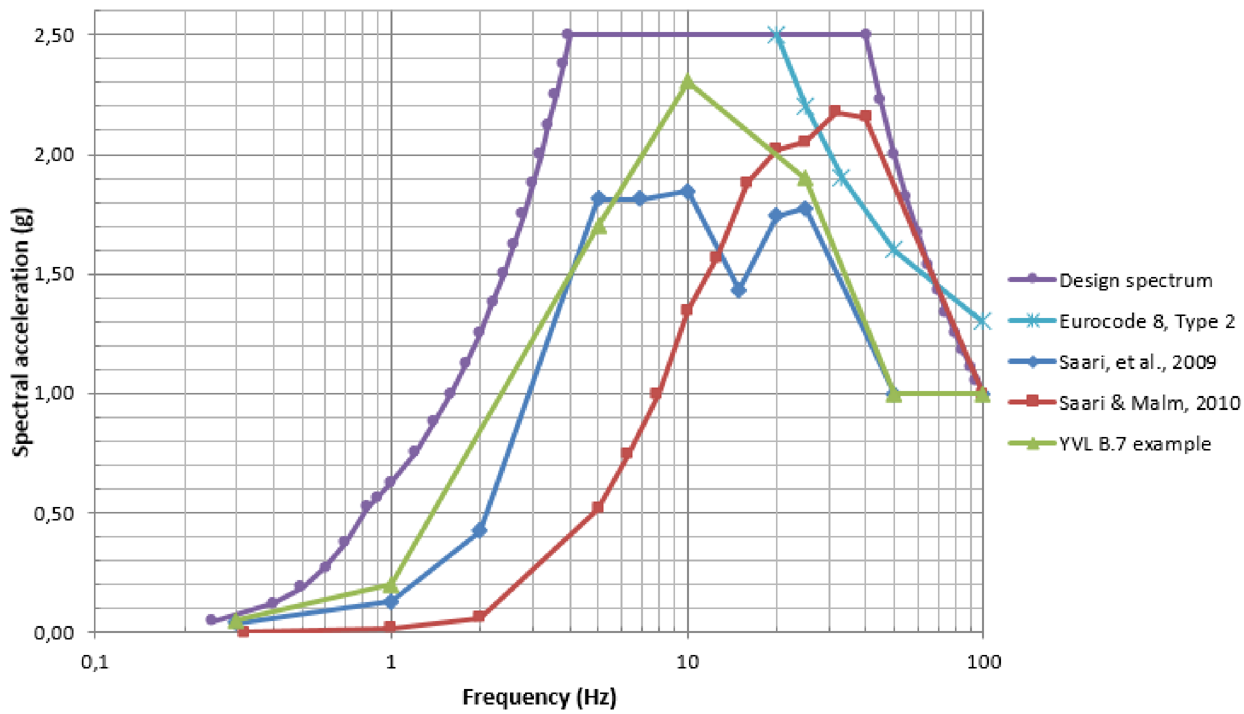


Fig. 1-8 (draft) spectra from different studies, enveloped by first proposal during 2017 for design spectrum to Hanhikivi 1 NPP

STUK asked the Norwegian NORSAR institute and Dr. Varpasuo as an independent specialist to review the seismic hazard analyses submitted by Fennovoima. Especially NORSAR criticized several points in the analyses, including the seismic source area delineation, selection GMPEs, the maximum cut-off magnitude for the Gutenberg-Richter equations, the non-systematic procedures of combining various studies, and the lack of references to more recent work on seismic hazard analysis. NORSAR experts also emphasized that the Senior Seismic Hazard Analysis Committee (SSHAC) Level -3 procedure (Budnitz et al 1997, ANSI 2008) is currently an internationally accepted state of the art approach to seismic hazard studies for nuclear facilities. NORSAR pointed out that there were several uncertain factors having effects in the opposite directions and it was not possible to conclude whether the proposed design basis earthquake was conservative or nonconservative.

Based on the criticism Fennovoima decided to start a more extensive seismic hazard analysis project with a broader group of international experts familiar with Fennoscandian seismic conditions. The project is described in Chapter 2. The project did not formally follow the SSHAC guidelines but included some important elements of the SSHAC-3 procedure such as an international expert group and internal review group. The results of this study were used in the SENSEI project as a reference case for the Hanhikivi sensitivity analyses.

In early 2010s there was a SSHAC-3 PSHA for the planned Thyspunt site in the Republic of South Africa. The South African regulatory body invited observers from foreign regulatory bodies to participate in some project workshops. Researchers from ISUH and ÅF-Consult were contracted to participate in the workshops on STUK's behalf to get more familiar with the practical implementation of the SSHAC-3 procedure.

1.1.5 PSHA related research in Finland and relationship with other countries

Research on probabilistic seismic hazard studies was started in Imatran Voima Oy (IVO, currently Fortum Oyj) in early 1980s (Varpasuo and Puttonen 1985). At that time there were no regulatory requirements on seismic hazard analysis or seismic design of NPPs in Finland, and the work was started on the company's own initiative. The Osmussaar earthquake (M4.6) in Estonia 1976, which was felt in Finland changed the perception concerning seismic risk. However, it was to be expected that requirements on seismic design would be implemented, and the Guide YVL 2.6 on seismic safety of nuclear facilities was published in 1988.

In 1984 STUK made the decision that the licensees should carry out Level 1 and 2 probabilistic risk analyses (PRA) with full scope of initiating events, including seismic events. The PRAs were to be developed gradually and no definitive schedule was set on seismic PRAs, but anyway this increased the need for seismic hazard estimates. The seismic PRA for Loviisa NPP was submitted in 1991 and for Olkiluoto 1 and 2 in 1997. The studies were carried out by the utility staff in cooperation with international consultants. The seismic PRA for Olkiluoto 3 was carried out by AREVA during the early construction period.

Fortum carried out the first Finnish full-scale PSHA in late 1990s for the planned fifth NPP unit. In connection with the IVO/Fortum hazard studies for the fifth NPP unit Jouni Saari (1998) published the doctor's thesis "Regional and local seismotectonic characteristics of the area surrounding the Loviisa nuclear power plant in the SE Finland".

Starting from the late 1970s a lot of work was done on geological disposal of low and intermediate level nuclear waste and spent nuclear fuel. This included also seismological research, but the main emphasis has been on rock displacements rather than ground motion. The long-term safety assessment has included palaeoseismic assessments for the spent fuel disposal (Hutri 2007). After the selection of the disposal site at Olkiluoto, microseismic monitoring has been carried out at the site since 2002. The recent M.Sc. thesis of Lauri Rinne (2021) is based on these monitoring records.

In late 2009 it was decided that seismic research should be included in the national nuclear safety research programme SAFIR (see http://safir2014.vtt.fi/). One reason for this was the Niigata earthquake causing damage in the Japanese Kashiwazaki-Kariwa NPP in 2007. The seismic safety assessment project SESA was included in the programme periods SAFIR2014 and SAFIR2018 (http://safir2018.vtt.fi/) covering the years 2011 – 2018 and after that minor seismic safety projects were included in the SAFIR2022 programme. The main participants in the projects were VTT, ISUH, and ÅF-Consult Ltd. The topics of the SESA project included PSHA, comparison of available PSHA computer programmes, development of Finnish GMPEs, computational simulation approach to hazard estimates, finite element studies of typical structures and large tanks with fluid content, and literature studies on seismic monitoring.

After the Kashiwazaki-Kariwa NPP event in 2007, IAEA established the International Seismic Safety Centre (ISSC) later renamed as External Events Safety Section (EESS), and ISSC started an Extrabudgetary Research Programme (EBP) on seismic events, seismic hazard, and structural analysis, also including some work on other external events. Fortum participated in the EBP from the beginning. In 2010 the expansion of the ISSC EBP was planned and STUK joined the EBP from the beginning of 2011. After the Fukushima Dai-ichi accident in March 2011 there we some revisions of the prioritization of EBP research topics. Fortum and STUK have participated, for example, in the development of IAEA guidance especially for regions with diffuse seismicity and Fortum has participated in structural analysis benchmark studies. The EBP provides a good opportunity to closely follow international research and participate in the discussions with international experts.

After the Fukushima accident the European Union (EU) organized so-called stress tests for the NPPs in Europe and their international peer review. The topics of the stress tests were seismic events, external flooding, other external natural events, loss of the ultimate heat sink, loss of electricity supply and severe accident management. The stress tests were defined and coordinated by ENSREG (European Nuclear Safety Regulators Group) in cooperation with WENRA (Western European Nuclear Regulators Association). The national stress test reports were completed by the end of 2011 and the international peer review was organized in 2012. The stress test reports included some plant level fragility estimates based on seismic PRAs. In the peer review of the Finnish stress test report there was some discussion on the seismic safety of the operating units which originally did not have earthquake as a design basis. The stress test reports are available at ENSREG's web pages (http://www.ensreg.eu/)

STUK participated in 2015–2018 as a lead organization with VTT in the OECD/NEA/CSNI task "*Comparison of probabilistic seismic hazard analysis (PSHA) in areas with different level of seismic activity*" (NEA 2019) initiated by the NEA CSNI WGIAGE working group based on discussions in NEA seismic workshops. The purpose of the project was to compare the methods and results of seismic hazard analyses as well as design values in regions with different levels of seismic activity.

1.2 Project SENSEI

The experience from the assessment of the licensees' seismic safety assessments, as presented in the previous section 1.1.4, gave the idea to improve national competencies on assessing updating hazard studies. Thus, the capabilities were developed in a calculation group consisting of Finnish competencies, but an external expert group was hired to give advice on current state-of-art practices. The hiring was carried out according to the legislation concerning large public procurements. As the first step STUK conducted a market survey in early 2016 to identify skilled and experienced service providers who would be willing and able to provide seismology related services for STUK. The project was planned to start by reviewing the state-of-the-art opinions for PSHA studies in Finland and establishing systematic way to identify essential parameters for further assessment.

1.2.1 Objective

The objective of the SENSEI project was to investigate the sensitivity of PSHA output for NPP sites in Finland to different choices of input parameters. It is widely recognised that many PSHA inputs carry significant uncertainty. Such uncertainties, epistemic in nature, are usually incorporated in the PSHA using logic trees, drawn up based on expert judgments. The logic trees comprise different alternatives of the inputs, such as maximum magnitude, type of faulting, ground-motion prediction equation (GMPE), etc., and each alternative branch is assigned a weight using expert judgment and data testing.

As the repeated seismic hazards estimates for the Finnish NPP's showed variability between the PSHA studies STUK made a market survey to check the basis for the research to evaluate the calculation methods and the uncertainties related to the input parameters. Corresponding calculation system for sensitivity modelling and analysis of PSHAs was discussed.

In addition, parameters used in PSHAs, such as seismic activity rates, seismic zoning, minimum and maximum magnitude, and attenuation parameters will be assessed for their sensitivity in the PSHA studies. Once the sensitivity of the PSHA parametric modelling would be available, other experts would re-evaluate the credibility of the input parameter ranges considering these results, making suggestions for future refinement/extension of the parameter ranges.

Also, the logic trees and ground motion prediction equations (GMPE) for Finnish circumstances would be assessed. The aim was to have expert judgement available, but in shorter and smaller extent than a SSHAC-3 level procedure would need. For that purpose, preliminary project plan with 4 different tasks was drafted, and costs were estimated. One of the prerequisites was to have experience in low-seismicity areas like that of Fennoscandia. Another aim was to support the goals of the OECD/NEA/CSNI task "*Comparison of probabilistic seismic hazard analysis (PSHA) in areas with different level of seismic activity*" (NEA 2019) creating a consultation platform in Finland. The initial time frame was allocated for two years parallel with the OECD task.

The above-mentioned issues were discussed in the market survey and STUK received more responses from experienced organizations and people than expected. For tendering, the project was revised somewhat compared to the market survey, and it was launched after the OECD task was practically completed in 2018. The preparation for the tendering was more demanding and time consuming than expected. It became obvious that parallel calculations and comparison would become necessary. Finally, the tendering was finalized and carried out with the aid of Government procurement company, Hansel Ltd. to have impartial competition between the service providers as required in the legislation. For this purpose, the project's tasks were carefully revised and needed expertise described and the scoring principle issued before the tendering. As it was obvious that several experienced companies would be participating in the competition, the task and qualification requirements for seismology, seismic engineering, and PSHA studies in low seismicity areas including Fennoscandia were carefully prepared for the official tendering. After the tendering, the service providers were evaluated and selected according to the beforehand given scoring principles and the project was launched during its kick-off meeting in early 2019.

1.2.2 Project organization

The project consisted of three groups with different roles. STUK commissioned the project, set the main goals, and provided the background and input documentation. The expert group reviewed the status quo of seismic hazard assessments at each nuclear plant site, identified methodologies and parameters to be studied. The calculation group executed the studies and calculations.

The participants from STUK had expertise in the areas of seismic risk assessment, probabilistic risk assessment, civil engineering, (seismic) structural analysis, geology, and seismology.

The expert group consisted of experts from the following four companies: IDOM Consulting, Engineering, Architecture S.A.U.; Lettis Consultants International, Inc.; Principia Ingenieros Consultores S.A. and TÜV SÜD Industrie Service GmbH. The procurement was divided into two lots, which were: Seismologist/Seismic hazard specialist, and Seismic Engineer.

The Finnish technical calculation group was formed from VTT Technical Research Centre of Finland (VTT), AFRY Oy formerly known as ÅF-Consult Oy (ÅF), and Institute of Seismology, University of Helsinki (ISUH).

1.2.3 Project workflow and tasks

The work in SENSEI advanced based on structured discussions between the expert group, the calculation group, and STUK during the main meetings as seen in fig. 1-9 and additional teleconferencing meetings between the main meetings. The direction of the work was determined by topics and issues raised by the international expert group.

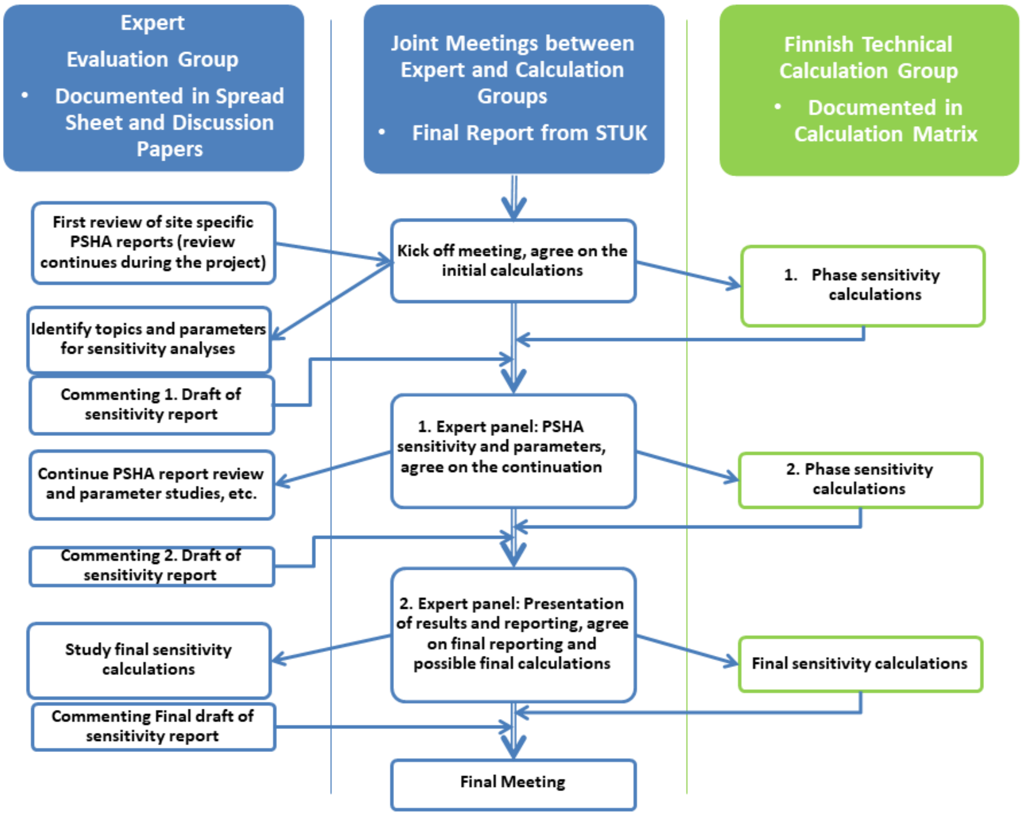


Fig. 1-9. The main meeting structure of the project

As shown in Fig. 1-9, expert group reviewed licensees' PSHA reports and identified parameters and methodologies for sensitivity analyses. At the same time calculation group established calculation models, made analyses as agreed with expert group. Results and findings were listed and closed. At the beginning it was agreed a baseline, around which chain of parameter studies were collected. Some findings turn out to need separate academic research and corresponding list was also made.

Expert team wrote explanatory descriptions to support common understanding in workshops and ensuring that calculation team was analysing correctly. Calculation team wrote a calculation report, where calculation matrix was presented and numerical results describing the sensitivity between parameter changes and hazard values. STUK's part was to collect and understand studied issues and sensitivities from its own point of view and to write the final report (this one).

1.2.4 Products of SENSEI

The main results to STUK from the SENSEI project are as follows: a deeper understanding of the most influential parameters and assumptions in hazard studies, justified or best estimate values for the aforementioned parameters and methodologies, benchmarking or international comparisons of the used methodologies and assumptions, and the identification of seismic research needs and topics for follow-up projects.

The documentation created in the project include STUK's summary report (this document), sensitivity report written by the calculation group (Appendix 2), project documentation including an excel spreadsheet used for managing and summarizing topics discussed with the experts, topic-specific short papers and presentations by experts. An additional task performed under the auspices of SENSEI was a master's thesis Rinne (2021) on the local studies of the Kappa parameter . STUK also received the OpenQuake calculation models used in SENSEI for in-house calculations and independent comparison studies.

2 Site specific PSHA reports under review

This section summarizes the site-specific PSHA studies that have been used as the reference material for the SENSEI project. The utilities initiated new studies after the authorisations 2010. Fennovoima started an extensive PSHA project in 2013. Re-evaluation of seismic hazard of the existing sites also became topical when new units were planned around 2010. Although the plans for new units by Fortum and TVO were not realized, the update of seismic hazard was still necessary according to the more explicit periodic update requirements in the new Guide YVL B.7 published in 2013. Fortum and TVO carried out the new PSHA studies in cooperation. Although Fortum and TVO were not in cooperation with Fennovoima, there were some common features, for example, in the definition of seismic source areas and treatment of the maximum magnitude due to the role of Helsinki University Institute of Seismology (ISUH) and ÅF/AFRY as consultants in both projects.

2.1 Loviisa and Olkiluoto

Fortum and TVO developed in 2014–2015 a plan for updating the Loviisa and Olkiluoto PSHAs. The licensees carried out the update in co-operation during 2015 – 2017. The hazard curves were calculated in the first stage (Saari and Malm 2016). The ground response spectra were calculated at the second stage (Malm and Kaisko 2017). In the updated PSHA, the seismic source areas, logic tree and maximum magnitude were redefined, and minor updates were made in the GMPEs.

The PSHA computation was carried out with the EZ-FRISK programme, whereas in in the VNS study in 2000 the SEISRISK III programme was used. The programmes use similar methods, and the change of program is not supposed to affect the results.

These studies were submitted to STUK only by TVO. Fortum continued the work for Loviisa and made some additional updates in GMPEs and in the hazard calculation in 2018 (Leppänen 2018). These calculations gave slightly higher PGAs, and the results were submitted to STUK in 2019 in the early stages of the SENSEI project. However, in the sensitivity calculations in the SENSEI project the VNS GMPEs described in (Leppänen and Varpasuo 2017) were used. The version of the VNS GMPEs used has no effect on the conclusions because a different set of GMPEs (NGA East) was selected for the sensitivity studies.

2.1.1 Earthquake catalogue

The earthquake catalogue was developed using the ISUH database covering historical and instrumental observations up to 2012. ISUH has removed fore- and aftershocks and nontectonic events (explosions, frost event) using a simple windowing technique and homogenized the magnitude scale using methods described by Korja & Kosonen (2015).

The observation threshold magnitude varies at different time periods. The threshold magnitude above which the catalogue can be considered complete was estimated separately for each seismic source area using a catalogue model presented by Kijko and Sellevoll. (1989, 1992). The time period covered by the catalogue was divided to a period of historical observations and a period of instrumental observations. The instrumental period was treated as one period or divided into early instrumental and later instrumental periods with different threshold magnitudes.

The coverage and completeness of the seismic instrumental records in the vicinity of the Loviisa NPP are debatable as there are less observations in the eastern part of the Fennoscandian shield. This is either due to a seismic quiescence or due to incomplete historic records - or both. To assess the seismicity near Loviisa NPP this is essential. The Loviisa NPP is located on the Wiborg rapakivi batholith which is one of the youngest batholiths in Finland. The seismicity in the batholith is characterized by shallow low-magnitude swarms that are felt or observed by local residents. The batholith is only 10 km deep, and batholith extends to the Russian territory, making the seismicity analysis a cross border challenge. Most of the batholith belonged officially to Swedish Kingdom after 1617 peace treaty, but the borderline was relocated towards west in 1721 and 1743, and during Finnish Autonomy in Russian Empire the border was returned eastwards in 1812. The current line was drawn in 1944. During the Soviet era, no macroseismic data could be collected in the vicinity of the border. The current borderline also divides the area by language, culture, and traditions, all of which pose obstacles in the investigation of pre-instrumental earthquakes. Moreover, pre-instrumental offshore seismicity is difficult to parameterise, even if the area of interest is located inside one country. Therefore, the FENCAT-catalogue is understood to be inhomogeneous in the area with respect to the historical timeline and geographical coverage. The current observations show that the swarm-like earthquakes occur in the western part of the batholith. Seismic monitoring of the Wiborg rapakivi granite batholith improved in 2003, when the station VJF was installed close to Russian border.

The uniform seismicity in the rapakivi batholith area is not unambiguous. The current observations confirm similar seismic swarms near the cities of Kotka and Wiborg. For the delineation of seismic source areas there have been several approaches for seismic hazards assessment: the whole area with low magnitude earthquakes can be merged to a larger source area covering the whole southern Finland (European scale), the area can be delineated according to the geologically known batholith (see below), or the western part with most of the observed earthquakes can be separated based on arguments concerning the existing seismological observations (see the calculation example below). In any of these cases, the possibility of larger and deeper earthquakes in the batholith or in the surrounding bedrock even below the batholith, cannot be excluded.

2.1.2 Seismic source areas and G-R parameters

In the new Loviisa PSHA studies started in 2015 by Fortum, the seismic source area delineation was thoroughly revised as compared to the earlier VNS study. The seismic source areas for southern Finland were defined by a group of seismologists and geologists from Finland and neighbouring countries as described by Korja et al. (2016).

A significant new feature is that the Wiborg rapakivi area, where the Loviisa power plant is situated, is treated as a separate seismic source area (see SSA 10 in Fig. 2-1. showing the lithotectonic units and the seismic source areas). Swarms of small earthquakes are typical of the rapakivi area and may require special attention in modelling source area seismicity with the Gutenberg-Richter equations.

The rapakivi granite is approximately 1650 million years old, lighter and younger than the surrounding bedrock. The area has an unusual seismicity of shallow earthquake swarms, and in addition there are no lineaments in this area. (Korja and Kosonen, 2015). According to the calculation team, the earthquake swarms are typically located in the uppermost 2 km of the crust. Elo and Korja (1993) have suggested that the rapakivi granite extends down to the depth of 10 km at least.

In the study by Korja et al. (2018) the Wiborg rapakivi granite area is seismic source area no. 10 in Figure 2-1. It is larger than the previous rapakivi area sources and covers larger portions of the Gulf of Finland and the Russian territory.

The same source area delineation was used for both Loviisa and Olkiluoto, but in the PSHA calculation only the source areas or parts of source areas within a 300 km radius from each site were considered, as shown in Fig. 2-1. Hanhikivi is also presented on the map with a demonstrative 300 km circle around it.

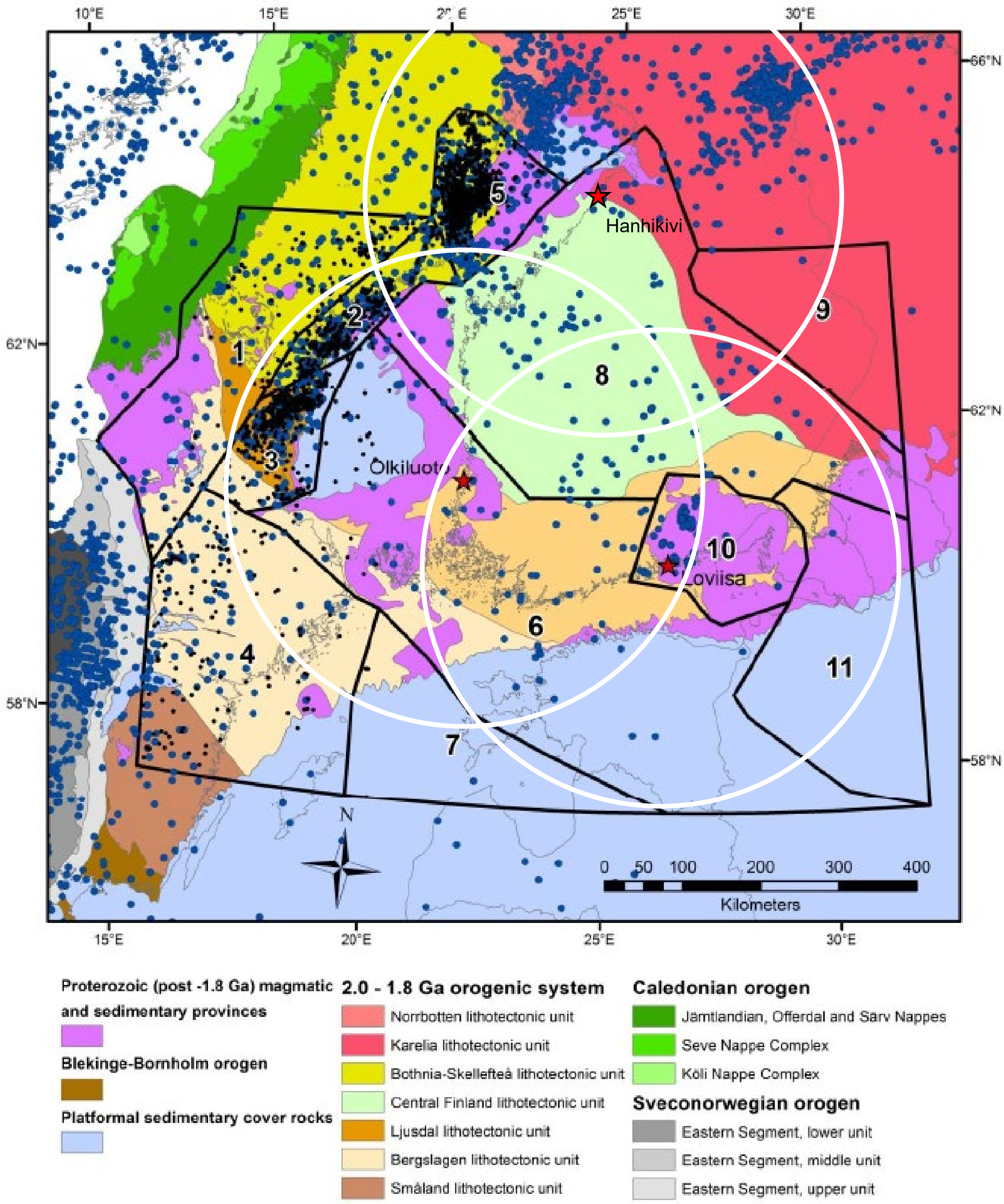


Fig. 2-1 The geological setting of Finland. Loviisa NPP is located clearly on the Rapakivi batholith, but Olkiluoto and Hanhikivi are on the southern and norther edge of the central Finland's granite massif [modified from Korja et al. 2016]

G-R parameters β and λ with their uncertainties δ_β and δ_λ were calculated for each seismic source zone. An individual minimum magnitude ($M_{min\text{-}cat}$), based on completeness, was used in fitting the parameters of the G-R equation for each SSA. The $M_{min\text{-}cat}$ magnitude was taken as the lowest threshold magnitude for completeness in the different observation periods (historical, early instrumental and later instrumental periods).

A uniform focal depth distribution was used ranging from 0 to 35 km or 45 km depending on the source area as described in (Korja et al. 2016).

2.1.3 Minimum magnitude

In the hazard calculation, the minimum magnitudes ($M_{min-haz}$) were chosen to be identical to the threshold magnitudes $M_{min-cat}$ of catalogue completeness for each SSA, which were also used in G-R-parameter calculation as described above. The $M_{min-haz}$ values range from 0,7 to 2,0. These values are much lower than the international practice and the $M_{min-haz}$ value was considered in the sensitivity calculations.

2.1.4 Maximum magnitude

In the hazard calculation, maximum magnitudes 5,5; 6,0; 6,5 and 7,0 were used with respective weights 0,70; 0,22; 0,06 and 0,02 for Loviisa and 0,72; 0,21; 0,06 and 0,01 for Olkiluoto. The maximum magnitudes and their weights were determined by Kijko's method (Kijko 2004). Kijko's method and an alternative Bayesian method are discussed in section 3.5.1 in connection with the SENSEI sensitivity calculations.

2.1.5 GMPEs

For the 2016 update of the Loviisa and Olkiluoto hazard curves the VNS GMPEs (Varpasuo et al. 2000) based on the Saguenay and Newcastle data sets (see also section 1.1.4.1) were reviewed and compared to recent Fennoscandian measurements (Lahtinen and Varpasuo 2016). The VNS GMPSs were found to correspond reasonably well to the new data. However, Fortum made some minor updates in the GMPEs and in the calculation of σ as described by Leppänen and Varpasuo (2017).

- Magnitude range was enlarged to two new magnitudes M 6.5 and M 7.0 not studied earlier
- Frequency range was enlarged to two new frequencies f = 50 Hz and f = 70 Hz not studied earlier
- Minor inaccuracies in recording station epicentral distances were corrected
- All fittings of GMPEs against recorded data were revised and checked using OriginPro 2016 software.

The VNS GMPEs published in 2017 were already used by ÅF in the in the update of the hazard curves (Saari and Malm 2016) and the ground response spectra (Malm and Kaisko 2017).

2.1.6 Logic tree

The PSHA logic tree included, in principle, five levels of choices as shown in Fig. 2-2 for Loviisa, but only one source area delineation was used in level 1. In level 2 three choices were used for the Gutenberg-Richter parameter β: its mean value and mean β and the lower bound $\beta - \delta_\beta$ and upper bound $\beta + \delta_\beta$. In level 3 three choices were used for the Gutenberg-Richter parameter λ: its mean value λ and the lower bound $\lambda - \delta_\lambda$ and upper bound $\lambda + \delta_\lambda$. In both cases the weights were 0,68, 0,16 and 0,16, respectively.

In level 4, four choices were used for M_{max}: 5,5; 6,0; 6,5 and 7,0 with site-specific weights.

In level 5, four choices of the GMPEs were used: SaguL, SaguT, NewcL and NewcT with the respective weights 0,3; 0,3; 0,2 and 0,2. These GMPEs are based on longitudinal and transversal accelerations of the Saguenay and Newcastle data sets, see also section 1.1.4.1. The total number of calculated cases is 3 × 3 × 4 × 4 = 144.

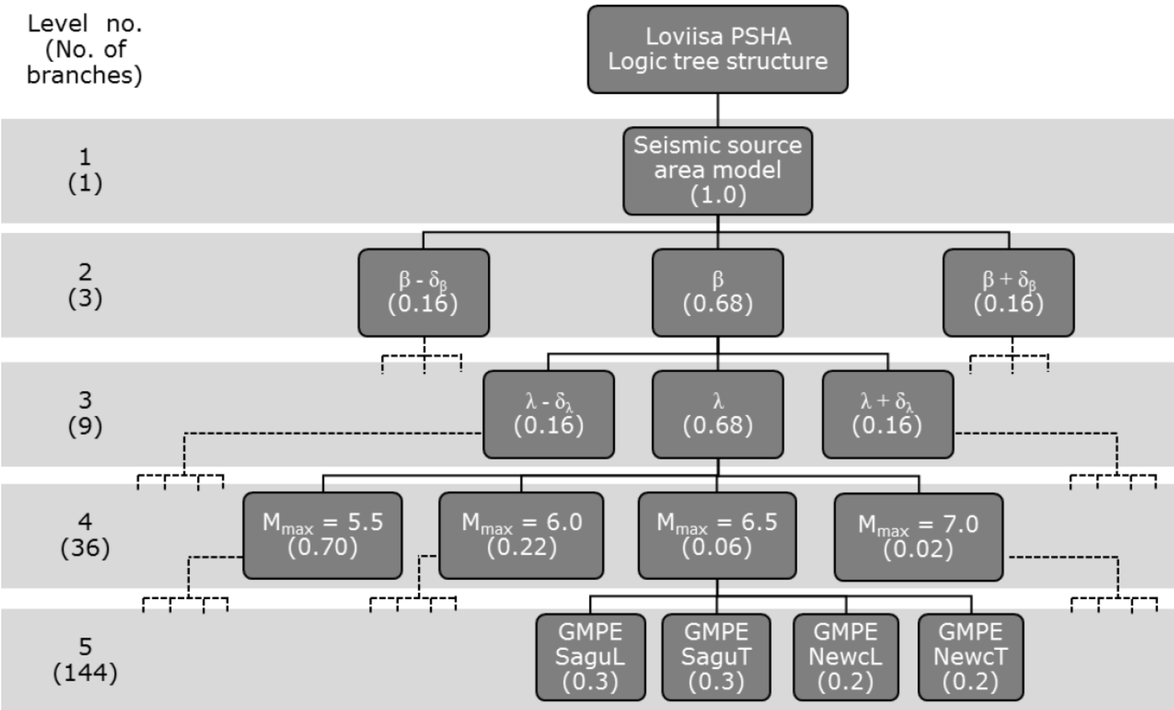


Fig. 2-2 The PSHA logic tree used in the Fortum (2017) study.

2.1.7 Results

The result of the PSHA computation was the horizontal site ground response spectrum corresponding to the design basis earthquake return time 100 000 years for different confidence levels and the hazard curve (exceedance frequency as a function of PGA) for the median, 5% and 95% confidence levels. The updated hazard curves for Loviisa and Olkiluoto are shown in Fig. 2-3. The updated hazard curves are less steep than in the earlier VNS study, meaning increased risk of high accelerations. For Loviisa the design basis PGA (median at AFE 10^{-5}) is higher than in the VNS study whereas for Olkiluoto it is lower.

The ground response spectrum shown in Fig. 2-4 was calculated in a later study (Malm and Kaisko 2017) for frequencies 0,3 Hz, 1 Hz, 5 Hz, 10 Hz, 25 Hz, 50 Hz, 70 Hz and PGA.

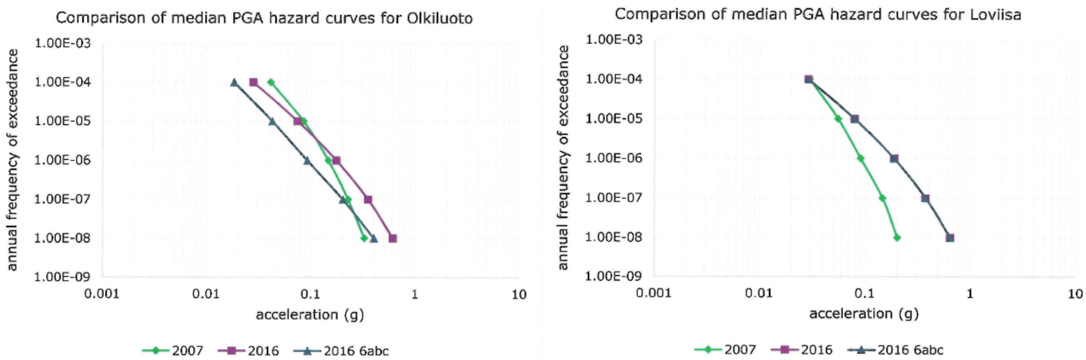


Fig. 2-3 Median PGA Hazard curves for Loviisa (left) and Olkiluoto (right) according to the VNS Study (Varpasuo 2007) and ÅF-Consult study (Saari and Malm 2016). The curve 2016 6abc refers to a sensitivity case where the Olkiluoto host source area 6 is divided into three regions 6a, 6b and 6c.

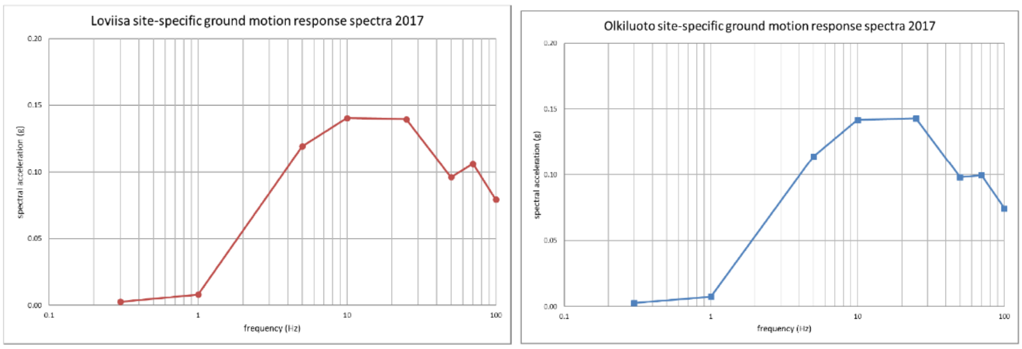


Fig. 2-4 Median ground response spectra for Loviisa (left) and Olkiluoto (right) according to Malm and Kaisko (2017).

2.2 Hanhikivi

The current seismic design basis and hazard studies are presented in the Seismic design basis of Hanhikivi 1, (Helander 2018) and additional spectra at lower annual frequency levels were presented in the report by Malm (2015).

Other background information and previous studies used in the SENSEI project are: (Saari 2015), (Saari et al. 2015), (Korja & Kosonen 2014) and (Kaisko 2017).

A uniform focal depth distribution ranging from 0 to 45 km was used for all seismic source areas. A sensitivity calculation was also carried out using a depth distribution of 0 to 30 km. (Saari et al. 2015).

The Hanhikivi seismic hazard studies have many common features with the Loviisa and Olkiluoto hazard studies. The Hanhikivi studies were carried out in 2013 - 2015 and some corrections and updates were made in 2018. The Loviisa and Olkiluoto studies were carried out in 2016 – 2018. Mainly the same consultants and international experts participated in both studies and some of the approach developed in the Hanhikivi project were later applied in the Loviisa and Olkiluoto studies. The most significant difference is the development of a new GMPE (Vuorinen et al. 2018) also known as referenced Pezeshk, which were used together with the Pezeshk GMPE (Pezeshk et al. 2011) in the Hanhikivi study whereas the VNS GMPEs were used in the Loviisa and Olkiluoto studies.

2.2.1 Earthquake catalogue

The main source of earthquake observation is the FENCAT catalogue. The parametric earthquake catalogue FENCAT covers the years 1375–2011. Macroseismic datapoint (MDP) datasets have been complied for 20 historical earthquakes, which has led to some changes in the non-instrumental part of the FENCAT. The instrumental dataset from FENCAT has been supplemented with a preliminary version of the 2012 earthquake catalogue and a micro-earthquake catalogue for 2000-2013 in Sweden. Mining-induced seismic events as well as events with questionable seismic origin have been removed from the data within or close to the study area (Korja and Kosonen 2015, Korja et al. 2016, Korja et al. 2018).

2.2.2 Seismic source areas and G-R parameters

Seismic source areas for the Northern Scandinavia were drawn up independently by two expert groups with members from Finnish and Swedish expert organizations. The source area delineations 1 and 2 are shown in Fig. 3-3.

G-R parameters were calculated in the same way as in Loviisa and Olkiluoto PSHAs, see section 2.1.2.

2.2.3 Minimum and maximum magnitude

In the hazard calculation, the minimum magnitudes ($M_{min\text{-}haz}$) were chosen to be identical to the threshold magnitudes $M_{min\text{-}cat}$ of catalogue completeness for each SSA, which were also used in G-R-parameter calculation in the same way as in Loviisa and Olkiluoto PSHAs, see sections 2.1.2 and 2.1.3. The $M_{min\text{-}cat}$ values range from 0,4 to 2,3 for the Hanhikivi SSA delineation 1 and from 0,4 to 2,2 for SSA delineation 2.

Maximum magnitude values of 5,5; 6; 6,5 and 7 were used with respective weights 0,70; 0,22; 0,06; 0,02. The weights were determined with the Kijko method (Kijko 2004.)

2.2.4 GMPEs

New GMPEs were developed in the Hanhikivi study based on Fennoscandian measurements. The new GMPEs reported by Vuorinen (2015) and Vuorinen et al. (2018) are of the referenced Pezeshk type (Pezeshk et al. 2011). The new GMPEs were used in combination with the original Pezeshk GMPEs. An unusual feature in the study was the change of weights of the alternative GMPEs in the middle of the frequency scale. The reason was that the Fennoscandian measurements did not cover sufficiently the relevant magnitude and frequency scale range.

2.2.5 Logic tree

The logic tree is otherwise similar to the one described with the Loviisa and Olkiluoto studies, but on level 1 two source area divisions were used with equal weights and on level 4 the Pezeshk and Vuorinen et al. (2018) GMPEs were used with weights varying with frequency. The logic tree was originally developed in the Fennovoima study and later used with minor modifications in the Loviisa and Olkiluoto studies.

2.2.6 Results

The latest results are presented in Fennovoima report FH1-00004885 (Rev. 3) Seismic design basis of Hanhikivi 1 (Helander 2018). The calculated hazard curve on the 2018 study and some earlier hazard curves are shown in Fig. 2-5. The uncertainties in the hazard analysis were considered quite large. Therefore, Fennovoima set the design basis PGA conservatively as 0,2 g.

The accepted design ground response spectrum for the Hanhikivi site is shown in Fig 2-6. For comparison, the figure also shows spectrum presented in the 2013 version of Guide YVL B.7 (actually OL3 design response spectrum) scaled to PGA = 0,2 g and the spectra calculated in the Hanhikivi 2018 PSHA and in the 2009 study with the VNS GMPEs.

The spectrum calculated in the 2018 PSHA has a distinctive shape with two peaks due to the change of weights of two different set of GMPEs in the middle of the frequency range. The design response spectrum was not based directly on the Hanhikivi PSHA but rather on expert judgement and the shape of the YVL B.7 (Olkiluoto) spectrum which was broadened to higher frequencies.

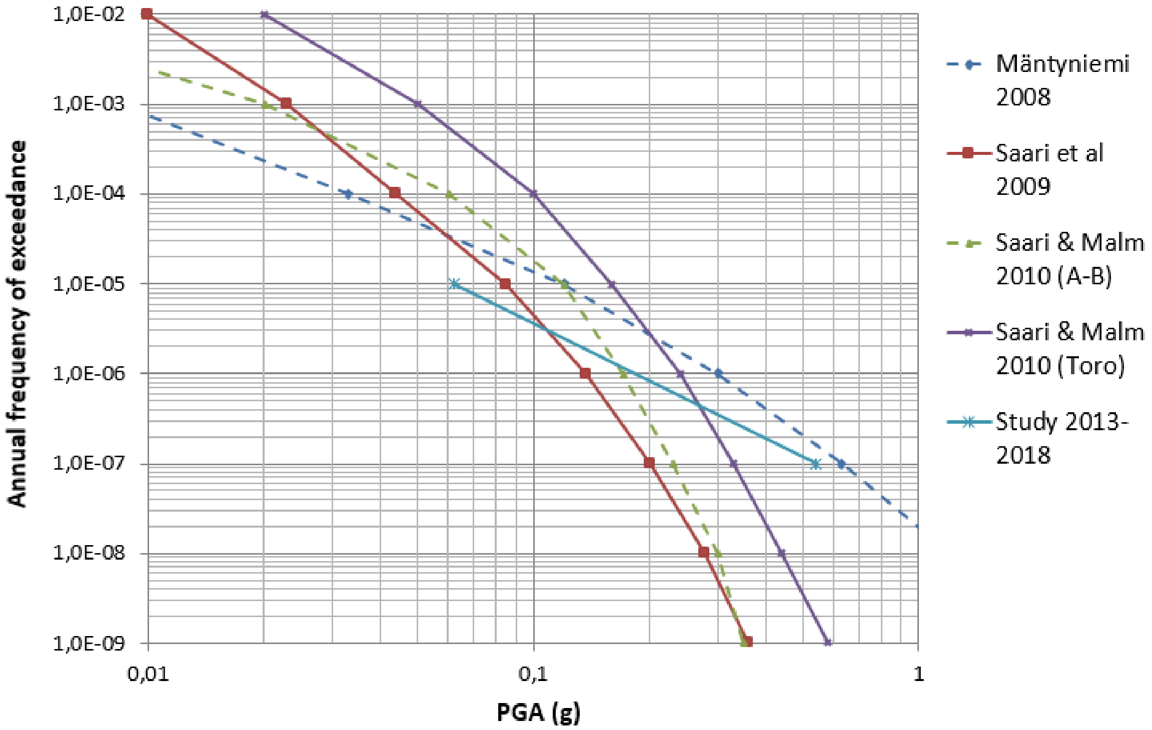


Fig. 2-5 Hanhikivi seismic hazard curves (median PGA) based on different studies. The results considered irrelevant are shown with dashed lines. The most recent results are shown by the curve named *Study 2013-2018* (Helander 2018).

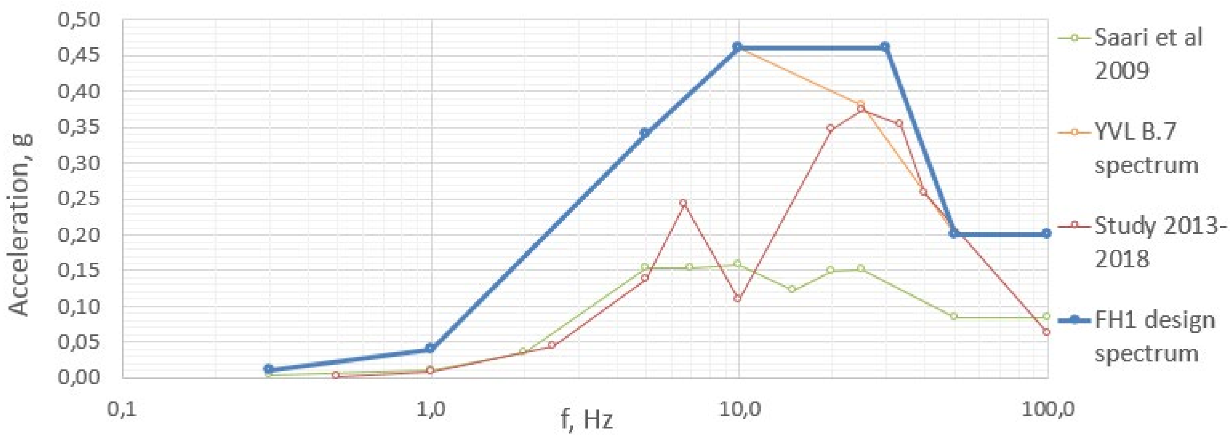


Fig. 2-6. Hanhikivi 1 design ground response spectrum, YVL B.7 example spectrum and the relevant calculated spectra (10^{-5}/a median 5% damping) for the Hanhikivi site (Helander 2018).

3 Topics and parameters for sensitivity analyses

The goal of the SENSEI project was to investigate sensitivity of seismic hazard predictions to different topics. Sensitivity to software, seismic source area models, activity parameters, maximum magnitude, minimum magnitude, depth distribution, ground motion prediction equations and model complexity have been investigated. This has led to a development of alternative assumptions and several discussions on used methodologies, especially on the completeness of the catalogue used. In addition, mean and median hazard as a design basis was discussed.

3.1 Software

Software EZ-FRISK (EZ-Frisk. Fugro USA Land, Inc. https://www.ez-frisk.com/) has been used in the reference studies conducted by the licensees and their consultants. Benchmarking references on EZ-FRISK (Thomas et al., 2010; Hale et al., 2018) were delivered by one of the experts.

The selection of suitable PSHA software for the sensitivity calculations was discussed at the beginning of the SENSEI project. Based on the recommendations on suitable software from the expert group OpenQuake software (OpenQuake-engine. 3.8. Jan 20, 2020. GEM foundation. https://github.com/gem/oq-engine) was chosen. Due to some benefits of OpenQuake, e.g., large logic trees, project SENSEI decided to migrate from EZ-FRISK to OpenQuake. A report of benchmarking the programs EZ-FRISK and OpenQuake in an established calculation example is available in open literature (Thomas et al., 2010). In addition, the SENSEI project carried out the verification of the two software by replicating the benchmark with a specific example, (Set 1 Case #10) from Thomas et al. (2010). In the SENSEI project some of the cases were calculated with both EZ-FRISK and OpenQuake. More details are available in appendix 3.1.

3.2 Seismic source area (SSA) models

Seismicity of Finland is diffuse and low. In general, no active faults or other seismogenic structures have been identified. Thus, seismic area sources represent homogenous seismicity in terms of earthquake activity rates and frequency-magnitude distributions. These seismic source areas (SSA) are defined as polygons for software input.

3.2.1 Dominant source areas

Based on the licensee's PSHA studies it was recognized that the seismic hazard of a site is dominated by the nearest source areas as seen in figures 3-2 and 3-4.

3.2.1.1 Loviisa and Olkiluoto

Olkiluoto and Loviisa share the same mapping of source areas (see Figure 3-1). Eleven source areas have been identified, but for each site only the SSAs that overlap the 300 km radius circle around the site are accounted for. Source areas used in the original studies are explained in more detail in Chapter 2. The numbering of the source areas has varied. In the following analyses the source areas 6 for southern Finland and 8 western and central Finland are the most dominant areas for Olkiluoto NPP, and the area 8 is relevant also for the Hanhikivi NPP. Source area 10 is the host area of the Loviisa NPP and thus the most dominant source area to Loviisa. As seen in Figure 3-2, most of the seismic hazard is due to source area no 10. The second most significance source area for Loviisa is source area no. 6.

As discussed in Chapter 2, SSA no. 10 is an area composed of Wiborg rapakivi granite that has an unusual seismicity of shallow earthquake swarms of low magnitude. According to the calculation team, the earthquake swarms are typically located in the uppermost 2 km of the crust. According to one of the experts, the unusual depth distribution may support lower maximum magnitudes, but more research on the subject would be required with an evaluation elsewhere in the world with a longer history of seismic observations in comparable circumstances.

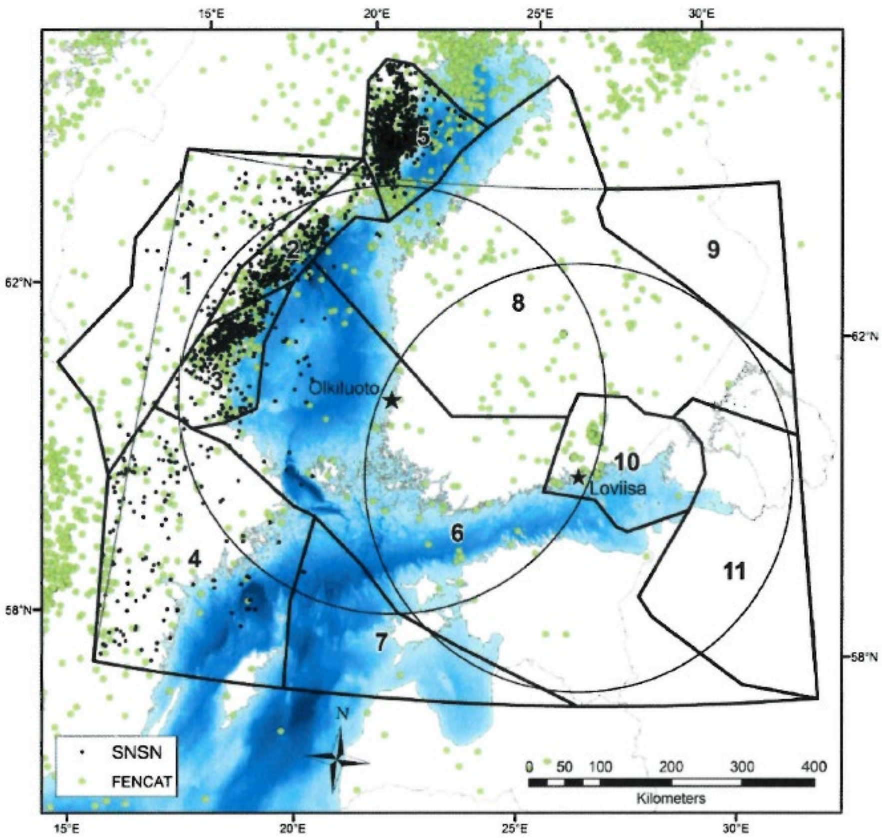


Fig. 3-1. Seismic area sources 1 to 11: the main division. The two circles with a 300 km radius encircle the NPP sites Olkiluoto and Loviisa denoted by stars. From (Korja et al. 2018).

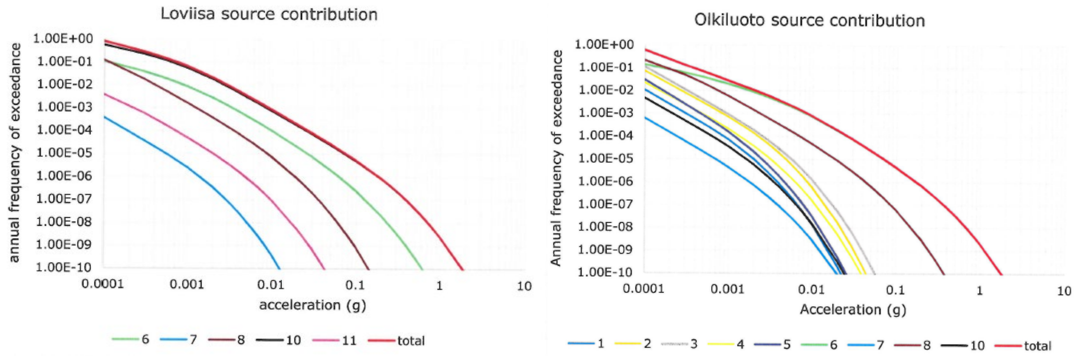


Fig. 3-2. The contributions of source areas to the hazard in Loviisa and Olkiluoto (Saari and Malm 2016).

3.2.1.2 Hanhikivi

In Hanhikivi, three alternative source area divisions were created, of which two models, 1 and 2, were used. In SENSEI they are called Map1 and Map2. The SSAs are presented in Figure 3-3. The SSAs 1.13 (SSA13 and SSA12 in the first model) and 2.11 (SSA11 in the second model) are the host source zones. For the Map1 calculations only SSAs 1.12 and 1.13 were used and for Map2 SSA 2.11 was used. In the SENSEI recreation process, SSAs 1.10, 1.12 and 1.13 were retained from Map1, and 2.5, 2.6 and 2.11 from Map2.

SENSEI developed a new seismic source zoning called Map4, comprising SSA 2.6 from Map2 (Fig. 3-3) and SSAs 5 and 8 from the Loviisa-Olkiluoto seismic source zone map (Fig. 3-1). In Map4, SSA8 became the host zone for the Hanhikivi NPP site, which was not the original intention of the developers of the Olkiluoto-Loviisa zoning. Hence, Map4 models can uncover unintended bias of zoning design.

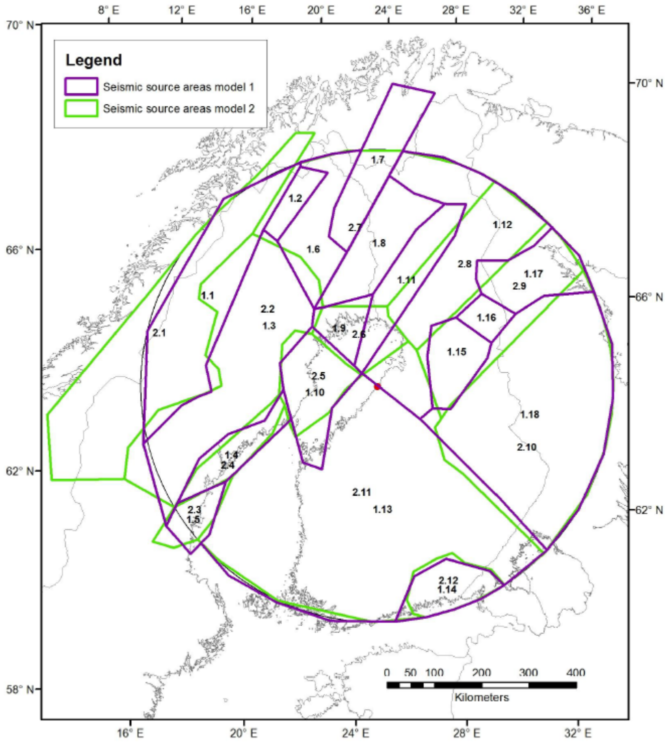


Fig. 3-3. Source area models 1 (purple) and 2 (green) for Hanhikivi (Korja and Kosonen 2015).

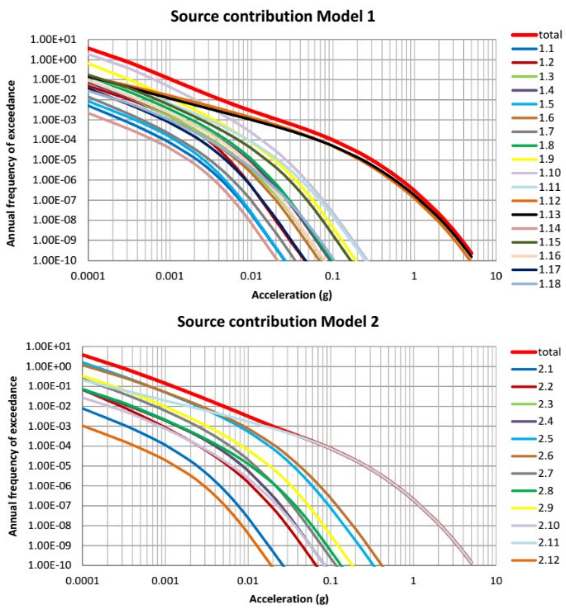


Fig. 3-4. The contributions of the source areas to the hazard in Hanhikivi (Saari et al. 2015).

3.2.2 Discussion and source areas in the sensitivity analyses

The expert group stated that the assumption that the seismicity rate per unit area in a source zone is constant may or may not be appropriate, depending on the spatial uniformity of the seismicity. The group stated that the issue may be particularly important for the source zones containing the site or very near the site and pointed out that Musson (2000) provides a nearest-neighbour simulation procedure to test the validity of the assumption.

Alternative SSA models were created based on the proposals by the expert group. The chosen alternative models can be thought as exercises, that can be argued to be as defensible as the original. The investigations with the alternative SSA models give information on the sensitivity of results to the hosting and nearby source areas.

3.2.2.1 Loviisa

It was pointed out by the expert group that the observed seismicity appears to be confined to the western portion of SSA no. 10 (Fig. 3-1), and thus source area no. 10 is uniform geologically rather than seismically. In addition, the seismicity per unit area of source area no. 10 is almost equal to that of source area no. 6, although one of the main arguments for a having the Wiborg rapakivi granite area as a separate source area has been the unique seismicity observed in the area (Korja and Kosonen 2015). According to the calculation group, the current geophysical or geological knowledge provides no explanation for the higher rate of observed seismicity in the western part of the SSA no. 10. The issue is complicated since the area is situated at a border zone between Finland and Russia. The seismicity data are more complete in the west of the batholith which has not belonged to Russia during the era of seismicity observations, and observations from the Russian territory started to be available only recently.

Different boundaries around the recorded seismicity were tested for SSA no. 10. SSA no. 10 was modified in two steps, which diminished the size of SSA no. 10 and increased that of no. 6 (Figure 3-5). The smallest version of SSA no. 10 is approximately one third of the largest one. No other area sources were included in the computations. The NGA-East weighted mean GMPE (Goulet et al. 2018) was used in the test. The calculation team noted that, with this approach, when attempting to obtain uniformity of seismicity in SSA no. 10, the geological uniformity of the contiguous SSA no. 6 was lost by assigning the eastern parts of the batholith to it. In other words, the new SSA no. 6 comprised parts of different tectonic regimes. More in-depth discussion on the choice to split SSA 10 is given in appendix 3.2.

Fig. 3-5. Two alternative designs of the seismic source area no. 10. Available earthquake epicentres (green dots) and the divisions of area source no. 10 by red lines. The excluded area was added to source area 6. The star denotes the NPP site.

The test by Musson (2000) was done to the original design and the two variations of SSA no. 10. Musson (2000) suggests testing the randomness/uniformity of the spatial distribution of epicentres in the area source. Twelve epicentres were removed from the data set since they were not recorded by the national network. The test indicated significant clustering. According to Musson (2000), either some justifying argument must be produced as to why the clustering should be allowed on tectonic grounds, or it should be modified. The calculation team commented that although the word swarm has been used, a largest magnitude, or a few largest magnitudes, can typically be discerned in the swarms, so they can also be understood as prolonged aftershock sequences, which challenges the capability of declustering algorithms to deal with very low-magnitude events.

The investigations on SSA no. 10 conclude that the split models given in Figure 3-5 appear more consistent with the observed seismicity than the original model, which supports transition from a uniform area of Wiborg rapakivi granite to SSAs where the distributions of observations are more uniform. However, as stated by the calculation group, the current geophysical or geological knowledge does not support higher rate of observed seismicity in the western part of the SSA no. 10 compared to the eastern part, and the issue may be more related to the completeness of catalogue than seismicity. The basis of SSA no. 10 has been that it is geologically uniform. In addition, if the unusual seismicity of SSA no. 10 is related to lower maximum magnitudes, splitting of SSA no. 10 may be a conservative assumption.

To provide information on the sensitivity of hazard prediction to SSA no. 10, a sensitivity study with the more conservative alternative model was done. The alternative source area that was used in the sensitivity analyses is the smallest alternative model presented in Figure 3-5. Only the westernmost third of SSA10 was retained, and the remaining part was merged with the contiguous SSA no. 6. The alternative SSA model was used alone as a single branch or together with the original design as weighted branches of the logic tree. In the weighted model, 0,33 weight was assigned to the split SSA branch, and 0,67 to the branch containing the original configuration of SSA no. 10.

3.2.2.2 Olkiluoto

No suggestions on alternative seismic source area designs were proposed for Olkiluoto. The border between the two relatively aseismic source areas 6 and 8 in Fig. 3-1 could be re-drawn according to geological features and relocated to the south of the Olkiluoto NPP as in the seismic source area delineation of the VNS study (Fig. 1-4). In the seismicity study by Saari and Malm (2016), the source area 6 has been divided into several sub-areas 6abc as in (Korja et al. 2016). However, there are no obvious alternative seismic source areas near Olkiluoto, and in SENSEI the focus was on the dominating SSAs no. 6 and 8 (Fig. 3-1).

3.2.2.3 Hanhikivi

In Map1, the site is located at the border between SSAs 1.12 and 1.13 (Figure 3-3). In Map2 the site is located clearly in SSA 2.11.

It was pointed out by the expert group that the source areas no. 8 and no. 6 of the Loviisa and Olkiluoto studies together are geometrically very similar to the hosting source areas 1.13 and especially 2.11 of Hanhikivi. In order to uncover unintended bias of zoning design, it was suggested that an additional SSA model should be constructed for Hanhikivi using the SSA 8 of the Loviisa and Olkiluoto model (Figure 3-1), and other compatible nearby SSAs from Map1 or Map 2.

Based on the proposal by the expert group, SENSEI developed a new seismic source zoning called Map4, comprising SSA 2.6 from Map2 and SSAs 5 and 8 from the Loviisa-Olkiluoto seismic source zone map. In Map4, SSA8 became the host zone for the Hanhikivi NPP site, which was not the intention of the developers of the Olkiluoto-Loviisa zoning. The sensitivity studies were made with the original Maps1 and 2 and the new Map4.

3.3 Parameters a and b of the Gutenberg-Richter relation

Parameters of the Gutenberg-Richter relation, λ and β, or a and b, define the seismicity of a specific source area, and it is evident that these G-R parameters have a significant impact on the seismic hazard results. G-R parameters are related to the completeness of catalogue in different time periods, which could not be investigated in SENSEI. However, completeness of catalogue was discussed. G-R parameters are source area specific. Seismic sources of the models are discussed in Chapter 3.2.

3.3.1 Gutenberg-Richter parameters of the dominant SSAs

As discussed in Chapter 2, the calculation of the G-R parameters a and b has been done according to Kijko and Sellevoll (1989, 1992) as explained by Korja et al (2016). G-R parameters were calculated for each SSA considering events down to the minimum magnitude of the SSA in the catalogue.

3.3.1.1 Loviisa and Olkiluoto

The main characteristics of the zones (SSAs) based on the report by Korja et al (2016) for Olkiluoto and Loviisa were analysed by one of the experts. Activity rates were calculated for M_w = 4 and normalized with the area. Normalized seismic activity rates for M_w = 4 are presented in Figure 3-6, and Gutenberg-Richter b-values in Figure 3-7. The Gutenberg-Richter relationship for zones in Loviisa is given in Figure 3-8. The Gutenberg-Richter relationship for zones in Olkiluoto is given in Figure 3-9.

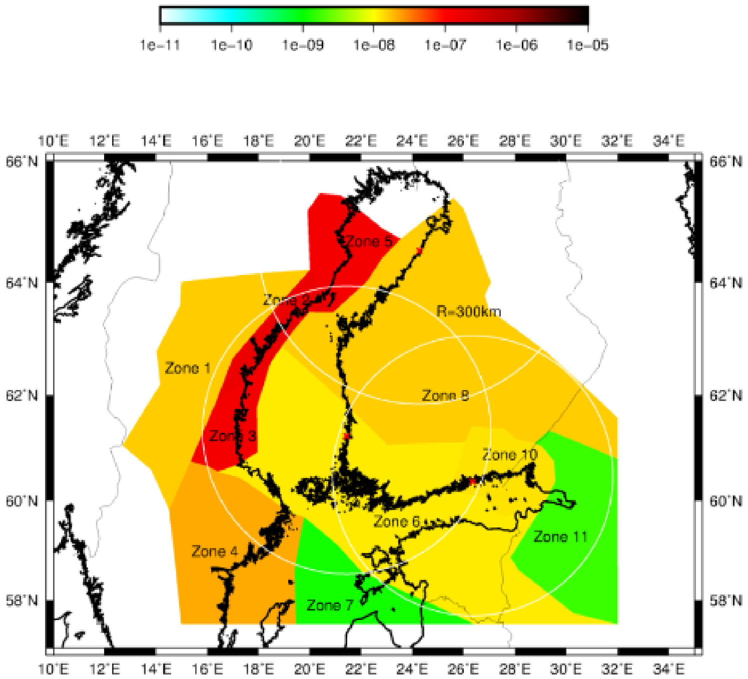


Fig. 3-6. Normalised seismic activity rates (events/yr/km²) for Mw =4 for Loviisa and Olkiluoto zonifications with 300 km circles around each site.

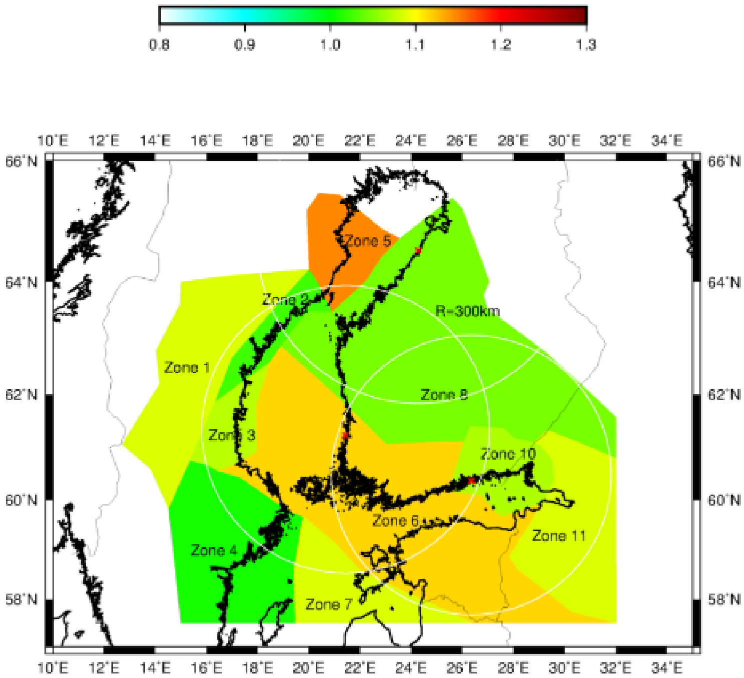


Fig. 3-7. Gutenberg-Richter b-value for Loviisa and Olkiluoto seismic source areas with 300 km circles around each site.

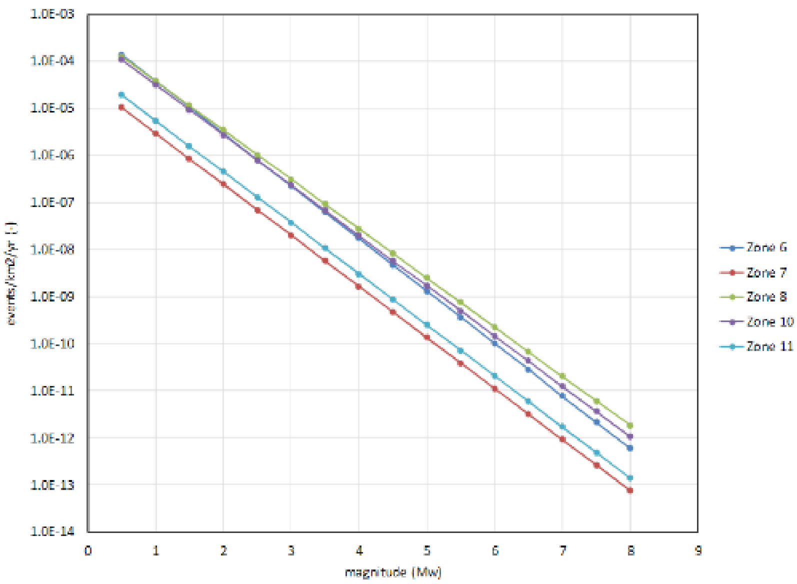


Fig. 3-8. Gutenberg-Richter relationship for seismic source areas around the Loviisa site

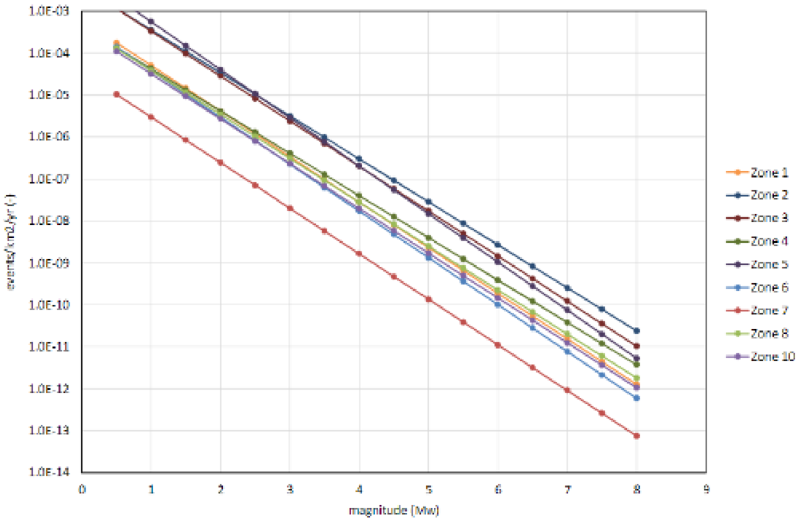


Fig. 3-9. Gutenberg-Richter relationship for seismic source areas around the Olkiluoto site

3.3.1.2 Hanhikivi

The main characteristics of the two source area delineations (zonifications) based on the report (Saari et al. 2015) were analysed by one of the experts using coordinates obtained from the report by Korja and Kosonen (2014). Activity rates have been calculated for $M_w = 4$ and normalized with the area. Normalized seismic activity rates for $M_w = 4$ are presented in Fig. 3-10 for the two zonifications, and Gutenberg-Richter b-values in Figure 3-11. The Gutenberg-Richter relationships for SSAs are given in Figure 3-12 and Figure 3-13.

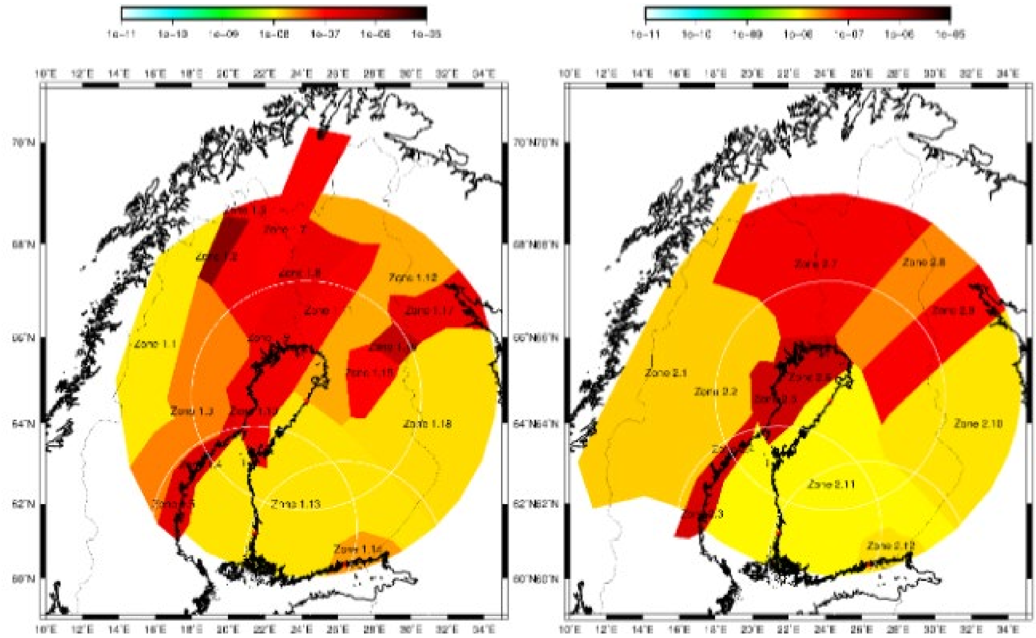


Fig. 3-10. Normalised seismic activity rates (events/a/km^2) for Mw =4 for zonification 1 (left) and zonification 2 (right) with 300km circles around Hanhikivi.

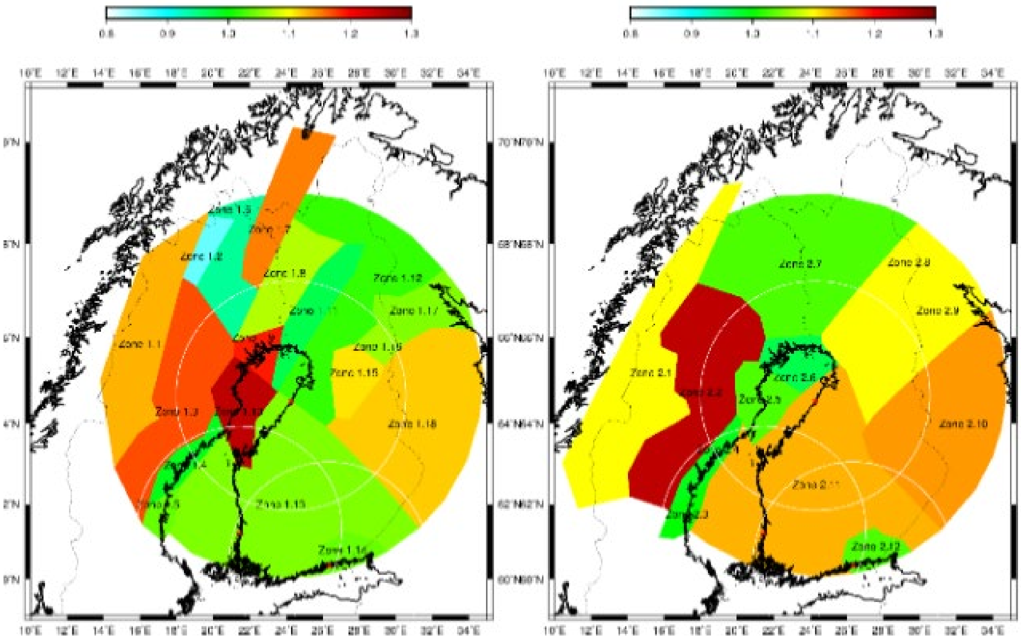


Fig. 3-11. G-R b-value for zonification 1 (left) and zonification 2 (right) with 300km circles around Hanhikivi.

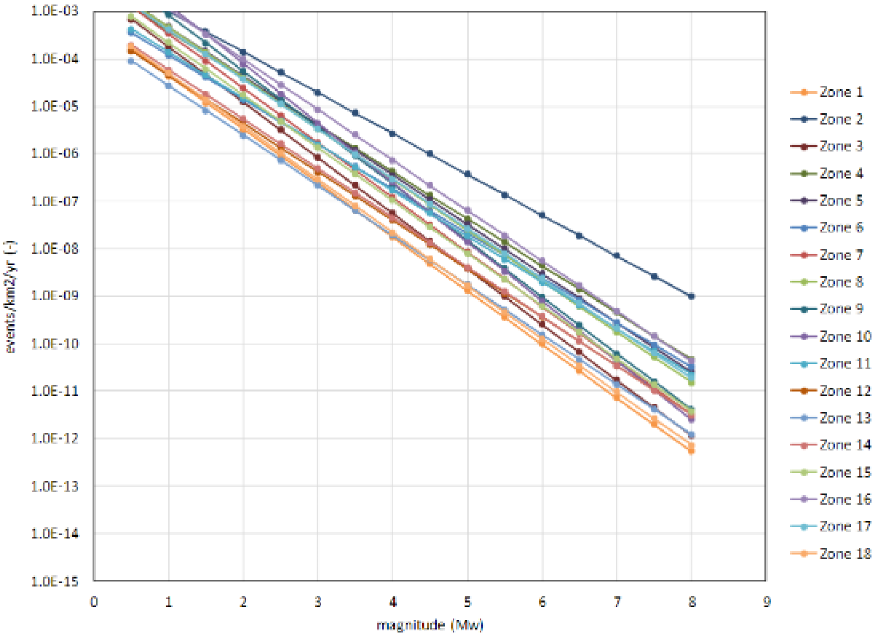


Fig. 3-12. Gutenberg-Richter relationship for zonification 1 around Hanhikivi

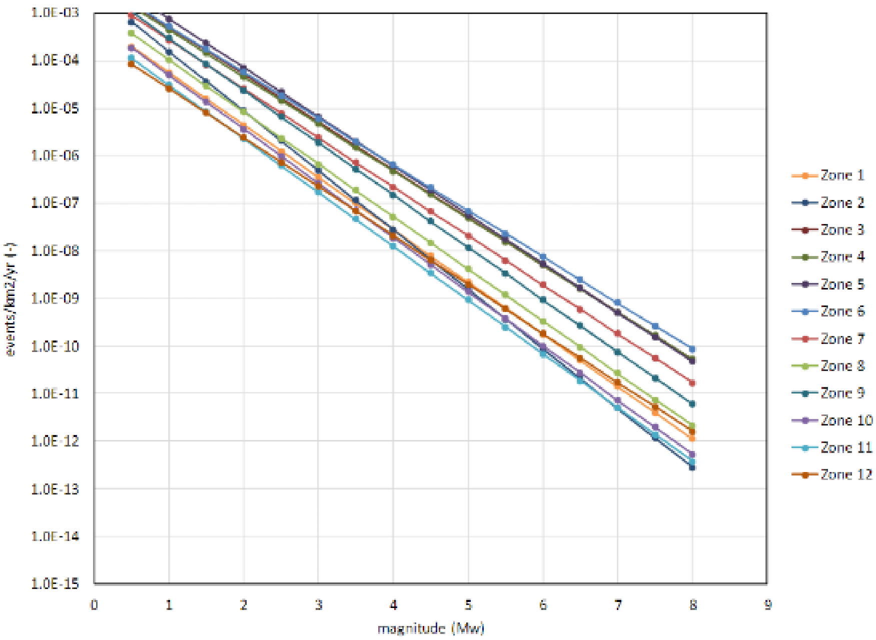


Fig. 3-13. Gutenberg-Richter relationship for zonification 2 around Hanhikivi

3.3.2 Discussion and determination of G-R parameters in the sensitivity analyses

Discussion on the completeness of the catalogue rose on several occasions during the project. Because the catalogue was not available, it was not possible to investigate the item further, and final conclusions on the completeness of catalogue were not made, although the small amount of data could indicate at least some level of incompleteness at least for larger historical earthquakes. Reviewing and continuous updating and homogenising of the catalogue could be a future research item.

The determination of Gutenberg-Richter parameters was challenging with the very limited data available, and it was not possible to draw conclusions on the G-R parameters used in the original studies. Thus, alternative choices for G-R parameters were not developed.

The λ value gives events of a specific magnitude. Magnitude rates for merged source zones 6, 8 and 10 of Loviisa and Olkiluoto SSA maps were compared by one of the experts. Based on the information found from Saari et al. (2015) and Korja et al. (2016), λ value of 0,0085 events per year was obtained for magnitude $M_w = 4$ for merged zones 6, 8 and 10. β value of 2,48 (b=1,1) was used. The λ value was compared to the G-R regression analysis done based on the information found on the observations. The analysis led to a λ value of 0,005 events / year, which is 60% of the value obtained in the original study. Thus, the expert concluded that hazard may be overestimated in the original study. On the other hand, the findings could be related to the completeness of catalogue. The findings indicate that reassessing the G-R parameters would be an interesting task, although it was not possible in SENSEI.

The slope of the G-R relation, the b value, or β, extrapolates the observed seismicity rates to magnitude ranges that represent non-observed seismicity. The effect of b, or β, can be more significant when the extrapolation is from small magnitude observations to a larger assumed M_{max}. As a sensitivity study, one set of calculations with different b values was carried out for Loviisa. An unaltered b value (1,07), a low b value (0,99; standard deviation subtracted) and a high b value (1,15; standard deviation added) were used for SSA no. 10, while the b value for SSA no. 6 was kept unchanged. To save resources, the study was not repeated to the other sites.

One of the experts pointed out, however, that the approach was incorrect, because branching as variable ±σ was not replicating the original distribution, assumed to be normal for both λ and β. In addition, the two variables a and b (λ and β) are not independent. The correlation coefficient (or COV) of λ and β is known from the report of the utilities. Branching λ and then independently branching β would have been correct only if they are independent (COV=0). If they are fully correlated (COV=1), then the high values of λ also imply high values of β, and the branches $\lambda + \delta_\lambda$ and $\beta - \delta_\beta$ should be excluded.

In the models used in the SENSEI project, variation of λ and β, or a and b, was modelled respecting the COV between λ and β as described in appendix 3.3. The modelled uncertainties were as in the original hazard studies.

3.4 Depth distribution

Earthquake focal depths determine the volume of the seismogenic crust and have significant effect on the seismic hazard prediction. In the previous hazard calculations, a uniform focal depth distribution was used ranging from 0 to 35 km or 45 km depending on the source area. The experts pointed out the need to analyse the effect of the different depth distributions around the NPP sites as Loviisa and Olkiluoto in southern Finland and Hanhikivi in northern Finland have different seismicity features and depth ranges (Mäntyniemi 2004), (Arvidsson et al. 1992), (Arvidsson and Kulhanek 1994), (Uski et al. 2012).

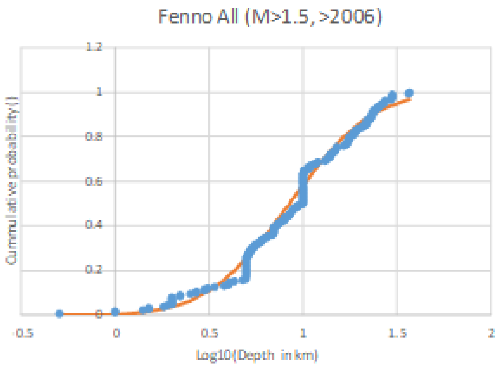
In Loviisa, the earthquake swarms in the Wiborg rapakivi massif are very shallow, typically located in the uppermost few kilometres. Very little seismicity is recorded near Olkiluoto, and the few observations available are shallow. Hanhikivi is situated in a very different environment, where also deeper earthquakes have been recorded. The depth distribution extends down to almost 36 km according to available data. Deeper earthquakes have also been recorded on the eastern coast of Sweden and the Gulf of Bothnia.

3.4.1 Depth distributions of the study regions

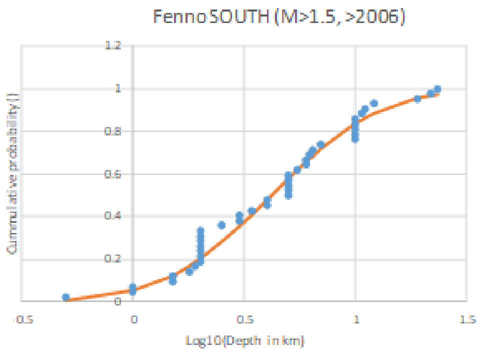
In SENSEI, the depth distributions of observations were examined by the calculation group. Some of the conclusions are summarised in appendix 3.4. The earthquake dataset used for the Fenno-G16 GMPE (from 2006 onwards) was extended with events between M1.5 and M2, resulting in a total of 188 events. The expert group noticed that there are numerous observations of events at depths 2 km, 5 km, and 10 km. One of the reasons is that the swarm-related events in the rapakivi massif around Loviisa are numerous and shallow. In addition, the quality of the depth determination is affected by the large azimuthal gaps, i.e., sparse seismic network compared to the earthquake depths resulting in repeated values in the depth estimations as noticed above. Thus, two data sets were used, the first with all 188 earthquakes and the second without depths 2 km, 5 km, and 10 km with multiple events.

Figure 3-14 shows the depth distributions for the entire dataset of 188 events, and for two subsets with events south of latitude 63ºN (42 events) and north of it (146 events). Latitude 63º runs about 200 km from both Hanhikivi and Olkiluoto, and Loviisa is situated further southward. Hence, depth distribution “North” is relevant for Hanhikivi and “South” for Olkiluoto and Loviisa. The depth of one M_w 1.8 event in the South subset was manually re-assigned from 0 km to 0,5 km in order to avoid problems in the log transformation. Figure 3-15 shows the corresponding depth distributions for the second, filtered, dataset.

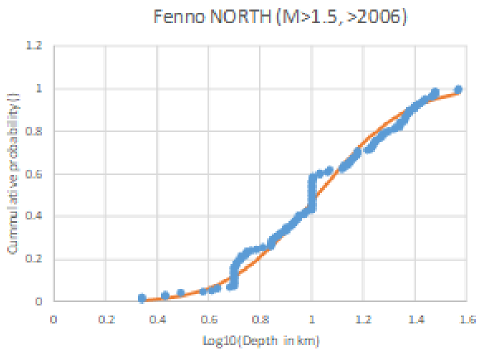
Veikkolainen et al. (2017) have also studied the differences between specific areas in the North, but the areas in that study were smaller.



a)

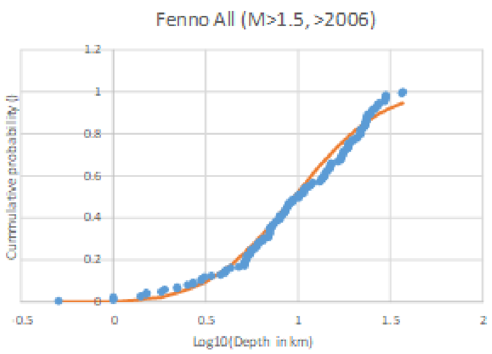


b)

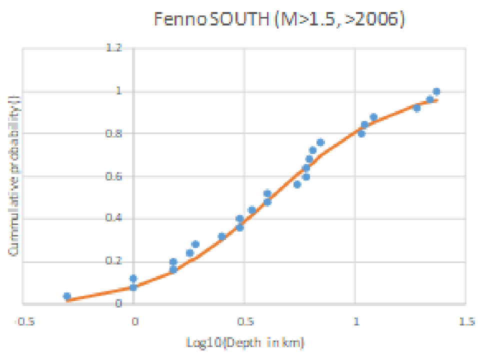


c)

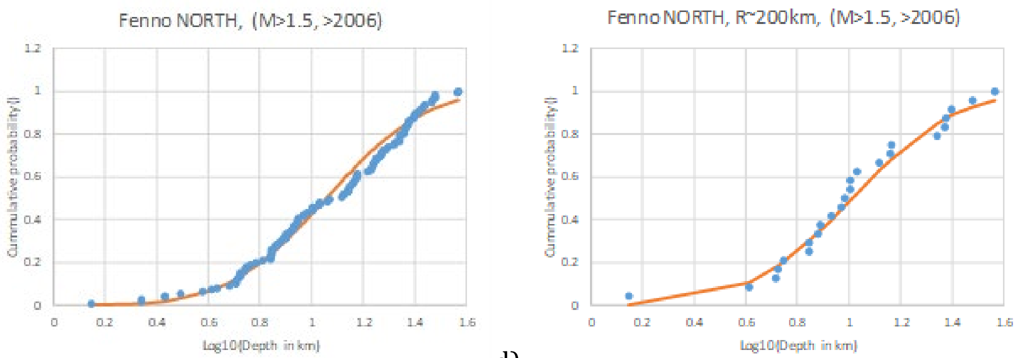
Fig. 3-14. Cumulative normal distribution of Log10(Depth) (orange) fitted to Fennoscandian depth distribution data (blue). a) represents the whole catalogue, b) represents the distribution of the southern sub-group and c) represents the distribution of the northern sub-group



a)



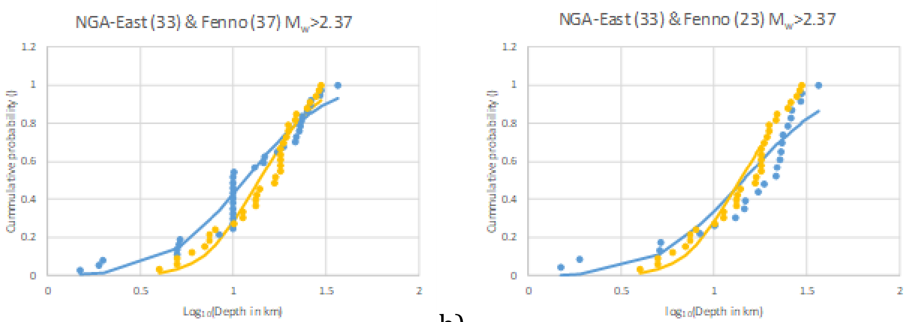
b)



c) d)

Fig. 3-15. Cumulative normal distribution of Log10(Depth) (orange) fitted to filtered Fennoscandian depth distribution data (blue). a) represents the whole catalogue, b) represents the distribution of the southern sub-group and c) represents the distribution of the northern sub-group, d) represents only the 24 data points closer than 200km of Hanhikivi 1

In addition, it was investigated, how much the Finnish depth distributions differ from the depth distributions of CEUS region found from the NGA-East dataset (Goulet et al. 2018). The investigation provides information on the differences of the regions, but it cannot be seen as an argument for any choice of depth distribution in Finland. Figure 3-16 shows the depth distributions of these NGA-East events and Fennoscandian events of comparative magnitude (M_w>2,37). In Figure 3-16a, all Fennoscandian events are included, while for Figure 3-16b the Fennoscandian events with depths 2 km, 5 km, and 10 km are removed. Based on the investigation, the spread of the depths is larger in Fennoscandia, but the mean appears comparable.



a) b)

Fig. 3-16. Normal distribution fitted to Log10(Depth). Blue dots are the Finnish data and blue lines the CDF fit to it. Orange are the NGA-East points and the corresponding CDF fit. In (a) for the Finnish data Median=1, Mean=1.06 and STD=0.34; in (b) for the Finnish data Median=1, Mean=1.16 and STD= 0.37. For the NGA-East data Mean=1.14 and STD=0.24 in both figures.

3.4.2 Discussion and depth distributions in the sensitivity analysis

It was discussed that the focal depth or depth range of the site zone probably have a significant impact on the results. The previous calculations by licensees (see chapter 2.2) have used a broad depth range from 0 km to 35 km (or 0 km to 45 km). It was suggested by the expert group that a mean focal depth of about 8 km could be applied, for instance uniform distribution from 6 km to 10 km, or from 0 km to 16 km.

Depth distribution and their treatment in EZ-FRISK was also discussed. Depth distributions are well represented by lognormal distributions, but EZ-FRISK allows only uniform distributions of depth. It was proposed that an equivalent uniform distribution could be formed by calculating hazard with 5 discrete depths representing the lognormal distribution and calculating hazard with a uniform distribution such that both hazards are close to equal.

Based on the discussion described above, the depth distributions North and South were determined for the PSHA calculations. The depth distributions are SSA dependent, but because in each SENSEI model only the SSAs closest to the investigated sites were included, Olkiluoto and Loviisa had only South distribution, and Hanhikivi had only North distribution. There was not sufficient data to estimate separate depth distributions for Olkiluoto and Loviisa. The suggested distribution is given in Figure 3-16, where both lognormal distribution and the corresponding uniform distribution are presented.

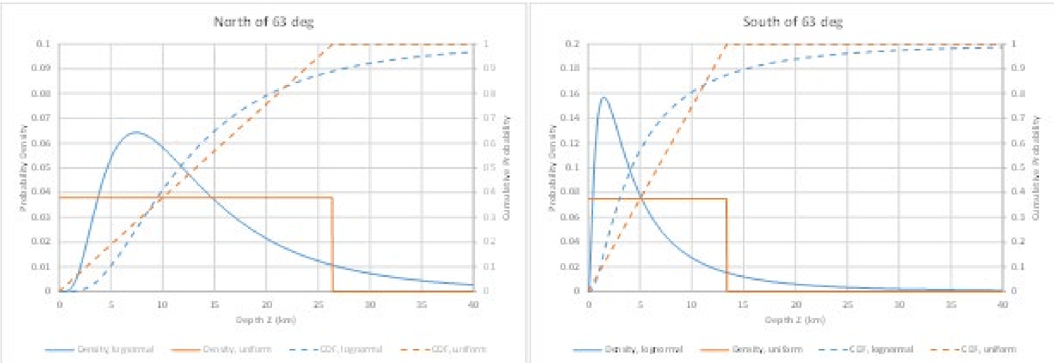


Fig. 3-16. Comparison of the uniform and lognormal distribution (G. Toro, SENSEI meeting slide)

EZ-FRISK defines the depth range using a minimum and maximum value. Between them, the uniform probability distribution is assumed. A single depth range of uniform probability distribution is proposed for the EZ-FRISK modes. EZ-FRISK input is given to SENSEI _ north (Hanhikivi) d_{min} 0 km, d_{max} 26 km and to SENSEI – south (Olkiluoto and Loviisa) d_{min} 0 km, d_{max} 13 km.

In OpenQuake, any distribution can be modelled using discrete depths without adding significantly to the complexity of the input files. For computational cost reasons, the 35km depth was divided in 14 and the 45km depth in 18 layers. Figure 3-17 presents how the data corresponds to the tracing of the intended lognormal distributions.

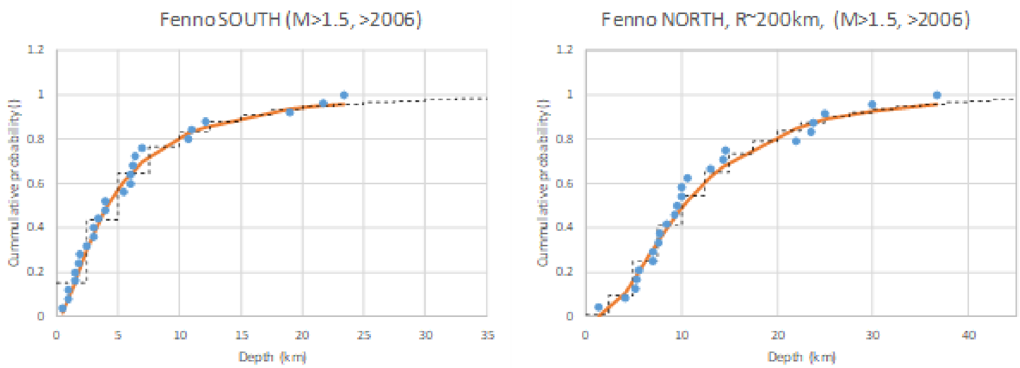


Fig. 3-17. Comparison between the target lognormal distribution (orange) and the discrete input of OpenQuake (dashed line) for the south and north depth distribution. Blue points represent the observed data points.

In SENSEI, the uniform depth distribution in Fig. 3-16 was tested only for Loviisa (0 – 13 km). For other sites, the developed alternative depth distributions were used only with OpenQuake and the lognormal distributions.

3.5 Maximum magnitude (M_{max})

Maximum magnitude gives the maximum magnitude used in the hazard integration influencing on the hazard predictions of especially lower frequencies of exceedance.

3.5.1 Maximum magnitude of the study region

It was stated by one of the experts and observed also in calculations that the 70% weighted maximum magnitude M_{max} of 5,5 controls the median values of the seismic hazard, and thus the other logic tree branches have practically no effect on the median ground response spectra. The M_{max} values of 6,0, 6,5, and 7,0 are included in the logic tree but they have no impact on the median hazard estimation.

It was also stated by the expert group that the dominating value 5,5 of the maximum magnitude is lower than values used in other countries. One of the experts stated that the considered values of M_{max} are lower than the values used in other countries in the same general region (e.g., Wahlström and Grünthal, 2000; Musson R. and Bungum H. 2011) and in other stable crustal regions (e.g., the CEUS-SSC study, NRC/DOE/EPRI, 2012). It is worth noticing also that Vanneste et al. (2016) suggest that a tentative value of 7,9 is used in all stable continental regions, however this purely statistical approach neglects many local seismic features e.g., stress regime, fault length and geometry, surface rupturing and observed seismicity.

The maximum magnitudes of the original studies are based on the method by Kijko (2004), which was criticised by one of the experts who proposed to consider also other methods such as the Bayesian approach. The two methods are discussed below.

3.5.1.1 Method by Kijko

In Kijko's method (Kijko 2004), the weights of the maximum magnitudes are estimated by applying fiducial inference. In this approach, M_{max} is interpreted as a random variable whose likelihood can be constructed as follows

$$\Pr[M_{max} < z] = 1 - \left(F_M(m_{max}^{obs}; z)\right)^n,$$

where $F_M()$ is the cumulative distribution function for the frequency magnitude (Gutenberg-Richter relation), m_{max}^{obs} is the maximum observed magnitude and n is the number of observations.

When applying this approach for a discrete set of values for M_{max}, e.g., {5,5, 6,0, 6,5, 7,0}, the likelihood function yields weights for the values after a normalization of the sum of likelihoods to 1.

While Kijko's method is widely used for the estimation of M_{max}, the method is also considered controversial. Fiducial inference is not generally accepted as a proper statistical inference method due to conceptual difficulties, see e.g. (Rønneberg 2017). In the context of the logic tree, conceptual ambiguities are unfortunate since it would be desirable to explicitly distinguish between aleatory and epistemic uncertainties.

A further problem with fiducial distributions is that they do not obey the probability theory axioms. For instance, the fiducial cumulative probability distribution for M_{max} derived by Kijko does not approach to 1 when M_{max} approaches infinity. Even if this issue could be resolved by a normalization of probabilities, it raises doubts against the approach.

The above-mentioned concerns with the fiducial inference (and Kijko's method) could be avoided by adopting the Bayesian approach, see next chapter.

3.5.1.2 Bayesian approach

In the Bayesian approach, a prior distribution needs to be defined for M_{max}. The worldwide data from other similar source areas are pooled to create a prior distribution of M_{max}, which is usually taken as normally distributed. The local information from the source zone of interest is used to construct the likelihood function. The posterior distribution of M_{max} for the source area is derived using the Bayes' Theorem.

To apply Bayesian approach in the PSHA logic tree context, the resulting (posterior) continuous distribution needs to be discretized. There are number of ways (principles) how to discretize a continuous probability distribution. One approach is to derive a discrete distribution that preserves moments (mean, variance, 3rd order moment, etc.) of the original distribution. Alternatively, one may fit the discrete distribution with the fractiles of the original distribution and preserve the mean value. Appendix 3.5 discusses the some of the pros and cons of the method, and the values used in the calculations.

3.5.2 Discussion and maximum magnitude in the sensitivity analyses

It was proposed by one of the experts that the following steps would be taken to obtain more defensible values of maximum magnitudes: consideration of source-specific maximum magnitude calculations in addition to regional maximum magnitude calculations; re-evaluation of the observed maximum magnitudes; and consideration of alternative approaches for the maximum magnitude calculations. In addition, conservatism in the methodologies used was advised by another expert.

As a sensitivity study, M_{max} was raised from 5,5 to 6,5 and to 7,5 for the simpler models. Finally, distributions of M_{max} were created with the Bayesian approach for the final more complex calculation models. The likelihood function in the Bayesian approach was updated using the Fennoscandian data. There was not enough data to develop new prior for the study region, and EPRI (2012), prior distribution for NMESE region was used. The final distribution of maximum magnitude is given in Table 3-1. The final distribution resulted in a median value on 6,64, which was not far from the studied value of 6,5.

Table 3-1. The continuous M_{max} distribution derived from the Fennoscandian likelihood function and the EPRI prior distribution discretized with Miller and Rice (1983) in 5 branches

Cumulative probability	Magnitude	Probability
0,0349	5,27	0,101
0,2117	6,10	0,244
0,5000	6,64	0,309
0,7883	7,14	0,244
0,9651	7,77	0,101

3.6 Minimum magnitude (M_{min})

In the previous Finnish PSHA studies, the used minimum magnitude M_{min} for the PSHA hazard integration has been source area specific and equal to the minimum magnitude used in the recurrence calculations ($M_{min\text{-}cat}$), which is not a standard practice according to the expert group. It was stated that too low a minimum magnitude complicates the interpretation of the results and comparison with other studies. Using a higher minimum magnitude also allows using published GMPEs that are applicable to moment magnitudes above 4 or 5. Currently GMPEs that enable the use of a smaller M_{min} e.g., 3-3.5 are available.

3.6.1 Minimum magnitude and CAV as a damage potential measure

According to the expert group, it is common practice to choose the minimum magnitude based on the damage potential of the earthquake. It was noted by one of the experts that minimum magnitude for the PSHA integration should be more of an engineering decision rather than a seismological one as discussed by Bommer and Crowley (2017). It was pointed out that EPRI NP-6389 (1989) has concluded that minimum moment magnitude of 5,0 is appropriate for PSHA of NPPs or other engineered structures and SHARE (2013) and UK maps use minimum magnitudes of 4,5 and 4,0 respectively. (Pagani M, et al. (2010), OECD (2019)) More detailed discussion can be found in Appendix 3.6.

It was proposed by one of the experts that cumulative absolute velocity (CAV) could be used to define damage potential of small magnitude earthquakes in Finland as described in the report *Use of CAV in Determining Effects of Small Magnitude Earthquakes on Seismic Hazard Analyses* by EPRI (2006). In the report it is stated that a CAV value of 0,16 g·sec has been defined in the past to characterize a conservative estimate of the threshold between damaging and non-damaging earthquake motions, and that based on that criteria moment magnitudes below 4,5 indicate very low damage potential. Moreover, it is stated that even the minimum moment magnitude 4,6 that has been used in the PSHA studies for the CEUS area may overestimate the hazard by including earthquakes that are not damaging but which contribute significantly to the hazard particularly in the high frequency part of the spectrum. It was concluded in the report that application of minimum CAV value reduces the contribution of small magnitude earthquakes resulting in a more realistic seismic hazard characterization. (EPRI, 2006) However, it is worth noticing that the threshold CAV value 0,16 g·sec is applicable for buildings of good design and construction (EPRI, 2006). Loviisa 1&2 and Olkiluoto 1&2 have not been originally designed against earthquakes, although seismic resistances of the units have been improved by continuous improvements. Thus, if a threshold CAV were to be used, unit specific or non-seismically designed NPP specific values should be determined. The calculation of CAV values from Finnish earthquake records was discussed as an interesting task to be considered, but the main focus was placed on M_{min}, which is another means to similar ends.

Minimum magnitude based on plant HCLPF (High Confidence of Low Probability of Failure) was also discussed. Reported perhaps outdated plant HCPLF values of the operating units of Loviisa and Olkiluoto were compared to the typical plant HCLPF values of the CEUS region by one of the experts. The comparison suggested a lower minimum magnitude than proposed by EPRI. A value of 4 was suggested but also considered conservative compared to the value used in SHARE (2013).

Acquiring a better justified M_{min} threshold would require more investigations on the fragilities of the NPPs in operation in Finland, which have not originally been seismically designed.

3.6.2 Minimum magnitude in the sensitivity studies

Based on the discussion described above, the same value for minimum magnitude for hazard integration was chosen for all SSAs, and value of $M_w = 4$ was chosen as the best estimate. Although minimum magnitude is not a typical parameter to be varied in a PSHA study, sensitivity to different minimum magnitude assumptions was investigated to give STUK and the calculation team understanding on the effect of the choice of minimum magnitude. Values 2, 3 and 4 were investigated, all of which can be argued as conservative values.

It should be pointed out that, unlike EZFrisk, OpenQuake models do not utilize λ as direct input. Instead, the parameters a, b, M_{min} and M_{max} are given, where a is the magnitude zero intercept of the G-R relationship. Using these parameters, a truncated G-R relationship is assumed in the OpenQuake models, between M_{min} and M_{max}. In the original EZFrisk models, the inputs were M_{min}, λ (corresponding to M_{min}), β and M_{max}. When M_{min} was altered, the G-R parameters were adjusted accordingly. In the case of Loviisa, the original minimum magnitudes were M_w = 2 and M_w = 0,7 for SSAs no. 6 and 10 respectively. The corresponding λ values were 0,563 and 1,972 events equal to or larger than M_{min} per year in SSAs no. 6 and 10, respectively. When increasing M_{min} to Mw=4, these values dropped to 0,0033 and 0,0006 events per year in SSA6 and SSA10, respectively.

3.7 Ground motion prediction equations (GMPEs)

Ground motion prediction equations (GMPEs) describe the attenuation of seismic waves from the earthquake source to a specific distance from the source. They have two main components: a mean prediction of the ground motion and the observed randomness of the ground motions (σ). GMPEs have significant effect on the shape of the calculated ground response spectra. It is important that the aleatory variability (σ) is adequately implemented in the hazard integration. It has been pointed out by Bommer and Abrahamson (2006) that the σ is often the source of increased hazard in recent PSHA studies. In addition, epistemic uncertainty of ground motion is typically incorporated in PSHA logic trees by a set of alternative GMPE branches with associated weights.

As discussed in Chapter 2, PSHAs on both Olkiluoto and Loviisa sites use VNS GMPEs that are based on only few records mostly from two strong motion events recorded at similar hard rock environments in Canada and Australia. The expert group was unanimous on the fact that the number of records is below the generally accepted level. In addition, these GMPEs treat transversal and longitudinal components of the records separately, which the expert group considered unorthodox. Also, other deficiencies were found, for instance the unclear treatment of the scaling with earthquake magnitude. Moreover, especially the most recently used sigma values were considered unconservative, because they were based only on few records, and at least for some frequencies the sigma values were significantly low indicating optimization based on few data points.

On the other hand, two GMPEs, Pezeshk et al. (2011) and a Fennoscandian GMPE (referenced Pezeshk, older version presented in Saari et al. 2015, and an updated version in Vuorinen et al. 2018) were applied for the Hanhikivi site. The equations have very different behaviours, which leads to an unstable behaviour at the transition zone of the two GMPEs, and to an unstable median value of the hazard prediction. The large differences between the models should have been clarified before application.

3.7.1 Discussion and GMPEs in the sensitivity analyses

Due to the deficiencies described above, all expert group members agreed that the sensitivity analyses should be done with GMPEs other than those used previously, and the final sensitivity studies were made with other models found from literature or developed by the calculation team members. The choice of appropriate GMPE models was made based on their suitability. Appendix 3.7 presents an overview of the comparison work done for the previously used GMPEs in Finnish hazard analyses. For future research it was proposed by one of the experts that a simulation based GMPE could be developed for Finland.

As criteria for GMPEs for SENSEI the following was noted: applicability for very hard rock sites; dataset, which should include also moderate magnitudes; testing against strong motion data; appropriate magnitude, distance, focal depth, and frequency range; and reasonable functional form. Based on the criteria, two equations from literature, Si et al. (2013) and NGA East (Goulet et al., 2018), were considered, and a Finnish equation Fenno-G16 (Fülöp et al. 2020). Model by Si et al. (2013) was excluded from the study because a minimum magnitude of 4 or lower was required.

The sensitivity studies were made with the original GMPEs, NGA East and Fenno-G16, and NGA-East GMPEs were chosen for the rest of the sensitivity studies due to the quality and quantity of data used in the calibration, the sophistication and effort of data analysis of the developing team, and the transparency of the background of the calibration work.

In addition to the mean prediction, attention to the sigma values was given. Because enough recordings at a given NPP site are not available, GMPE predictions rely on data collected at a broad range of regions that are seen representative to the site investigated. The ground-motion variability over these sites and sources is assumed to be applicable to the hazard prediction at the individual NPP site (the assumption of ergodicity, ES model). Such treatment of the randomness in a ground motion dataset leads to the largest value of σ, called total or ergodic standard deviation. The total σ is calculated from the difference, in natural logarithm units, between an observed and the GMPE predicted ground motion parameter (i.e., the residual). In Finland, it is obvious that detailed single-station variability studies will not be relevant due to the lack of instrumentation and observations at the NPP sites.

In seismically active regions, it is possible that repeated recording exists at the site of interest, and an attempt can be made to only account for the randomness at that specific site. This randomness should comprise the between-event residual and the single-station within-event residual for the NPP site. This treatment of the ground motion dataset would lead to a decrease of the randomness leading to a σ specifically to the NPP site.

However, the use of single-station σ in the PSHA analysis, would require the estimation of the site term (i.e., how much the median site observations deviate from the median prediction of the GMPE) and its epistemic uncertainty and the epistemic uncertainty of the single-station within-event deviations at different sites within the dataset. Hence, the larger variability of the total σ, would be replaced by a smaller variability and two elements of epistemic uncertainty. The advantage is that both epistemic uncertainties are reducible, e.g., by acquiring additional data or knowledge.

3.7.1.1 NGA East

The NGA-East model consists of a suite of 17 mean ground-motion predictions developed for very hard rock (V_{s30}=3000m/s) sites for Central and Eastern North America. Associated with the 17 mean predictions, the NGA-East GMPE provide three estimates for the total/ergodic σ and for the single-station σ. The three estimates are termed "low", "medium", and "high" estimates. (Goulet et al., 2018) Due to several models it was proposed by one of the experts that only median equations from the NGA-East GMPEs are used. It was also proposed that equation G16 (Graizer, 2016) could be excluded, if the Fenno-G16 GMPE is used, because Fenno-G16 is an adaptation of the G16 GMPE to Fennoscandia.

The models in SENSEI were using the 17 mean ground motion predictions of NGA-East combined with the 3 options of the ergodic σ predictions. There is a significant variation in the mean predictions. In addition, σ is given for low, central, and high estimate. For simpler models, weighted average NGA-East m model was used. The model is weighted between the 17 mean predictions, using weights published together with the GMPEs. For randomness the ergodic σ central prediction was used.

The selection of the NGA-East GMPE for most sensitivity calculations is based on the opinions of the expert group and a comparison of the alternative GMPS with each other and with a limited set of Finnish and international ground motion observations.

3.7.1.2 Fenno-G16

Fenno-G16 (Fülöp et al. 2020) is a model created by part of the calculation team before and during SENSEI. The model uses NGA-East model G16 (Graizer, 2016) and both Fennoscandian recordings and eastern Canadian NGA-East data. The model is valid for hard rock sites with shear wave velocity of 2800 m/s and moment magnitudes from 2,0 to 7,0. The Fenno-G16 GMPE provide estimates for the total and single-station σ, but due to data limitations it only recommends the use of the total σ (Fülöp et al., 2020).

In SENSEI, Fenno-G16 GMPE was used for investigations with minimum magnitudes 2 to 3 where the NGA-East was not applicable due to the low magnitude range. Otherwise, NGA-East GMPEs was used.

3.7.2 Attenuation - kappa calculations at Olkiluoto

A separate study (Rinne 2021) was launched to investigate the seismic wave attenuation. As the crystalline hard rock is known for its high seismic velocities and low attenuation, the values were quantified in a thesis work based on seismic monitoring carried out at the geological repository site near the Olkiluoto NPP. The aim was to quantify the κ-parameter that is used to estimate the decay of seismic spectral amplitudes with frequency due to near-site anelastic attenuation. It is a key input parameter in the stochastic method of strong ground motion simulation (Douglas et al., 2010).

Most of the research concerning κ around the world use earthquakes with $M > 3$ for κ calculations. Original work of Anderson and Hough (1984) use magnitudes above $M = 5$. This poses a challenge for κ-calculations in Olkiluoto. Bedrock of Olkiluoto is seismically very stable and has microearthquakes with $M \leq -0.5$ and the original κ-method (Anderson & Hough, 1984) might prove problematic. Biasi and Smith (2001) introduced different method to calculate the κ-parameter, the displacement kappa, when they were working with the Yucca-mountain project in Nevada, US. There are few if any studies of κ-values of blasts. As there is abundant data from blasting gathered by Olkiluoto seismic monitoring network, the κ-parameter were also be calculated from blasts as it offers deeper insight into the κ-parameter itself.

Data and records collected at the Olkiluoto NPP site was provided by Posiva for the thesis work. Seismic activity in and around Olkiluoto geological repository called ONKALO has been monitored since 2002. The amount of microearthquakes corresponds directly with the excavation work and blasting and it is considered that the seismic activity is directly induced by excavation, mainly blasting (Kaisko & Malm, 2019). Material for the study consists of 51 microearthquakes and 5 blasts, both located inside the ONKALO spent nuclear fuel repository. Selection of microearthquakes used in the study was based on the availability of fault-plane solutions (Kaisko & Malm, 2019) for each event. Blasts that were selected, were single blasts, even though most of the blasting inside ONKALO are conducted in series (excavation rounds). Single blasts were selected to avoid the overlap of different blasts in the same series.

The attenuation was analysed within the frequency range of 100 – 300 Hz. Results showed that the κ-values in Olkiluoto were low when compared with previous studies (Fig. 3-18 and 3-19) in different geological environments. κ-values in Olkiluoto for X-component were between 0,00002 and 0,01, 0,0005 and 0,015 for Y-component and between 0,002 and 0,017 for Z-component. Average (arithmetic mean), geometric mean and median values were approximately between 0,004 and 0,004 for the microearthquakes. The κ-values calculated from the single blasts were in the same order but somewhat higher. The low values were derived reliable from a few sensors but give reliable quantification of the κ-value at Olkiluoto at a frequency range higher that typically recoded in higher magnitudes. Thus, this introduced new challenges to assess the effects in earthquake engineering. It is well known that low kappa increases the high frequency vibrations as shown in the following pictures. As the Vs is higher and κ lower at the Olkiluoto site than in earlier studies, there is a new challenge to estimate the seismic amplification in Finnish circumstances. The assessment of the low κ within the GMPEs was not yet carried out in the sensitivity studies.

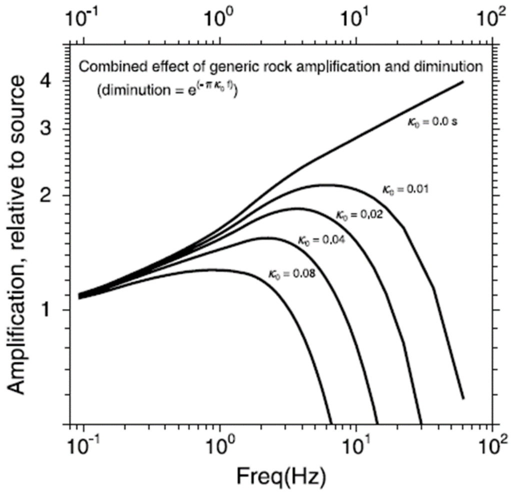


Fig. 3-18. Combined effect of amplification/deamplification for a generic rock site. (D. Boore, 2003)

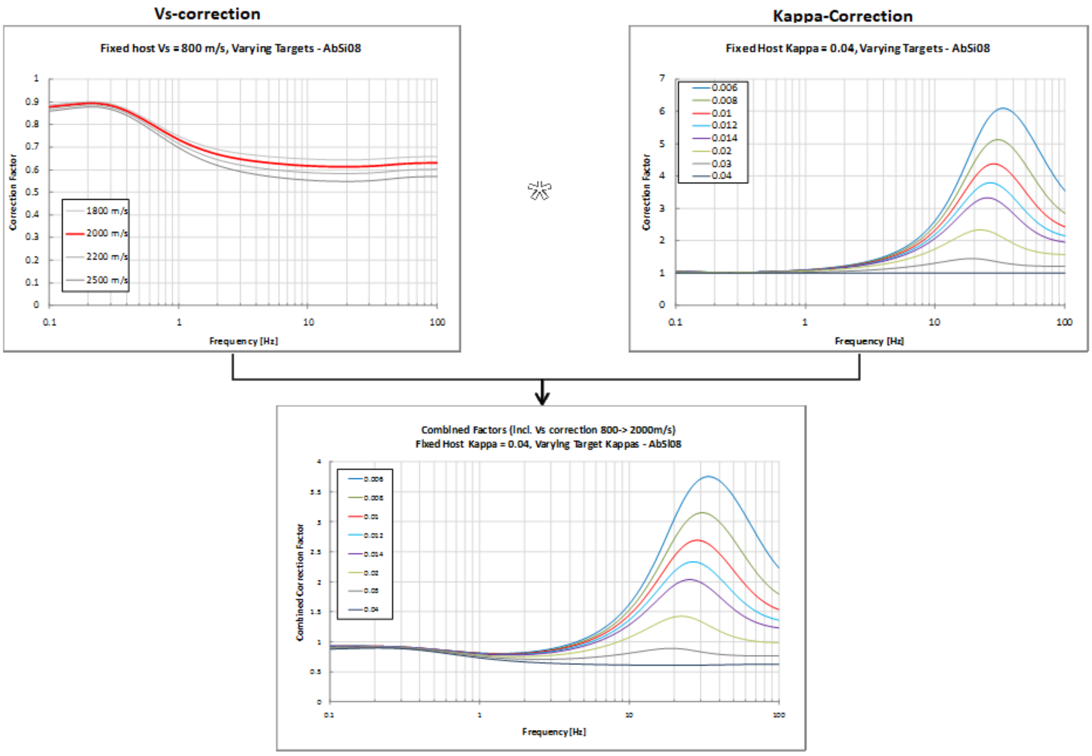


Fig. 3-19. Example of Vs- and Kappa-correction functions evaluated for Abrahamson & Silva (2008).

3.8 Model complexity and median vs. mean hazard

Because the design basis hazard in Finland is based on median value, it was jointly decided that in the sensitivity analyses the PSHA models were trimmed to the most essential branches considering median prediction. The trimming of the models resulted to simple models that had only one branch for a single SSA map, so called one branch models. This approach was selected in order to save computational time, while still getting reasonable estimates and comparisons. In addition to the one branch models, more complex models were created, where parameters and their variations were chosen based on the proposals from the expert group.

The focus in SENSEI was the design basis hazard, and some of the experts criticised the YVL guides for demanding the use of median hazard as a design basis.

It was pointed out by one of the experts that there are strong reasons to use mean hazard as the basis for seismic design (McGuire, Cornell, and Toro, 2005): use of mean hazard is consistent with modern interpretations of probability in the context of decision theory; mean hazard is insensitive to whether an uncertainty is classified as aleatory or epistemic; the mean risk can be calculated by convolving the mean hazard curve with the mean fragility curve, but a similar operation cannot be performed with the median hazard curve; and there are also precedents on the use of mean hazard or risk for setting design levels, including U.S. Regulatory Guide 1.208 and ASCE 7-16.

Also opposing arguments were presented, such as the stability of the median hazard values, and the fact that mean hazard blurs the distinction between aleatory variability and epistemic uncertainty, although mean values represent the range of epistemic uncertainties better and is more consistent with mean risk estimates. As a reference for discussion on benefits of median value, paper by Abrahamson and Bommer (2005) was given.

One of the experts pointed out, however, that although median hazard is often considered more stable than e.g., the mean hazard, this is not the case in the current Hanhikivi PSHA, because the epistemic distribution of hazard is strongly bimodal due to the use of only two very different GMPEs. However, the expert also stated that setting the design requirement to 1E-5 mean hazard might be a too conservative requirement. Nonetheless, the behaviour of the median should be stable in PSHA analyses.

It was pointed out by another expert that the choice between mean and median should be based on the use of the hazard results. For probabilistic risk analysis (seismic PRA) mean would be a consistent choice, but for deterministic design both mean and median are used in recent nuclear codes and in practise.

To answer the criticism and discussion from the expert group, both median and mean values were calculated in the sensitivity analyses. Because mean and median values were equal for the so called one branch models, the calculated median and mean are informative only for the more complex models.

3.9 Calculation cases for sensitivity analyses

3.9.1 Calculation procedure

The sensitivity analyses comprised the following steps:

1. **Establishment of the baselines**: Baseline PSHA models, their input, and the most representative results (LBasM/OBasM/HBasM) were collected from the seismic hazard reports submitted to STUK by the utilities. Simplifications were used when model results were replicated, and the constructed baseline models and their results are not exact replicas of the PSHA studies of the utilities. These baselines constituted the basis of comparison with the SENSEI results. Because the PSHA models of the utilities are complex, the logic-trees of the baseline models were trimmed to the most essential branches (LSenBM/OSenBM/HSenBM) that match their median hazard results as closely as possible.

2. **Sensitivity to ground motion prediction equations (GMPEs)**: GMPE was handled as a separate item, before considering other input parameters.

3. **Sensitivity to other input parameters**: The last part of the calculation sequence focused on all other PSHA input parameters except GMPE. The results were compared to the results of the baseline models (Olkiluoto and Hanhikivi) or their trimmed versions (Loviisa)(LSenBM/OBasM/HBasM).

Because the focus of the project was not to produce new ground response spectra but to give understanding on sensitivities, to reduce costs, ground response spectra was created only for few frequencies: 1 Hz, 5 Hz, 25 Hz, and PGA. The choice of frequencies was based on STUK's experience on most relevant frequencies in recent PSHA studies. The number of studied frequencies was kept small in order to keep the calculation time shorter and the manual processing of the results easier.

The final more complex model for Loviisa, L12, was extended to include all the spectral frequencies supported in the NGA-East GMPE in order to investigate the effect of the new GMPEs to the frequency contents of the PGAs. The comparison of the results is shown in Fig. 3-20. The frequencies chosen for the general analysis appear to be appropriate for sensitivity analyses. However, the more accurate spectral shape is broader. In addition, the PGA hazard is generally plotted at 100 Hz in the SENSEI project, but the NGA-East GMPE differentiates between 100 Hz and PGA. Moreover, the calculated low kappa values at Olkiluoto (see 3.7.2) may change the frequencies of interest to higher frequencies due to weak attenuation of seismic energy in Fennoscandian crystalline bedrock. No kappa-corrections were applied in the SENSEI-calculations.

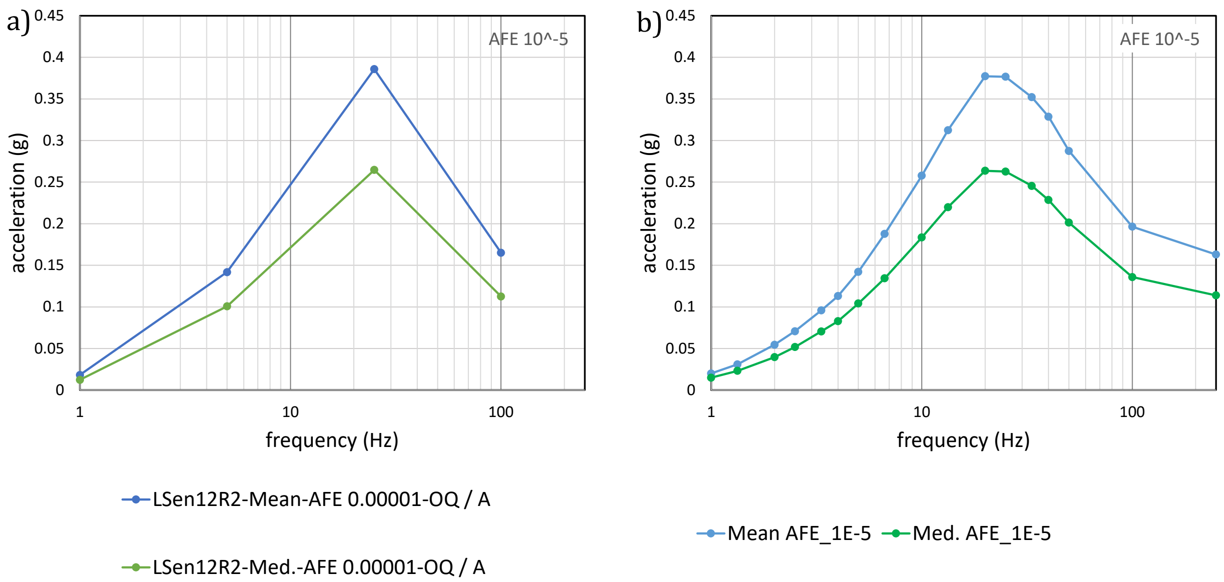


Fig. 3-20. The Loviisa SENSEI PSHA results using model LSen12(R2). Comparison of the calculated frequencies for the general results (i.e., 1Hz, 5Hz, 25 Hz and PGA) and for the detailed results with all frequencies supported in NGA-East.

3.9.2 Establishment of the baseline for calculations

Establishment of the baseline models and their condensation to one-branch models (reduction to a minimum amount of representative logic tree branches) are presented in Table 3-2. For Olkiluoto and Hanhikivi, trimmed models OSenBM and HSenBM were not computed, and the results of the sensitivity analyses were compared to results OBasR and HBasR.

Table 3-2. *Steps to synthetize the Loviisa baseline PSHA model (LBasM) to LSenBM.*

Model name	SSAs	Parameters (β, λ)	Depth distr.	GMPE	M_{min}	M_{max}	No. of branches
The reference results in the synthetizing process are the LBasR (Fig. 2-3)							
LBasM	-	-	-	-	-	-	144
	10 & 6	Mid branches (β, λ) with 100%	-	-	-	-	16
	10 & 6	Mid branches (β, λ) with 100%	-	-	-	5.5/ 6/ 6.5/ 7	4 for each M_{max}
LSenBM	10 & 6	Mid branches (β, λ) with 100%	-	-	-	5.5	4
The outcome is the LSenBM model and parameters with the results LSenBR							

Note: The hyphen stands for the original parameter setting for the LBasM according to Saari and Malm (2016) and Malm and Kaisko (2017a).

3.9.3 Sensitivity to ground motion prediction equations

The first stage of sensitivity testing focused on the influence of GMPEs (Table 3-3). The analyses were made using Loviisa SSAs 10 & 6 and activity parameters. Since most GMPEs have a limited validity range, these tests were run with a compatible level of M_{min}, which was set to the threshold value of $M_w = 4$. The primary purpose of the tests was to assess the influence of the earlier and new candidate GMPEs on the hazard results. The new candidate GMPEs Fenno-G16 and NGA-East were chosen for sensitivity analyses of other parameters.

When Mmin was raised from its original values in the Loviisa baseline model to a M_w of 4, the activity parameters had to be adjusted accordingly. In the baseline model (LBasM), source areas SSA6 and SSA10 were defined with a minimum magnitude of M_w of 2 and M_w of 0.7, respectively.

In addition to GMPE investigation, the variation of b value was investigated for NGA-East GMPE (models LG7 to LG9 in Table 3-3). An unaltered b (β) value (1,07), a low b value (0,99; standard deviation subtracted) and a high b value (1,15; standard deviation added) were used for SSA10, while the b value for SSA6 was kept unchanged.

Table 3-3*. Steps for studying the GMPE sensitivity of the hazard at Loviisa NPP site.*

Model name	SSAs	Activity parameters (β, λ)	GMPE	M_{min}	M_{max}	No. of branches
The reference for comparing all the results from these models is LSenBR.						
LG1	10 & 6	Mid branches (β, λ) with 100%	VNS 2017	4	5.5	4
LG2	10 & 6	Mid branches (β, λ) with 100%	VNS 2017	4	6.5	4

LG5a	10 & 6	Mid branches (β, λ) with 100%	Pezeshk et al. 2011	4	6.5	1
LG5b	10 & 6	Mid branches (β, λ) with 100%	T-97	4	6.5	1
LG6a	10 & 6	Mid branches (β, λ) with 100%	Fenno-G16, Single-station Sigma	4	6.5	1
LG6b	10 & 6	Mid branches (β, λ) with 100%	Fenno-G16, Total Sigma	4	6.5	1
LG7	10 & 6	Low branch β- for Zone10, mid branch λ with 100%	NGA-E, weighted average model (WA)	4	6.5	1
LG8	10 & 6	Mid branches (β, λ) with 100%	NGA-E-WA	4	6.5	1
LG9	10 & 6	High branch β+ for Zone 10, mid branch λ with 100%	NGA-E-WA	4	6.5	1

Notes: Other parameters were from the original setting of the LBasM model according to Saari and Malm (2016) and Malm and Kaisko (2017a).

3.9.4 Calculation sequence in the main sensitivity analyses

After the initial GMPE comparison, the sensitivity to other input parameters was assessed. The model cases for Loviisa are given in Table 3-4, for Olkiluoto in Table 3-5, and for Hanhikivi in Table 3-6. They map the variation of hazard with minimum magnitude (Mmin), ground motion prediction equation (GMPE), depth distribution, maximum magnitude (Mmax), seismic source area (SSA) delineation, and logic-tree complexity.

Table 3-4. *Steps for studying sensitivity of the hazard at Loviisa NPP site.*

Model name	SSAs	Activity param. (β, λ)	Depth distr.	GMPE	M_{min}	M_{max}	No. of branches
The reference here is the LSenBR.							
LSen1	10 & 6	Mid β, λ with 100%	-	Fenno-G16 (Tot)	2	5.5	1
LSen2	10 & 6	Mid β, λ with 100%	-	Fenno-G16 (Tot)	3	5.5	1
LSen3	10 & 6	Mid β, λ with 100%	-	Fenno-G16 (Tot)	4	5.5	1
LSen4	10 & 6	Mid β, λ with 100%	-	NGAE-W (ES Cen)	4	5.5	1
LSen5	10 & 6	Mid β, λ with 100%	0-13km	NGAE-W (ES Cen)	4	5.5	1
LSen6	10 & 6	Mid β, λ with 100%	South	NGAE-W (ES Cen)	4	5.5	1

LSen7	10 & 6	Mid β, λ with 100%	South	NGAE-W (ES Cen)	4	6.5	1
LSen8	10 & 6	Mid β, λ with 100%	South	NGAE-W (ES Cen)	4	7.5	1
LSen9	Split SSA#10	Mid β, λ with 100%	South	NGAE-W (ES Cen)	4	6.5	1
LSen10	Original (2/3) / Split (1/3)	Mid β, λ with 100%, host SSA all β, λ's	South	NGAE-W (ES Cen)	4	6.5	18
LSen11	Original (2/3) / Split (1/3)	Mid β, λ with 100%, host SSA all β, λ's	South	NGAE-W (ES Cen)	4	M_{max}	90
LSen12	Original (2/3) / Split (1/3)	Mid β, λ with 100%, host SSA#10 all β, λ's	South	NGAE-51 (ES)	4	M_{max}	4590

Notes: The hyphen stands for the original parameter setting for the LBasM according to Saari and Malm (2016) and Malm and Kaisko (2017a). Abbreviations: ***Tot*** the total sigma, ***NGAE*** NGA-East, ***W*** weighted average, ***ES*** Ergodic sigma, ***Cen*** central branch of the sigma estimate in NGA-East GMPE. The grey shading accentuates the relevant changes in each model.

Table 3-5. *Steps for studying sensitivity of the hazard at Olkiluoto NPP site.*

Model name	SSAs	Activity parameters (β, λ)	Depth distr.	GMPE	M_{min}	M_{max}	No. of branches
The reference here is the OBasR.							
OSen1	6 & 8	Mid β, λ with 100%	0-35km	Fenno-G16 (Tot)	2	5.5	1
OSen2	6 & 8	Mid β, λ with 100%	0-35km	Fenno-G16 (Tot)	4	5.5	1
OSen3	6 & 8	Mid β, λ with 100%	0-35km	NGAE-W (ES Cen)	4	5.5	1
OSen4	6 & 8	Mid β, λ with 100%	0-35km	NGAE-W (ES Cen)	4	6.5	1
OSen5	6 & 8	Mid β, λ with 100%	South	NGAE-W (ES Cen)	4	6.5	1
OSen6	6 & 8	Mid β, λ with 100%, host SSA all β, λs	South	NGAE-W (ES Cen)	4	6.5	9
OSen7	6 & 8	Mid β, λ with 100%, host SSA all β, λs	South	NGAE-W (ES Cen)	4	M_{max}	45
OSen8	6 & 8	Mid β, λ with 100%, host SSA all β, λs	South	NGAE-51 (ES)	4	M_{max}	2295

Notes: The hyphen stands for the original parameter setting for the OBasM according to Saari and Malm (2016) and Malm and Kaisko (2017a). Abbreviations: ***Tot*** total sigma, ***NGAE*** NGA-East, ***W*** weighted average, ***ES*** Ergodic sigma, ***Cen*** central branch of the sigma estimate in NGA-East GMPE. The grey shading accentuates the relevant changes in each model.

Table 3-6. *Steps for studying different types of sensitivity of the hazard at the Hanhikivi site.*

Model name	SSAs	Activity parameters (β, λ)	Depth distr.	GMPE	M_{min}	M_{max}	No. of branches
The reference for comparing all the results from these models is HBasR							
Hsen1	Map1,2	Mid β, λ	-	Fenno-G16 (Tot)	2	5.5	2
Hsen2	Map1,2	Mid β, λ	-	Fenno-G16 (Tot)	3	5.5	2
Hsen3	Map1,2	Mid β, λ	-	Fenno-G16 (Tot)	4	5.5	2
Hsen4	Map1,2	Mid β, λ	-	NGAE-W (ES Cen)	4	5.5	2
Hsen5	Map1,2,4	Mid β, λ	-	NGAE-W (ES Cen)	4	6.5	3
Hsen6	Map1,2,4	Mid β, λ	North	NGAE-W (ES Cen)	4	6.5	3
Hsen7	Map1,2,4	Mid β, λ	North	NGAE-W (ES Cen)	4	M_{max}	15
Hsen8	Map1	Mid β, λ with 100%, host SSA all β, λs	North	NGAE-W (ES Cen)	4	M_{Max}	45
Hsen9	Map2	Mid β, λ with 100%, host SSA all β, λs	North	NGAE-W (ES Cen)	4	M_{Max}	45
Hsen10	Map4	Mid β, λ with 100%, host SSA all β, λs	North	NGAE-W (ES Cen)	4	M_{Max}	45
Hsen11	Map1,2,4 (0,33 each)	Mid β, λ with 100%, host SSA all β, λs	North	NGAE-W (ES Cen)	4	M_{Max}	135
Hsen12	Map1,2,4 (0,33 each)	Mid β, λ with 100%, host SSA all β, λs	North	NGAE-51 (ES)	4	M_{Max}	6885

Notes: The hyphen stands for the original parameter setting for the HBasM according to Saari and Malm (2016) and Malm and Kaisko (2017a). Abbreviations: ***Tot*** total sigma, ***NGAE*** NGA-East, ***W*** weighted average, ***ES*** Ergodic sigma, ***Cen*** central branch of the sigma estimate in NGA-East GMPE. The grey shading accentuates the relevant changes in each model.

Models Lsen1 to Lsen9, Osen1 to Osen5 and Hsen1 to Hsen6 are rather simple models referred here as one branch models. Models Lsen10, Osen6 to Osen7, and Hsen7 to Hsen11 are more complex models with variation in activity parameters and maximum magnitude.

Models Lsen12, Osen8 and Hsen12 are the most complex models, in which the NGA-East GMPE is used with all its 17 mean prediction branches and 3 ergodic σ estimates, resulting in 17×3=51 logic-tree branches for the GMPE in the NGAE-51 (ES) model. The Lsen12 model has a logic-tree with 9(βλ) × 5(Mmax) × 51(GMPE) × 2(zoning) =4590 branches. The Osen8 model has a logic-tree with 9(βλ) × 5(Mmax) × 51(GMPE) = 2295 branches. The Hsen12 model has a logic-tree with 9(βλ) × 5(Mmax) × 51(GMPE) x 3(zoning) = 6885 branches. Models Lsen12, Osen8 and Hsen12 are presented in Figure 3-21.

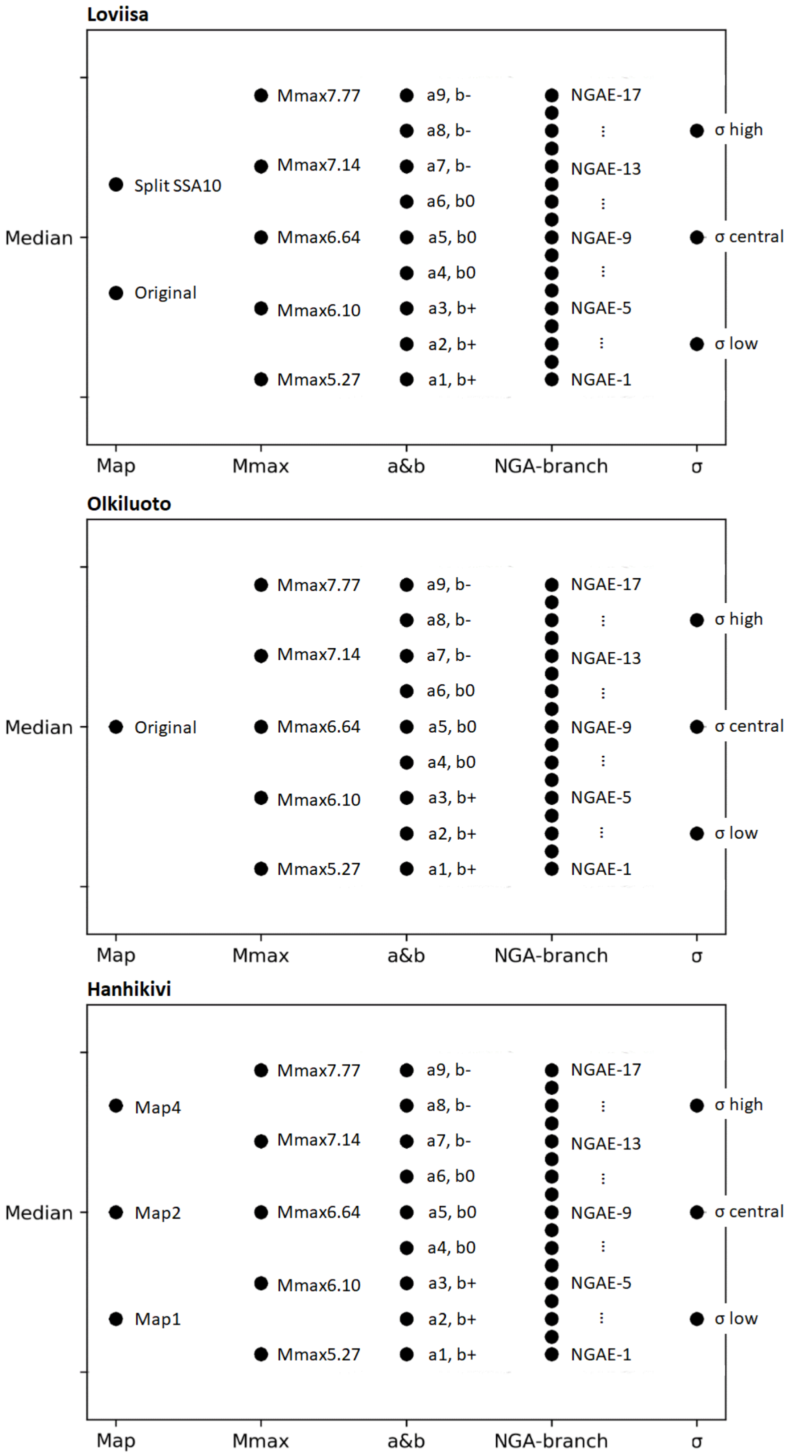


Fig. 3-21. Legend for different NPP sites. Maps are different depending on the site and number of models used. M_{max} shows the EPRI M_{max} model options. The a & b are the Gutenberg-Richter activity parameters. The NGA-branch shows the 17 GMPE mean prediction options for the NGA-East model. The σ are the low, central, and high prediction for ergodic sigma model.

4 Results of the calculation cases, their analysis, and relevance of findings to nuclear safety

4.1 Summary of the calculations

4.1.1 One-branch calculations

Figures 4-1 to 4-3 show a summary of the results of the so-called one branch calculations, which depict the effect of changing a single parameter to acceleration spectrum.

Figure 4-1 presents the variation/sensitivity for Loviisa.

- Decrease of accelerations from M_{min} 2 (LSen1) to M_{min} 4 (LSen3) is about 20%.
- Increase of accelerations between M_{max} 6,5 (LSen7) and M_{max} 7,5 (LSen8) is almost unnoticeable. However, the effect of changing M_{max} from 5,5 to 6,5 is more significant. (LSen6)
- Fenno-G16 (LSen3) gives 1,5 – 2 times the accelerations compared to NGAE. (LSen4)
- The effect of splitting source area 10 can be seen from LSen7 and LSen9. The resulting accelerations are 1,5 – 1,8 times the non-split SSA.

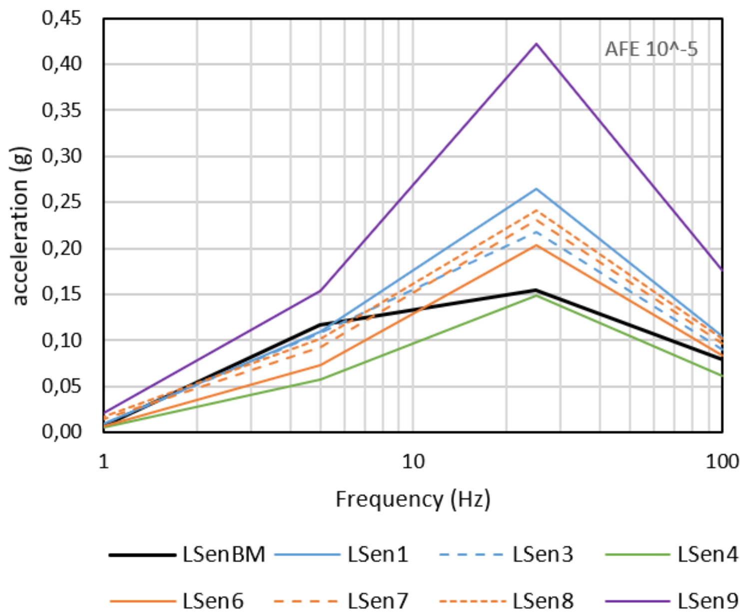


Fig. 4-1. Comparison of the one-branch models presented in Table 3-4: LSen1, 3, 4, 6, 7, 8 and 9 for Loviisa. The thick black line marks the pre-SENSEI baseline, the blue lines show the effect of changing M_{min} from 2 (solid blue LSen1) to 4 (dashed blue LSen3) with Fenno-G16 GMPE, and the green line (LSen4) shows the NGA-East WA GMPE result for M_{min} = 4. The orange lines show the effect of increasing M_{max} from 6,5 (solid orange LSen7) to 7,5 (dashed orange LSen8). The purple line (LSen9) shows the effect of diminishing SSA10 into one third of the original surface area.

Figure 4-2 presents the variation/sensitivity for Olkiluoto. Decrease of accelerations from M_{min} 2 (OSen1) to M_{min} 4 (OSen2) is about 20%.

- Increase of accelerations from M_{max} 5,5 (OSen3) to M_{max} 6,5 (OSen4) is about 20%.
- Depth distribution from 0-35 km (OSen4) to south (OSen5) cause about 30% increase to accelerations.
- Fenno-G16 (OSen2) gives 50% higher accelerations compared to NGA-East (OSen3)

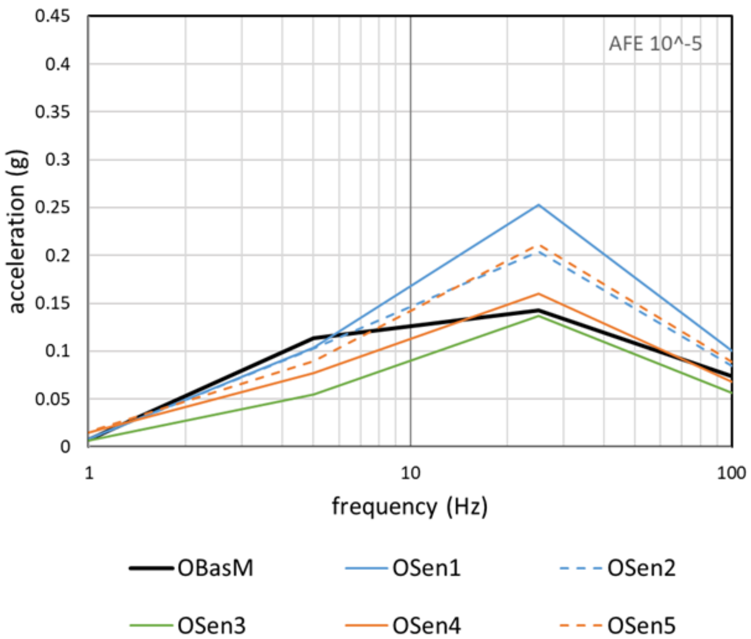


Fig. 4-2. Comparison of the one-branch models OSen1, 2, 3, 4 and 5 for Olkiluoto. The thick black line (OBasM) marks the pre-SENSEI baseline, the blue lines show the effect of changing Mmin from 2 (solid blue OSen1) to 4 (dashed blue OSen2) with Fenno-G16 GMPE, and the green line (OSen3) shows the NGA-East WA GMPE result for Mmin = 4. The orange lines show the effect of changing the depth distribution from 0–35 km (solid line OSen4) to the southern distribution (dashed line OSen5).

Figure 4-3 presents the variation/sensitivity for Hanhikivi.

- The decrease of accelerations from M_{min} 2 (HSen1) to M_{min} 4 (HSen3) is about 20% changes in PGA are very small. Effects to Map1 are higher.
- The increase of accelerations from M_{max} 5,5 (HSen4) to M_{max} 6,5 (HSen5) is about 30% (Map1) and 40% (Map2) increase to accelerations.
- Depth distribution from 0-35 km (HSen5) to north (HSen6) causes less than a 10% (Map1) and minimal (Map2) increase to accelerations.
- Fenno-G16 (HSen3) gives 1,5 - 2 as high accelerations as NGA-East (HSen4).

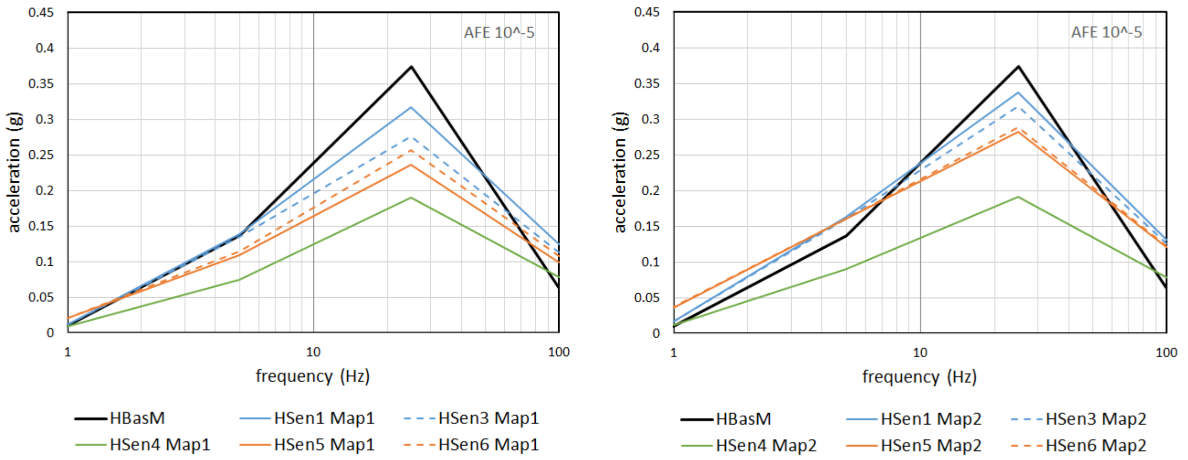
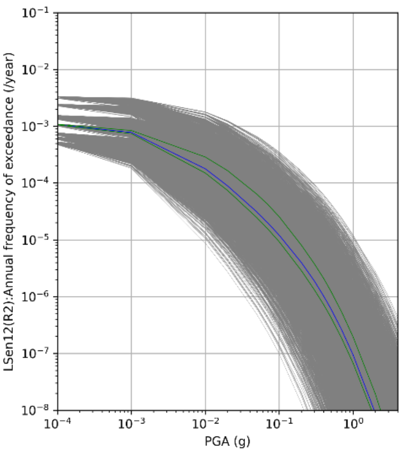
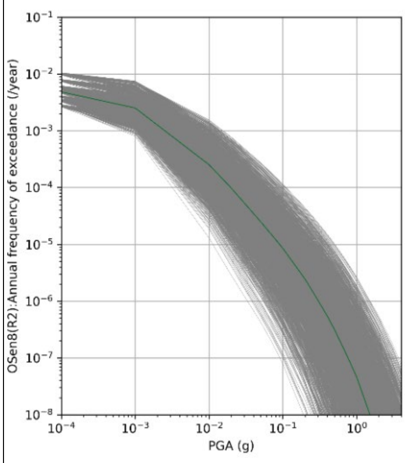
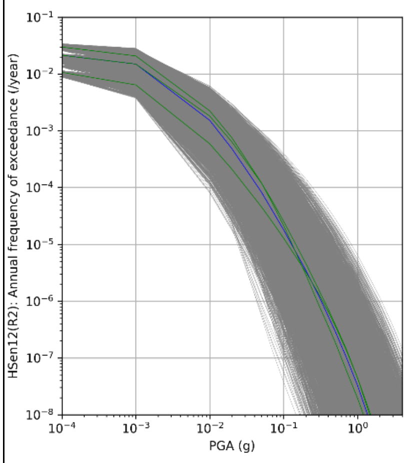
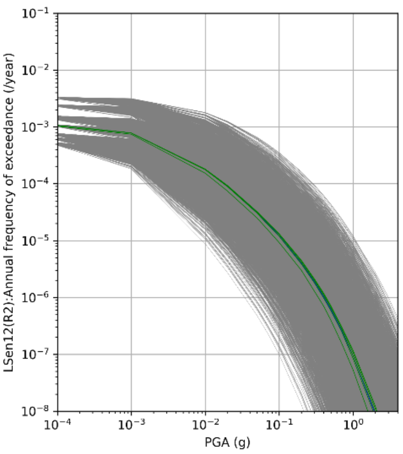
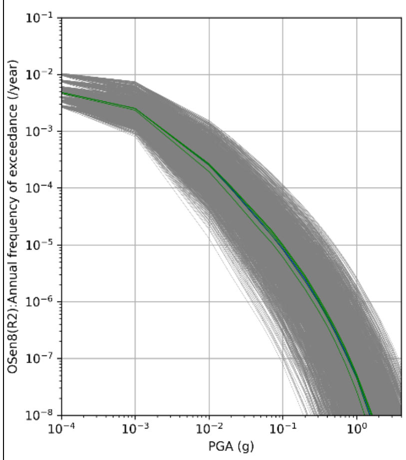
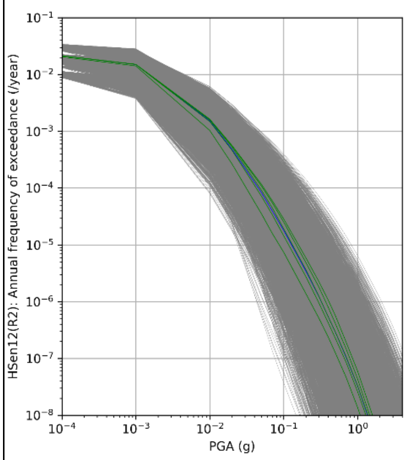
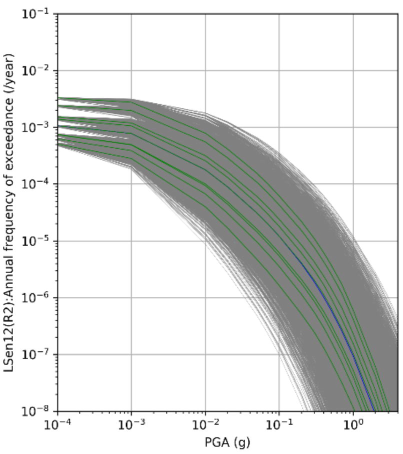
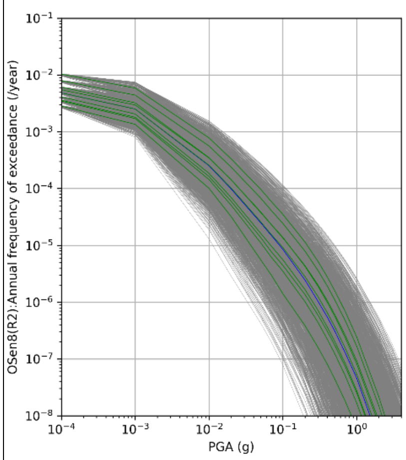
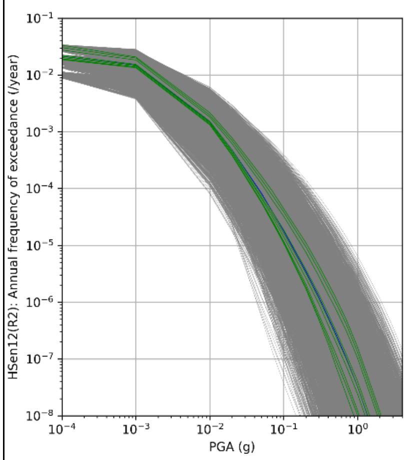


Fig. 4-3. Left side figure: Map1, right side figure: Map2. Comparison of the one-branch models HSen1, 3, 4, 5 and 6 for Hanhikivi. The thick black line marks the pre-SENSEI baseline, the blue lines show the effect of changing M_{min} from 2 (solid blue HSen1) to 4 (dashed blue HSen3) and the green line (HSen4) shows the NGA-East WA GMPE result for M_{min}4. The orange lines with higher M_{max} 6,5 show the effect of changing the depth distribution from 0–35 km (solid orange HSen5) to the northern distribution (dashed orange HSen6).

4.1.2 Complex models

Figures 4-4 to 4-6 show a summary of the results of the complex LSen12(R2), OSen8(R2) and HSen12(R2) models. The grey lines are the hazard curves resulting from each individual logic-tree branch. The blue line is the overall median hazard curve calculated from all individual hazard curves (i.e., all branches of the logic-tree). The green lines represent the median hazard calculated from the logic-tree branches crossing the different nodes (Fig. 3-21) in the branching of the tree at the level of: (i) SSA maps, (ii) M_{max}, (iii) a and b parameters, (iv) mean prediction of the 17 NGA-East GMPE branches and (v) randomness estimate of the GMPE branches.

For instance, when it comes to SSA maps, the LSen12(R2) model used two options for SSA maps, the one with the original seismic source zone no. 10 and the other with the divided SSA no. 10 as seen in Figure 3-21. The divided SSA no. 10 results in a hazard above the overall median, while the original one is below the overall median. The effect of the SSA maps appear to be strongest in the 10^{-4}...10^{-5} range of AFE's. The model OSen8(R2) utilized a single SSA map. Hence, the sensitivity to SSA division cannot be distinguished. However, for HSen12(R2), the influence of Map1, Map2 and Map4 described in chapter 3.2 is significant, especially for higher values of AFE. The sensitivity to other parameters can similarly be read from Figure 4-4.

	Loviisa - LSen12(R2)	Olkiluoto - OSen8(R2)	Hanhikivi - HSen12(R2)
SSA map			
M_{max}			
a & b			

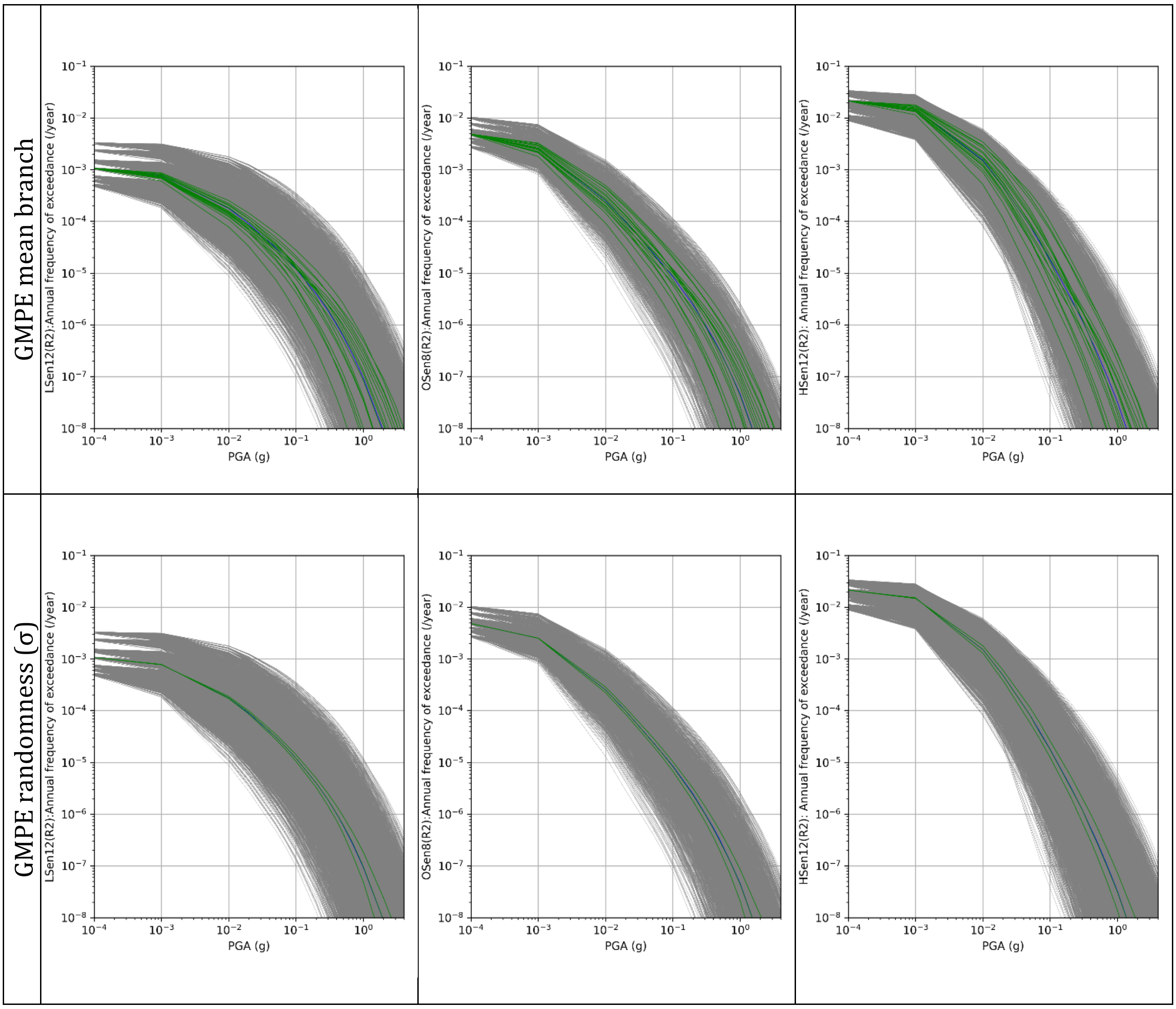
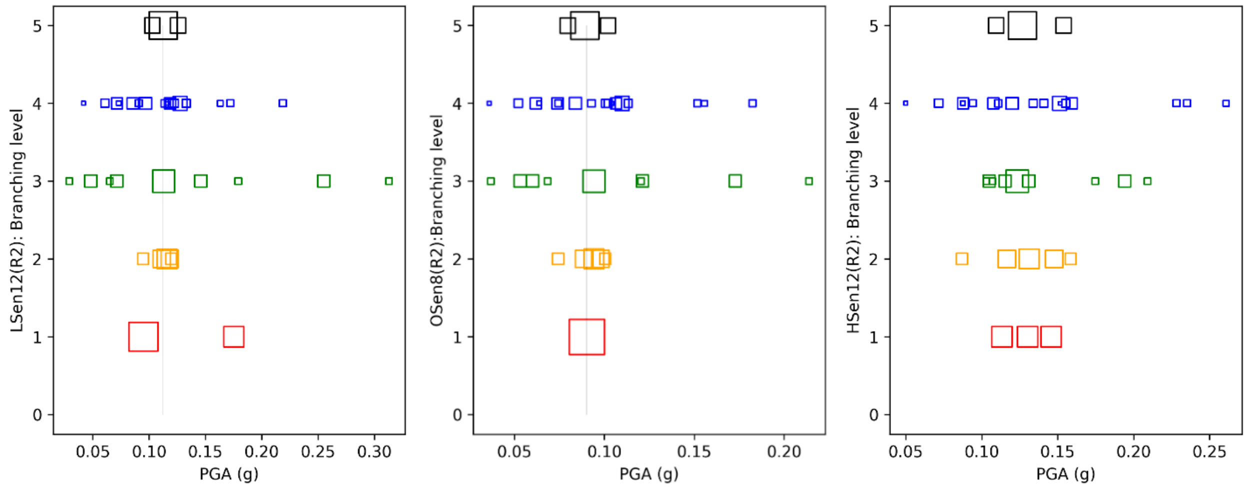
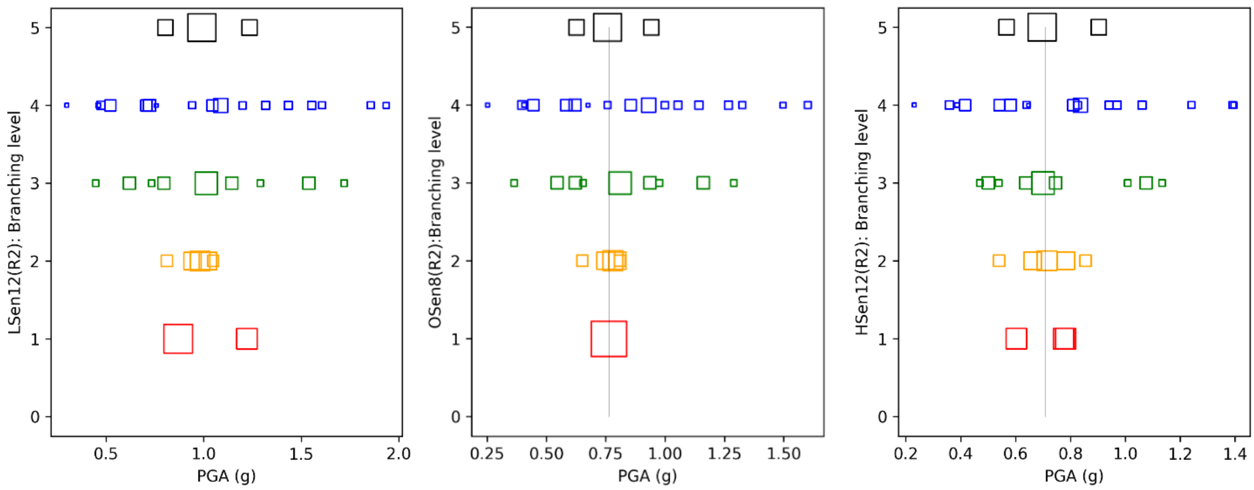


Fig. 4-4. Influence of input parameters on the hazard curves for Loviisa (LSen12(R2)), Olkiluoto (OSen8(R2)) and Hanhikivi (HSen12(R2)). The significance of the green and blue lines is explained above the figure.

The median hazard values, corresponding to the different input parameters have been extracted from the hazard curves in Fig. 4-4 for 10^{-5} and 10^{-7} AFE, and presented in Fig. 4-5 for PGAs and in Fig. 4-6 for the spectral acceleration of 1 Hz. These, so called tornado plots, present the range of hazard obtained as a result of the different branching levels in logic-tree.

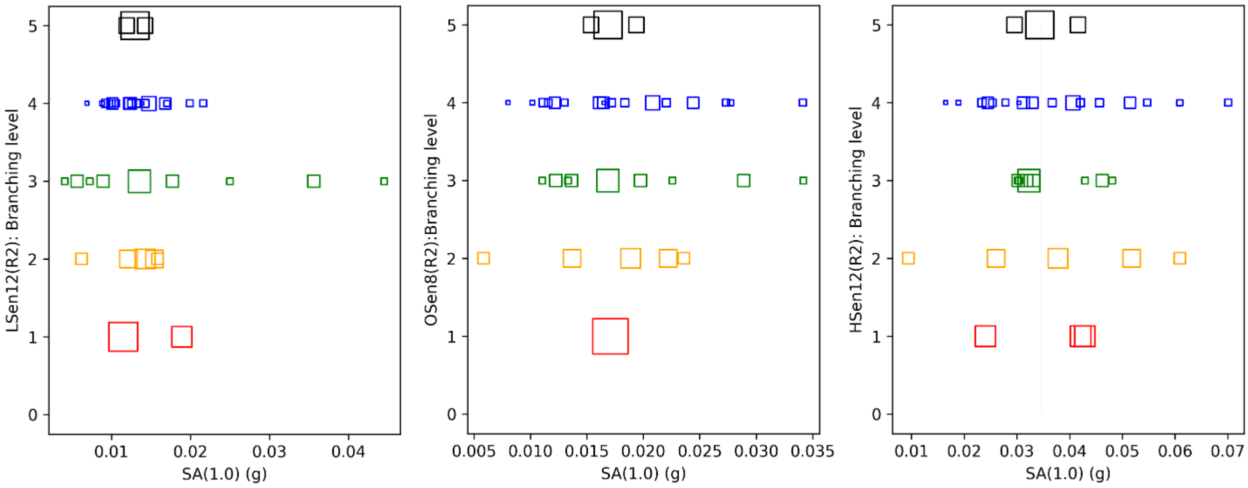


a)

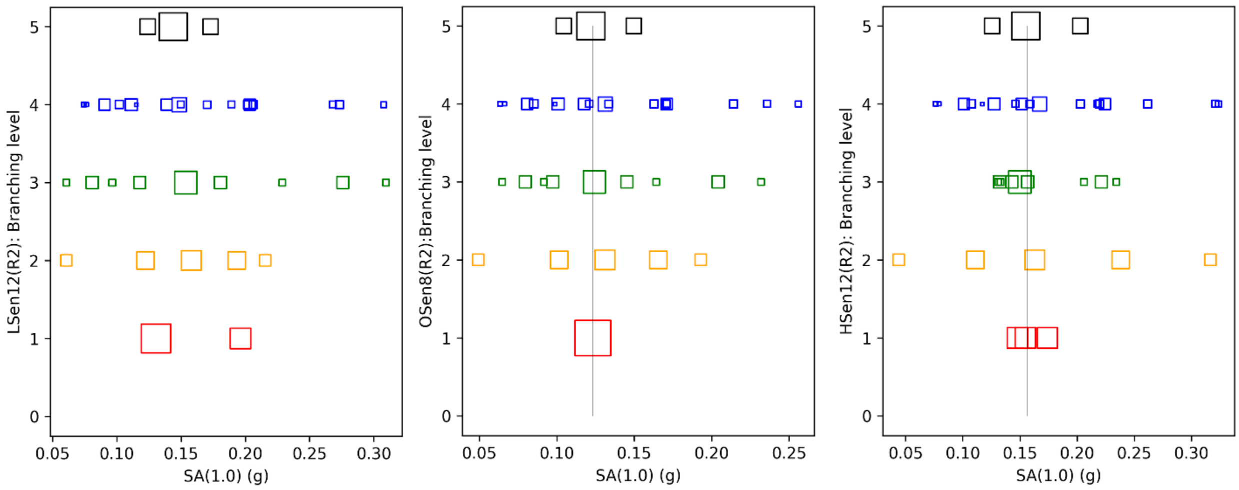


b)

Fig. 4-5. Summaries of sensitivity of PGA hazard with input parameters at (a) AFE 10^{-5} and (b) AFE 10^{-7}. LSen12(R2) for Loviisa, OSen8(R2) for Olkiluoto, and HSen12(R2) for Hanhikivi. Level 1 (red) for SSA maps, Level 2 (yellow) for M_{max}, Level 3 (green) for a and b parameters, Level 4 (blue) for GMPE mean prediction, and Level 5 (black) for GMPE σ. The vertical grey line shows the overall weighted median hazard.



a)



b)

Fig. 4-6. Summaries of sensitivity of 1Hz hazard with input parameters at (a) AFE 10^{-5} and (b) AFE 10^{-7}. LSen12(R2) for Loviisa, OSen8(R2) for Olkiluoto, and HSen12(R2) for Hanhikivi. Level 1 (red) for SSA maps, Level 2 (yellow) for M_{max}, Level 3 (green) for a and b parameters, Level 4 (blue) for GMPE mean prediction, and Level 5 (black) for GMPE σ. Grey line shows the overall weighted median hazard.

4.2 Discussion on sensitivity of results to investigated topics

4.2.1 Seismic source area (SSA) models

For Loviisa, the host zone SSA 10 was split for the sensitivity study, and the observed seismicity was distributed into a much smaller surface area. Using the smaller surface area led to a major increase in hazard, which was expected. When comparing LSen9 to LSen7 (Figure 4-7), at AFE 10-5, the PGA value was increased approximately 82%. At frequency 25 Hz, the increase was 84%, at 5 Hz almost 66%, and at 1 Hz 47%, respectively.

LSen10 was a computation of a logic-tree model, to which the original SSA10 was incorporated with a weight of 2/3 and the new, smaller delineation with a weight of 1/3.

In addition, all the activity parameters of the host zone, SSA10, were incorporated, which resulted in 18 branches. The output decreased from LSen9, as expected, due to the 2/3 weight of the original branch. The median output values of LSen10 were close to those of LSen7. The mean values of LSen10 were much larger than the median values, but even so remained below the LSen9 values.

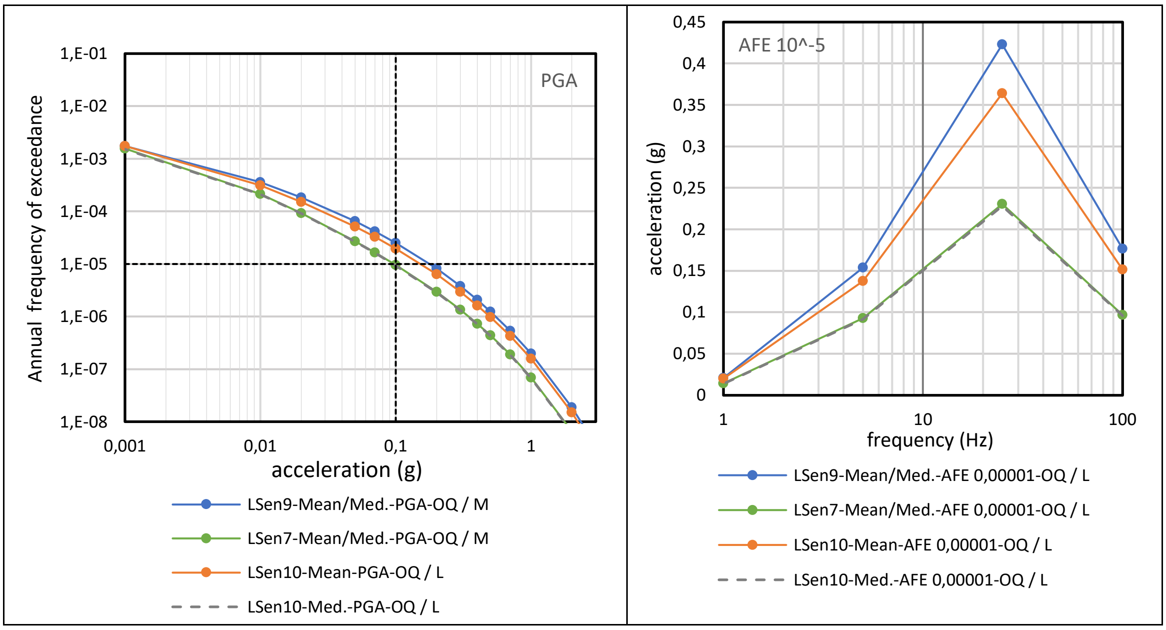


Fig. 4-7: The apparent non-uniformity of seismic activity in the original SSA10 was noted. SSA10 was divided, retaining the active part as SSA10 and assigning the remaining part to SSA6. The division increases the hazards significantly.

There were alternative seismic source area delineations also for Hanhikivi. An additional SSA model (named Map4) was constructed for Hanhikivi using the SSA8 from the Loviisa and Olkiluoto source area delineation. The effect of different maps was studied in HSen5, HSen6 and HSen8 to HSen10.

For HSen5, at 10^{-5}, for frequencies 100 Hz (PGA) and 25 Hz, the output value from the model Map1 is the smallest and that of Map4 the largest, whereas for 5 Hz and 1 Hz, the value corresponding to Map2 is the largest and that of Map1 is the smallest. The relative increase from the smallest to the largest value is 27% in the case of PGA and 25 Hz, but 45% for 5 Hz and 80% for 1 Hz. For HSen6, the output features were similar, except for 5 Hz, which had the smallest value from Map1 and the largest from Map4. The differences between maps Map2 and Map4 are insignificant for frequencies 1 Hz and 5 Hz. It is worth noticing that HSen5 and HSen6 had different depth distributions, but the effect of depth is smaller than the effect of different source zone models.

In models HSen8 (Map1), HSen9 (Map2), and HSen10 (Map4), where the uncertainties in λ and β are modelled, Map4 clearly gave the highest values in both median and mean prediction. The effect was largest for frequencies 25 Hz and 100 Hz (PGA), and, as with HSen5 and HSen6, the difference between maps Map2 and Map4 was negligible for 1 Hz.

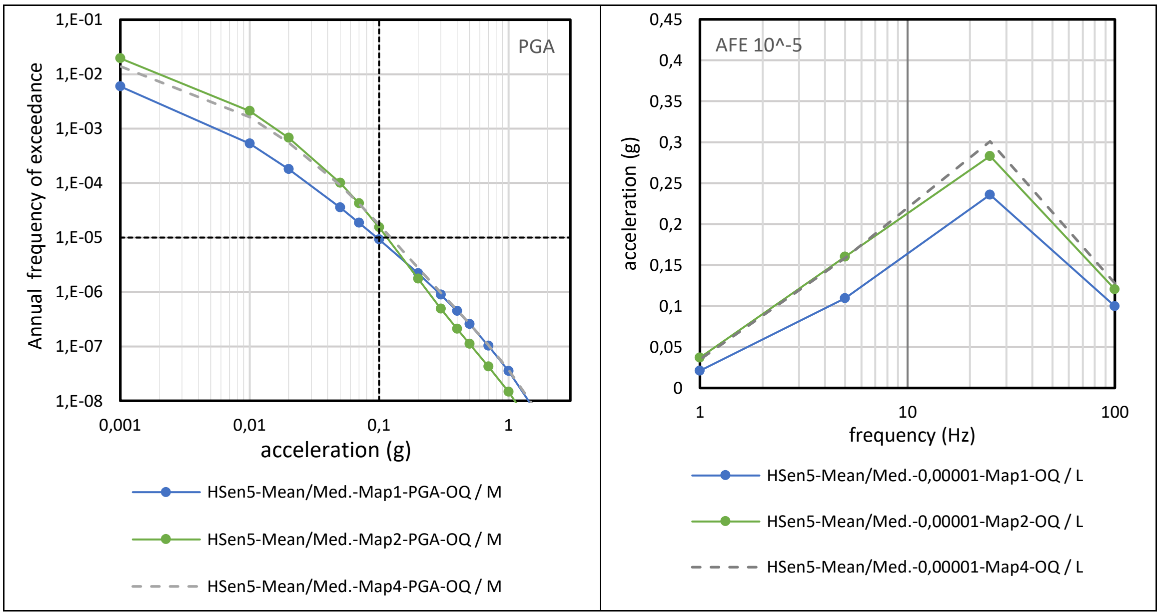


Fig. 4-8. Model HSen5 with maps Map1, Map2 and Map4.

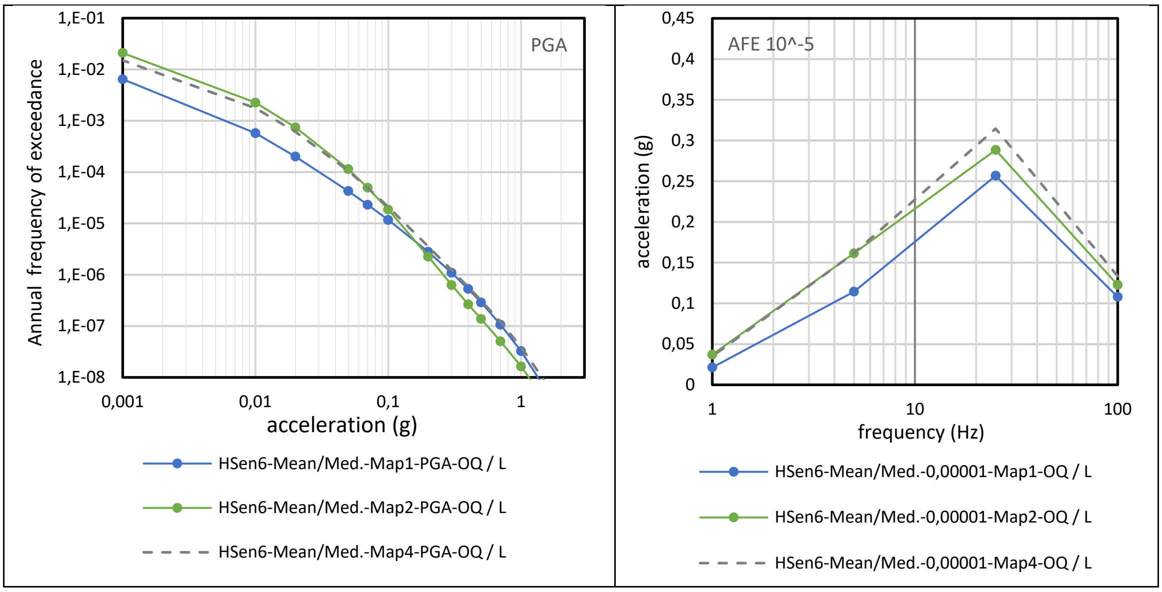


Fig. 4-9. Model HSen6 with maps Map1, Map2 and Map4.

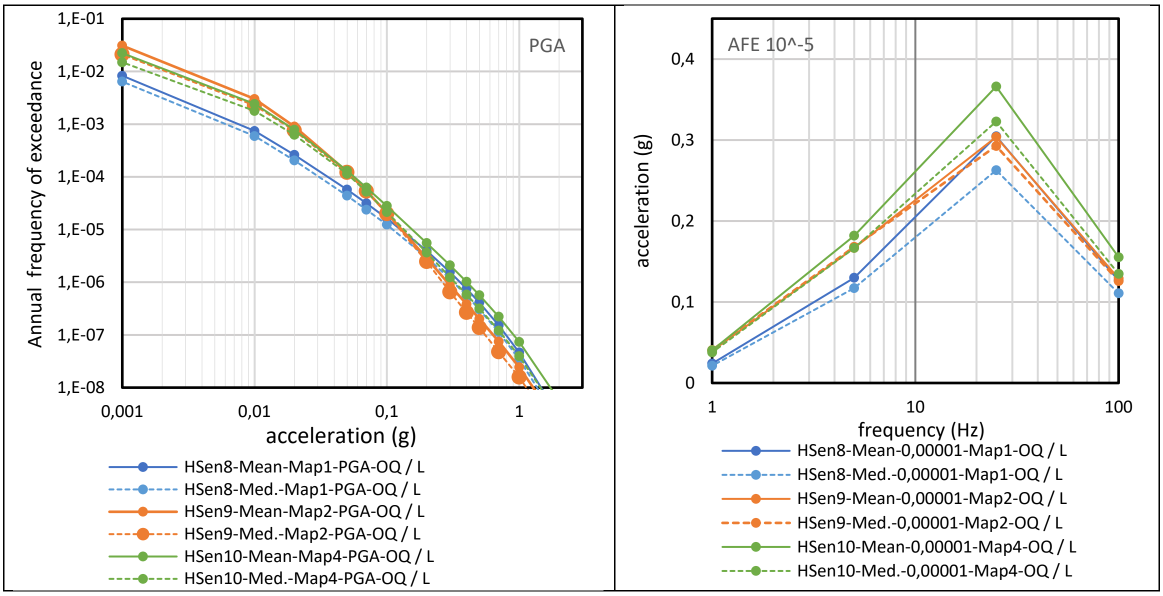


Fig. 4-10. Models HSen8 (Map1), HSen9 (Map2), and HSen10 (Map4).

The exercises show, as expected, that the SSA design can have a major impact on spectral acceleration values, because changing the surface area affects the seismicity rate per unit area. The output depends on how the seismicity rates are affected by the new boundaries.

4.2.2 G-R parameters

One set of calculations with different b values was carried out for Loviisa (models LG7-LG9). The effect was largest for 25 Hz. Compared to the original b value, the lower b value increased the acceleration values by approximately 6% at 25 Hz, and the higher b value lowered the output by 5% at 25 Hz as seen in Figure 4-12. The effect on the PGA is minimal as seen in Figure 4-11.

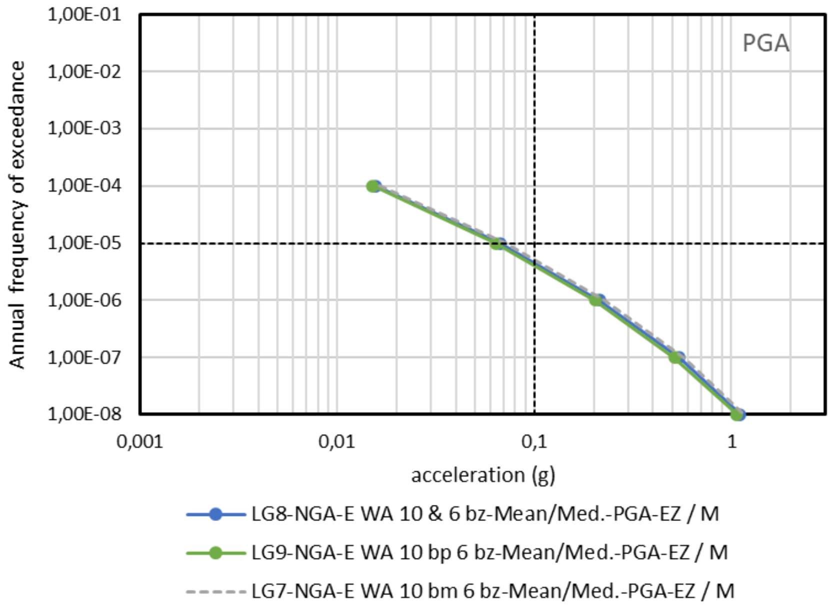


Fig. 4-11 LG7-8: Effect of the Gutenberg-Richter β on PGA. *LG8 = unaltered* b *value, LG7 = low* b *value, LG9 = high* b *value for SSA10.*

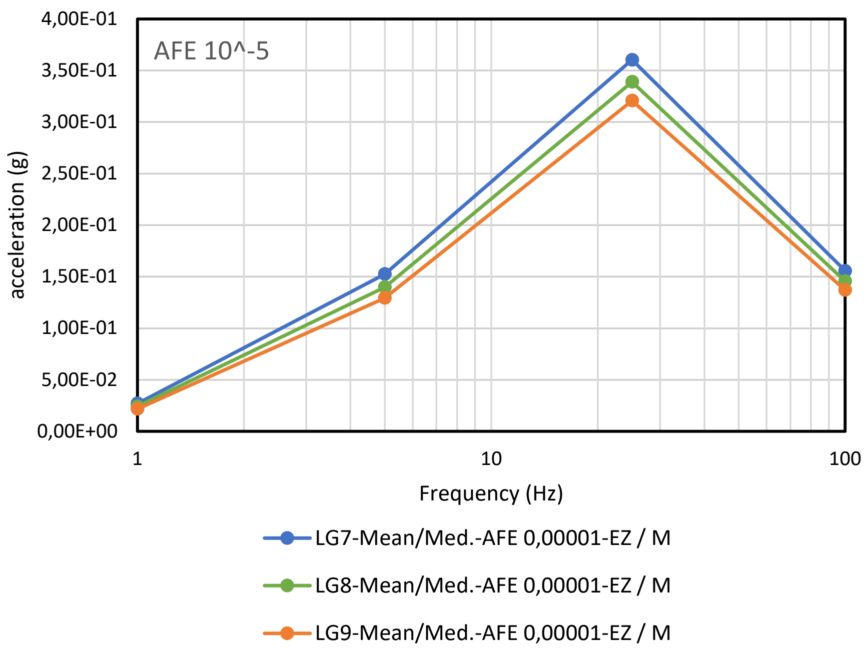


Fig. 4-12. Effect of the G-R b value. The green line (LG8) shows output for unaltered b value, the blue line (LG7) for a low b value and the orange (LG9) for a high b value for SSA10.

In addition, after one-branch investigations, models were created where uncertainties in λ and β were included (LSen10 to LSen12, OSen6 and OSen7, and HSen8 to HSen10). The figure below shows comparison between steps OSen5, where uncertainty was not modelled, and OSen6, where uncertainty in β and λ was included in the model for source area no. 6 as reported in the original hazard studies (i.e., 9 branches). The mean hazard is slightly increased and, the median hazard slightly decreased.

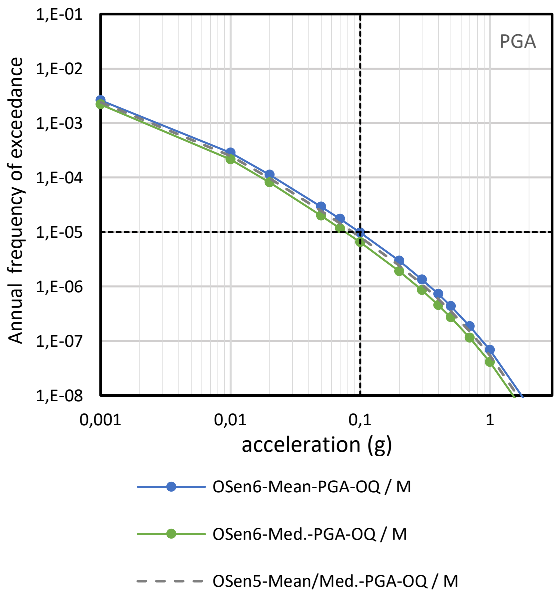


Fig. 4-13. The uncertainty in β and λ, reported in the original hazard studies for SSA6, was included in the model (i.e., 9 branches). The mean hazard is slightly increased, and the median hazard slightly decreased.

It is evident that the uncertainty of the catalogue, and therefore, of parameters λ and β, or a and b of the Gutenberg-Richter model have significant effect on the hazard prediction. Due to lack of information on the catalogue, the item was not investigated as thoroughly as the expert group would have preferred, however the focus of the project was to study the sensitivity to the input parameters.

4.2.3 Depth distribution

For Loviisa, steps LSen4 to LSen6 focused on depth. In LSen4 the depth distribution was uniform from 0 km to 35 km, and in LSen5 uniform from 0 km to 13 km. Shift from LSen4 to LSen5 increased the output values, which was expected. PGA values increased by 40%, 25 Hz values by 41%, 5 Hz values by 28%, and 1 Hz values by 21%. In LSen6 the depth distribution South was used. Because the difference between the uniform distribution of 0–13 km and the distribution South is small (see Fig. 3-16), the results of LSen6 were very similar to the results of LSen5.

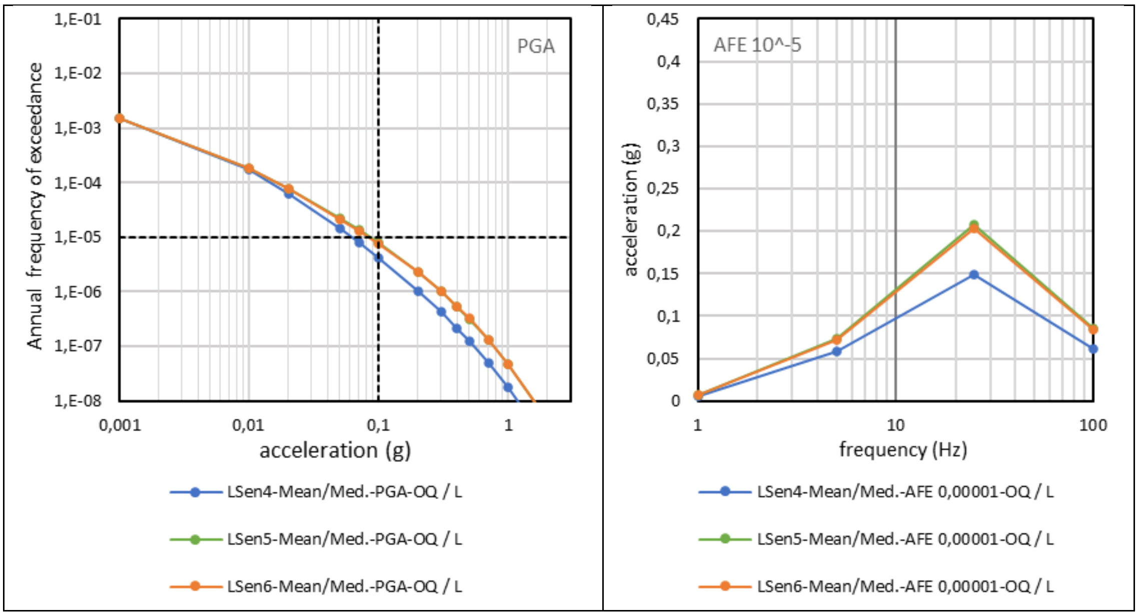


Fig. 4-14. The depth profile varies from the uniform 0-35km (LSen4) of earlier models to uniform 0-13km (LSen5) distribution and finally to the “South” depth distribution (LSen6) proposed in SENSEI for the Loviisa and Olkiluoto NPP sites.

For Olkiluoto, steps OSen4 to OSen5 shifted the depth distribution from the uniform distribution of 0 km to 35 km to the distribution South, and the effect was similar to Loviisa.

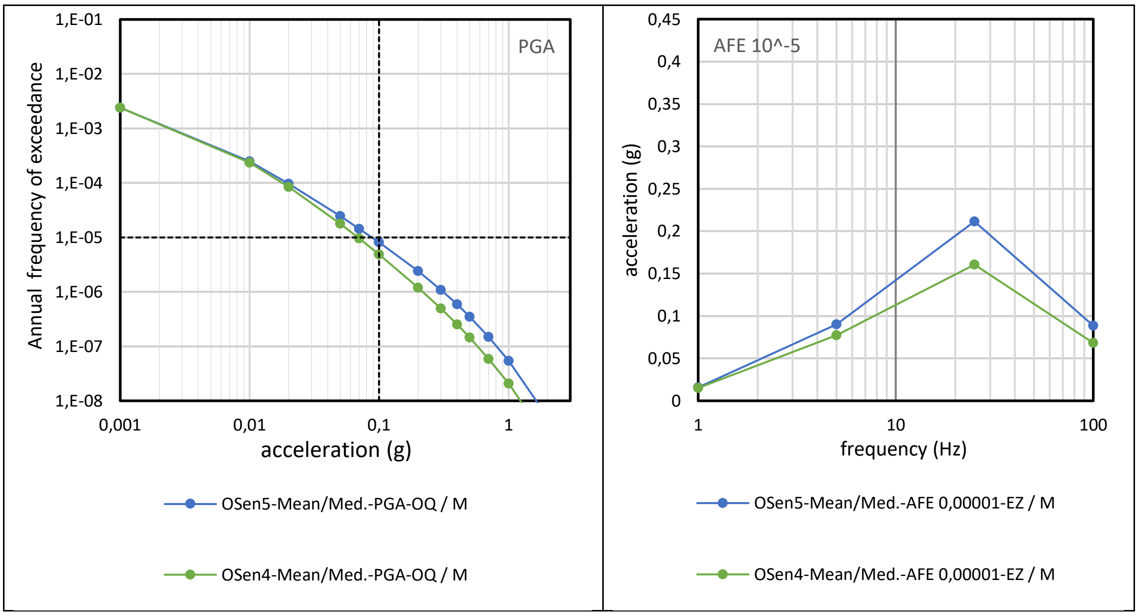


Fig. 4-15. The uniform 0-35km depth profile is replaced with the final “South” depth distribution proposed in SENSEI for the Loviisa and Olkiluoto NPP sites. The hazard remains unchanged at low acceleration levels starting to differ at 0.01g. There is some increase throughout the spectra.

For Hanhikivi, the original distribution in the Fennovoima hazard analysis (Helander, 2018) (uniform 0–35 km) and the new depth distribution "North" were not that different, which resulted in minor differences between the output from steps HSen5 and HSen6.

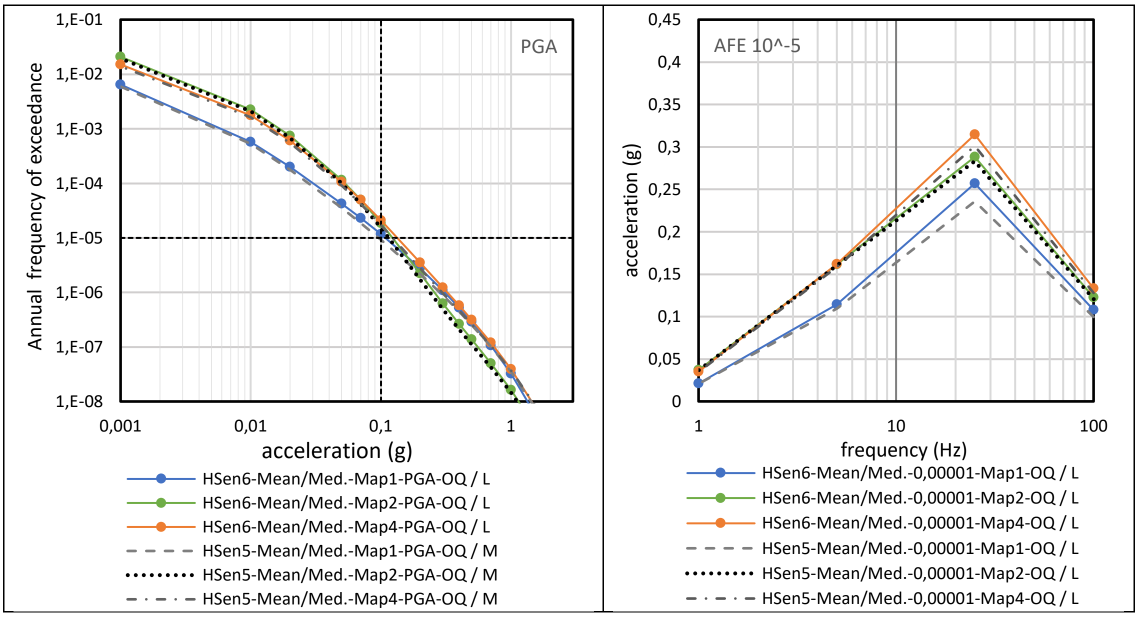


Fig. 4-16. The uniform 0-35km depth profile is replaced with the final "North" depth distribution proposed in SENSEI for the Hanhikivi NPP site. Hazard remains almost unchanged, but some increase at 25Hz and PGA spectra can be noted.

Sensitivity to depth distribution behaved as expected. Distributing the observed seismicity over a smaller crustal volume and closer to the ground surface results in higher hazard estimates.

4.2.4 Maximum magnitude (M_{max})

For Loviisa, steps LSen6 to LSen8 compared the one-branch test for M_{max} values 5,5, 6,5 and 7,5, respectively. The increase of M_{max} from 5,5 to 6,5 increased PGA by 15% and spectral acceleration at 25 Hz by 13%, at 5 Hz by almost 28% and at 1 Hz by almost 100%. The shift of M_{max} from 6,5 to 7,5 increased the PGA output value by a further 5%, the 25 Hz value by 4%, 5 Hz by almost 10%, and 1 Hz by 23%. The difference between values 6,5 and 7,5 was not as high as between values 5,5 and 6,5, perhaps due to the very low probability of high magnitude events in the Gutenberg-Richter approximation.

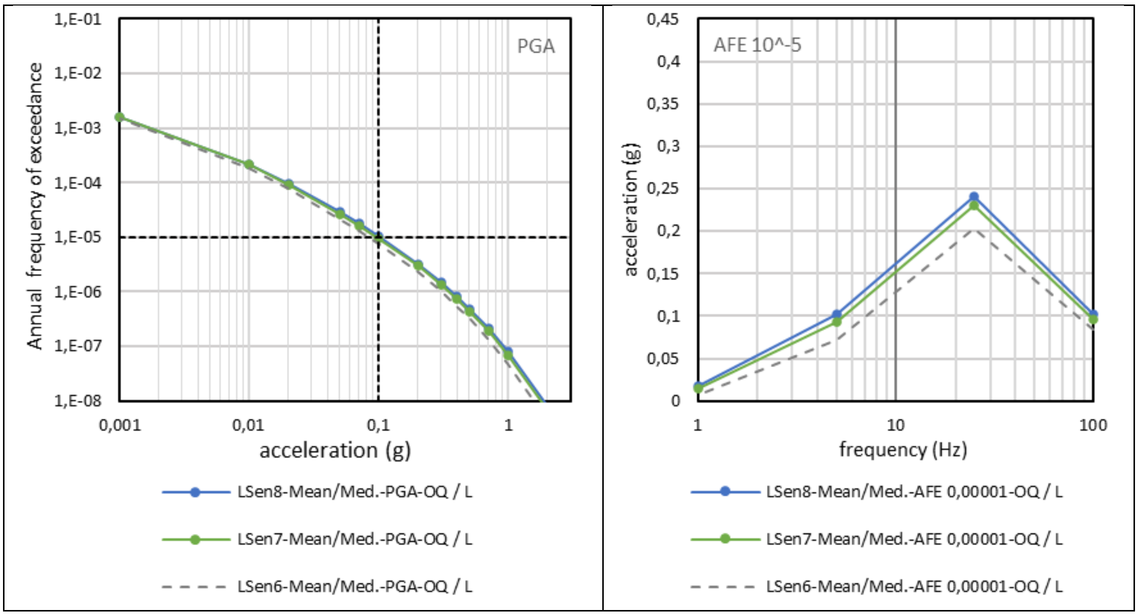


Fig. 4-17. The effect of the maximum magnitude M_{max}. The maximum magnitude is raised from M_w5.5, used in all earlier models (LSen6) to M_{max}=M_w6.5 (LSen7). M_w6.5 is close to the final M_{max} values re-evaluated and proposed in the SENSEI project. LSen8 presents the effect of M_{max}=*M_w7.5.*

In the case of Olkiluoto, the steps OSen3 and OSen4 compared the output from M_{max} values 5,5 and 6,5. At AFE 10^{-5}, the increase of the spectral accelerations was 20% for PGA, 17% for 25 Hz, 40% for 5 Hz and 130% for 1 Hz.

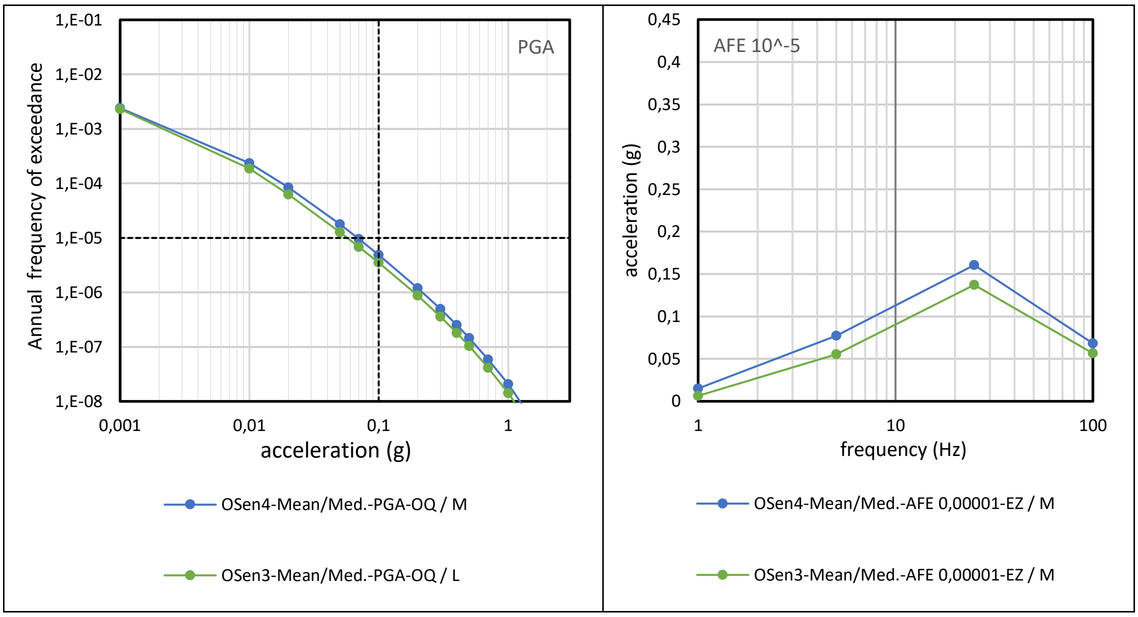


Fig. 4-18. The maximum magnitude is raised from Mw5.5, used in all earlier models to M_{max}=Mw6.5. Mw6.5 is close to the final M_{max} values proposed in the SENSEI project. No significant effect on the hazard curve.

In the case of Hanhikivi, step HSen4 used M_{max} of 5,5 and HSen5 M_{max} of 6,5. The relative increases for the frequencies investigated were 22% for PGA, 19% for 25 Hz, 42% for 5 Hz, and 73% for 1 Hz when using Map1, and 45% for PGA, 40% for 25 Hz, 72% for 5 Hz, and over 200% for 1 Hz, when using Map2 zones.

The results for Hanhikivi show that the relative increases were different for the two source models used. The proportions were higher in the case of Map2, which also gave higher absolute spectral acceleration values.

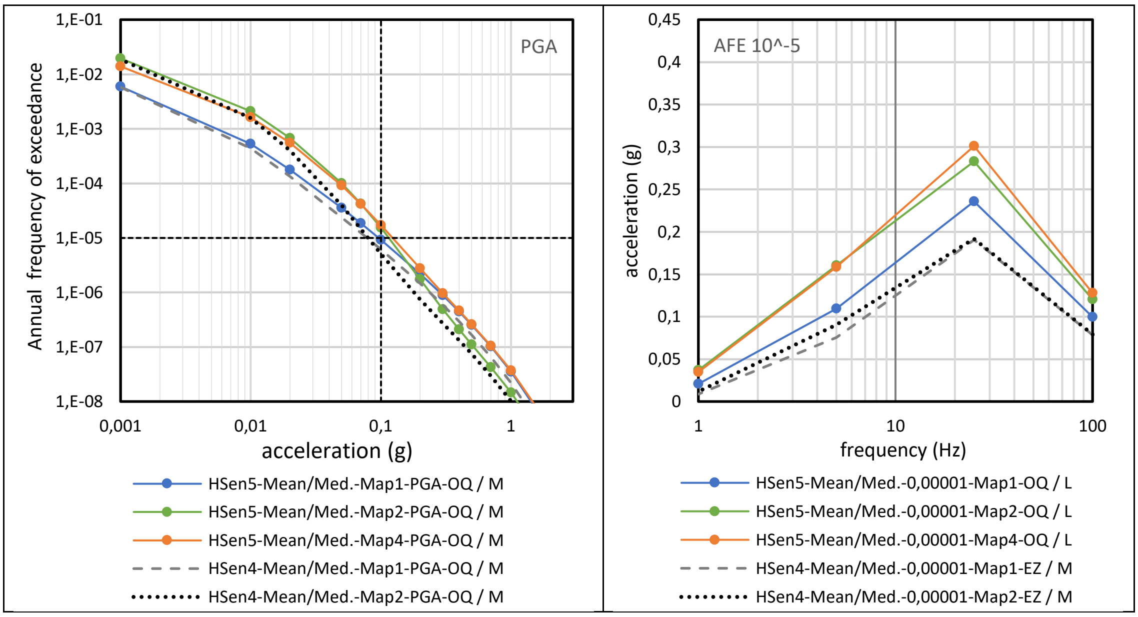


Fig. 4-19. The maximum magnitude is raised from Mw5.5, used in all earlier models to M_{max}=Mw6.5. Mw6.5 is close to the final M_{max} values proposed in the SENSEI project. A new source area model, Map4, has been used. Some increase in the hazard curves and clear increase throughout the spectra.

In all three cases, the proportion of the increase was different for the different frequencies. The largest relative increases were always found at 1 Hz, the second largest at 5 Hz, the third largest at PGA and the smallest relative increases at 25 Hz. The absolute spectral acceleration values were in reverse order; the smallest absolute values were found at 1 Hz and the largest at 25 Hz.

As a summary, although the very low probability of large magnitude events in the Gutenberg-Richter model reduces the effect of maximum magnitude, it cannot be concluded that the effect of M_{max} is small in general. Earthquakes at longer distances contribute more to low-frequency motion. As a result, a change in M_{max} in a distant source may have a larger effect at low frequencies.

4.2.5 Minimum magnitude (M_{min})

For Loviisa, the steps LSen1, LSen2, LSen3 focused on minimum magnitude, with M_{min} values 2, 3 and 4, respectively. At AFE 10^{-5}, the effect was negligible at 5 Hz and 1 Hz, at 25 Hz, the increase of M_{min} from 2 to 4 decreased the output value by almost 18%, and at

PGA the corresponding decrease was approximately 14%. At AFE 10^{-7} the behaviour followed a similar pattern, but the relative effect was smaller. When M_{min} was raised from 2 to 4, there was almost no effect at 5 Hz and 1 Hz, at 25 Hz the decrease was 8%, and at PGA almost 6%.

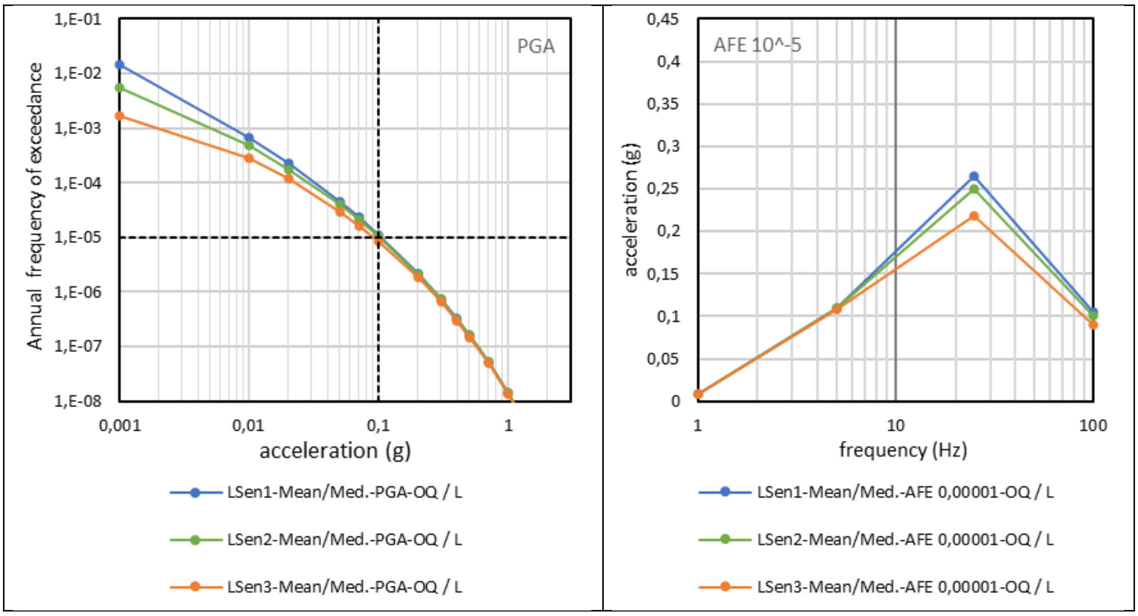


Fig. 4-20. The effect of M_{min}. The LSen1 model uses the Fenno-G16 GMPE with total σ, M_{min} 2, and M_{max}5.5. LSen2 and LSen3 set M_{min} to 3 and 4 respectively.

For Olkiluoto, the behaviour was similar to Loviisa. In step OSen1 M_{min} was 2 and in OSen2 M_{min} was 4.

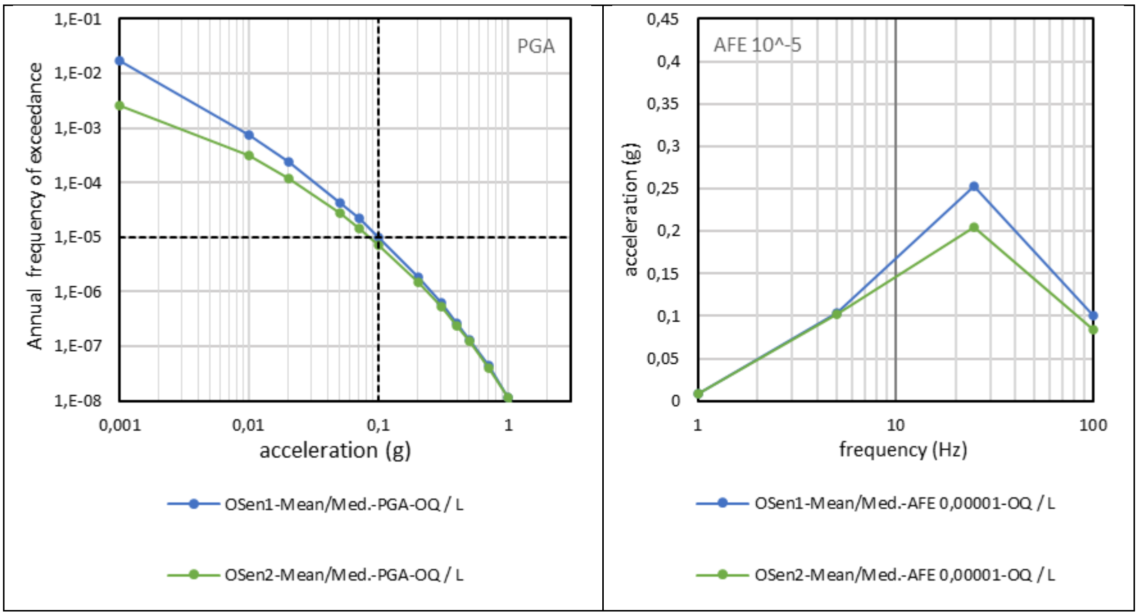


Fig. 4-21. The starting model (OSen1) uses the Fenno-G16 GMPE with total σ, $M_{min}2$, and $M_{max}5.5$. OSen2 raises M_{min} to $M_{min}4$.

The results were similar for Hanhikivi. For Map1, increasing M_{min} from 2 (HSen1) to 3 (HSen2) had no effect at 5 and 1 Hz, and fractions of per cent decrease at 25 Hz and PGA. When increasing M_{min} further to 4 (HSen3), the effect remained small at 5 Hz and 1 Hz, but the decrease at 25 Hz was 8% and at PGA over 5%. The behaviour was similar using Map2, but the absolute spectral acceleration values were larger.

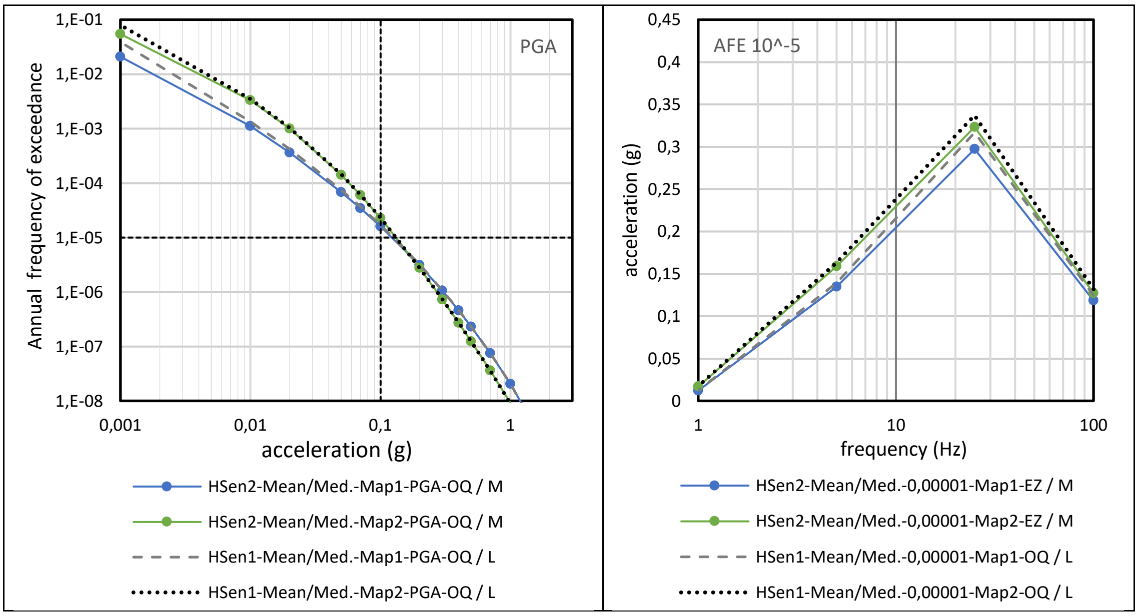


Fig. 4-22. Compared to HSen1 the minimum magnitude was raised from $M_{min}2$ to $M_{min}3$. Results show that PGA hazard decreases at low acceleration levels. Also, a small reduction at AFE 10^{-5} spectra.

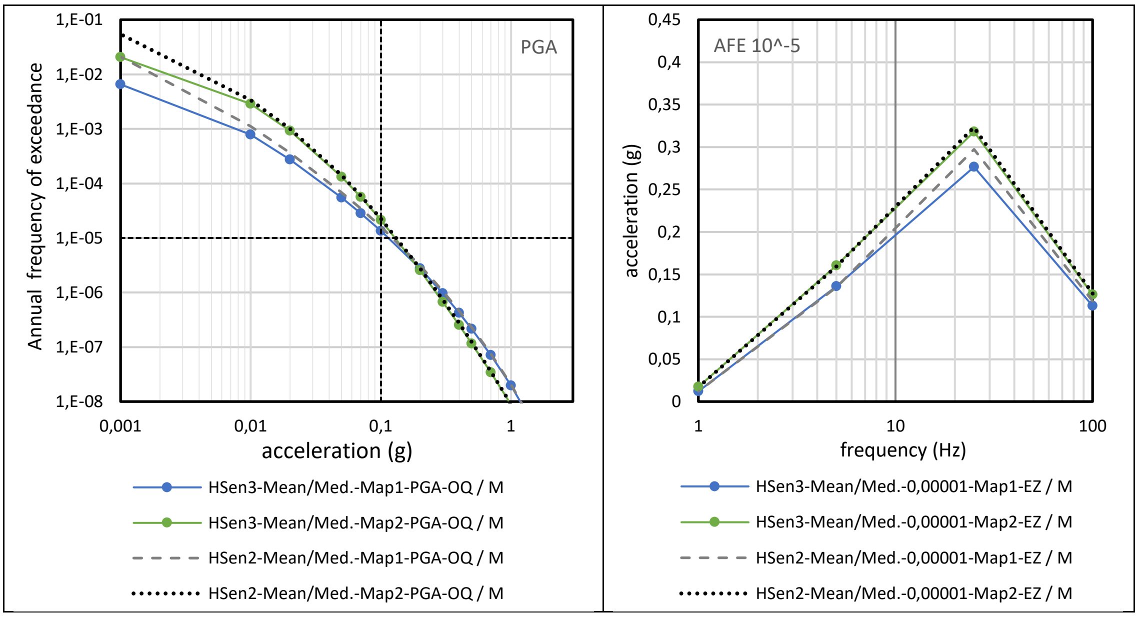


Fig. 4-23. Compared to HSen2 the minimum magnitude was raised from $M_{min}3$ to $M_{min}4$. Results show that PGA hazard decreases at low acceleration levels. Also, a small reduction on Map1 at AFE 10^{-5} at 25 Hz.

The trend of behaviour was as expected and as explained by Bender and Campbell (1989). The small-magnitude earthquakes influence the short return periods of the hazard curve affecting the high frequencies.

4.2.6 Ground motion prediction equations (GMPEs)

The first stage of sensitivity testing focused on GMPEs. The study was made only for Loviisa. M_{min} of 4 and M_{max} of 6,5 were used. Step LG2 had the GMPE from the Olkiluoto study, steps LG5a and LG5b had the GMPEs from the Hanhikivi study, steps LG6a and LG6b had the Fenno-G16 GMPE, and steps LG8 to LG9 had the NGA-East GMPE. Differences in the predicted PGA values are presented in figures 4-24 to 4-28.

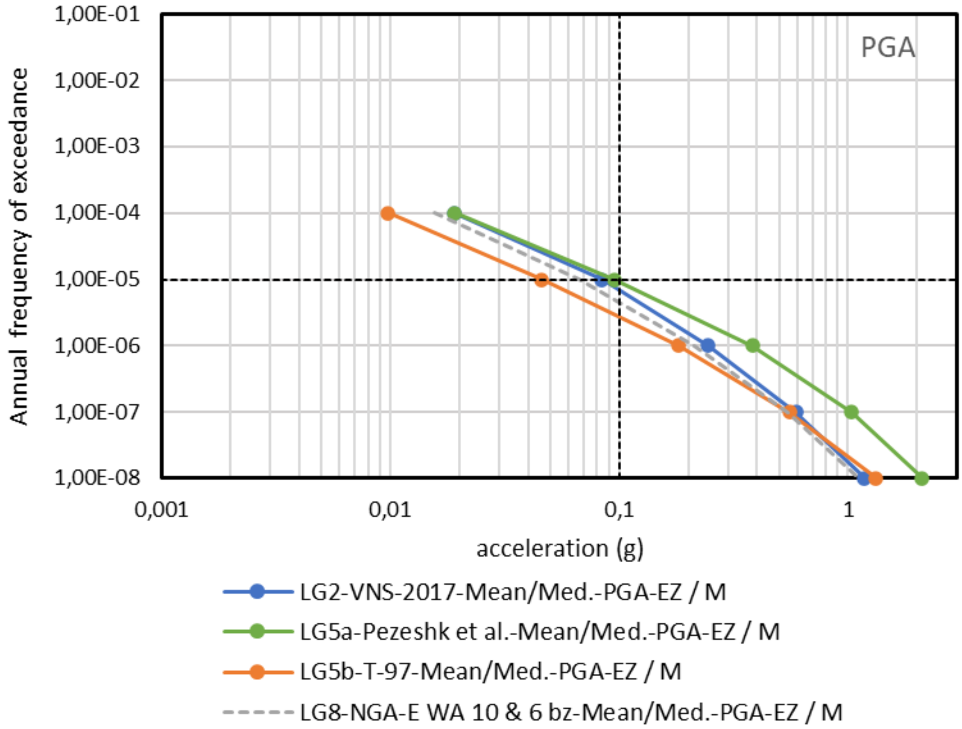


Fig. 4-24. LG2, 5a, 5b, 8: The GMPEs used in the Loviisa and Hanhikivi studies compared to NGA-E.

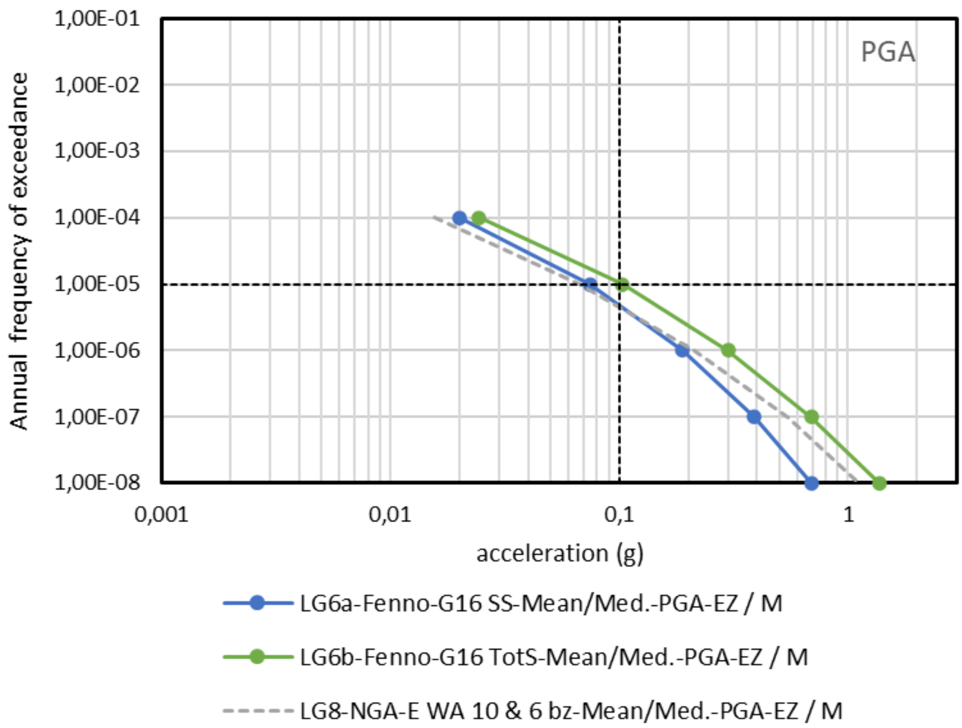


Fig. 4.25 LG6a, 6ba, 8: Fenno-G16 single station, and total sigma compared to NGA-E.

GMPEs NGA-East and Fenno-G16 (described in chapter 3.7.2), were chosen to further studies in SENSEI. Fenno-G16, when used with total sigma as recommended, resulted to higher hazard estimates than NGA-East. This is partly due to a larger mean prediction of Fenno-G16 for magnitude 4-5 earthquakes, but also due to a larger total sigma value. The significant effect of sigma a can also be discerned, when comparing the Fenno-G16 Total Sigma and Fenno-G16 single station (SS) sigma results.

For Loviisa, steps LSen3 and LSen4 show the higher hazard values from the Fenno-G16 model compared to the NGA-East model at AFE 10^{-5}. The PGA values are 32% lower for NGA-East than for Fenno-G16. The corresponding reduction at 25 Hz is 32%, and at 5 Hz almost 47%. At 1 Hz, the reduction is almost 34%.

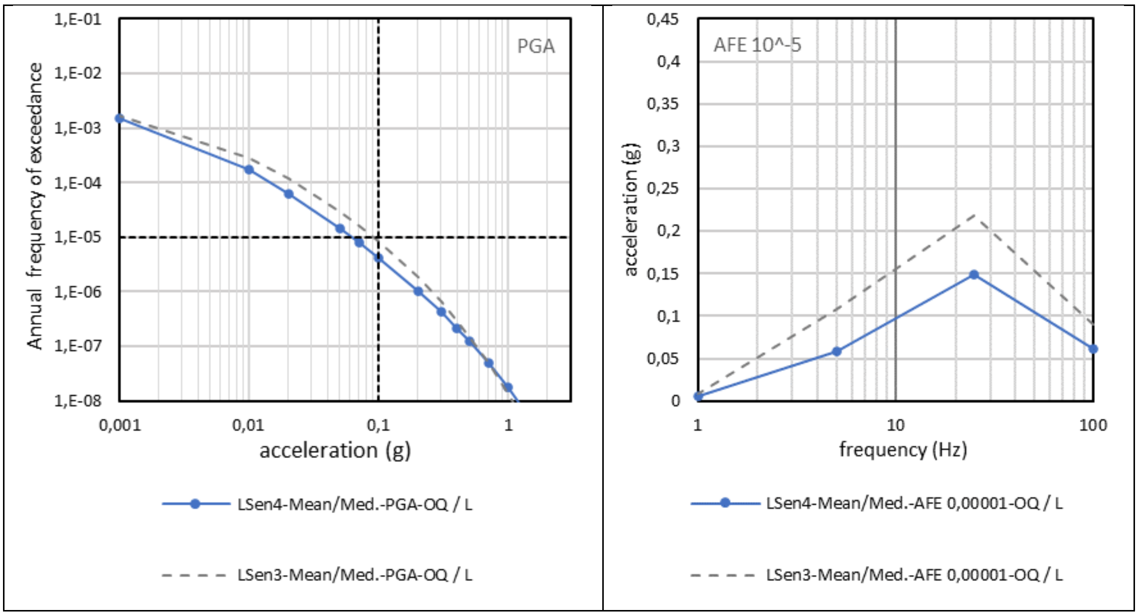


Fig. 4-26. LSen4: GMPE replaced from Fenno-G16 in LSen3 to the weighted NGA-East GMPE with ergodic σ (central prediction). Results show decrease of hazard, driven by both a lower mean prediction of the GMPE and smaller σ.

For Olkiluoto, similar studies are in steps OSen2 and OSen3. The depth range used extended down to 35 km, so the absolute values are lower than those from the new depth distribution "South", but the proportional changes were similar to Loviisa. When replacing Fenno-G16 by NGA-East WA, the PGA (EZ) value at AFE 10^{-5} was reduced by 32%, at 25 Hz by 32%, at 5 Hz by 45% and at 1 Hz by almost 26%.

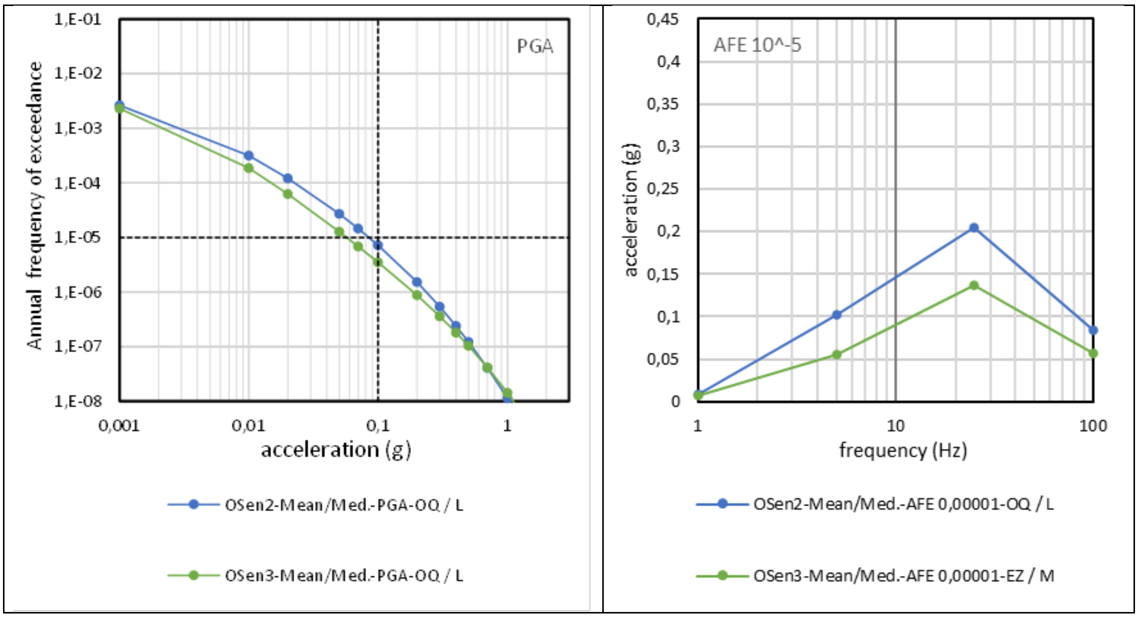


Fig. 4-27. OSen3&2: GMPE replaced from Fenno-G16 in OSen2 to the weighted NGA-East GMPE with ergodic σ (central prediction). Results show decrease of hazard, driven by both a lower mean prediction of the GMPE and smaller σ. The reduction of the 5 Hz, 25 Hz, and PGA in the spectra can also be noted.

For Hanhikivi, the corresponding steps were HSen3 and HSen4, with two branches for the source areas. For Map1 and AFE 10^{-5}, the reductions were 37%, 40%, 44%, and 30% for 100, 25, 5, and 1 Hz, respectively. In the case of Map2, the corresponding values were 37%, 40%, 40% and 30%.

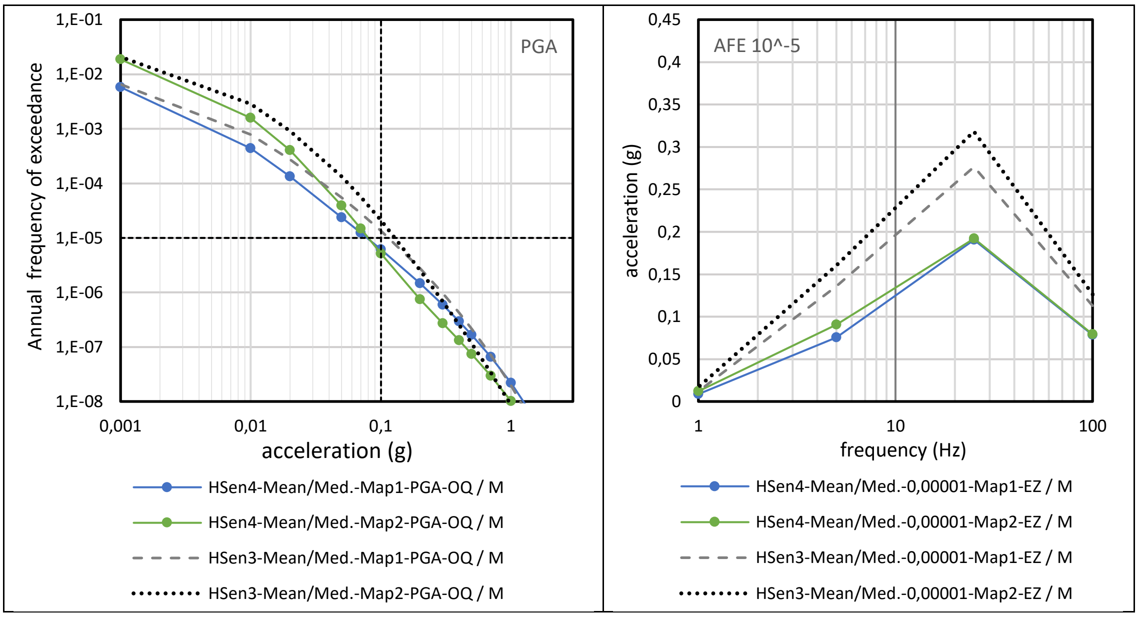


Fig. 4-28. HSen4&3: GMPE replaced from Fenno-G16 in HSen3 to the weighted average of the 17 NGA-East GMPE branches with ergodic σ (central prediction). Results show decrease of hazard, driven by both a lower mean prediction of the GMPE and smaller σ. The reduction of the 5Hz, 25Hz, and PGA within the spectra can also be noted

In summary, when replacing Fenno-G16 by NGA-East WA, the proportions of reductions at the three sites range from 26% to 47%.

4.2.7 Model complexity and median vs. mean hazard

For Loviisa, in LSen10 the original SSA10 was incorporated with a weight of 2/3 and the new, smaller delineation with a weight of 1/3. In addition, all the activity parameters of the host zone, SSA10, were incorporated, which resulted in 18 branches. Because the small-size SSA had less weight, the output decreased. The median output values of LSen10 are close to those of LSen7, and it can be argued that the alternative, smaller area has no effect in the logic-tree in practice if weighting of 1/3 is used. In addition to the branches in LSen10, the M_{max} uncertainty is included in LSen11, and LSen12 includes also branching of the NGA-East GMPE. Because the median of the M_{max} distribution is close to that used in model LSen10, difference between models LSen10 and LSen11 is not large. Model LSen12 results to slightly higher hazard predictions than model LSen11.

In the complex models mean prediction clearly exceeded the median prediction, which was expected.

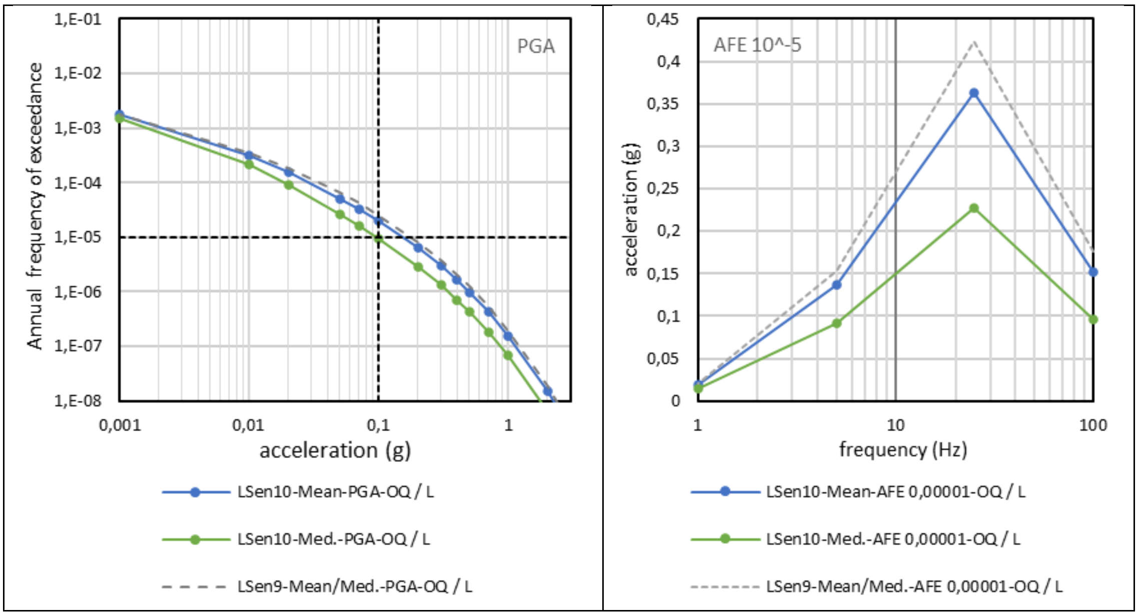


Fig. 4-29. LSen10: First model with logic-tree. Original SSA10 included with 66% weight and the divided SSA10 from LSen9 with 33% weight. The uncertainty in β and λ, reported in the original hazard studies for SSA10, was included in the model (i.e., 9 branches).

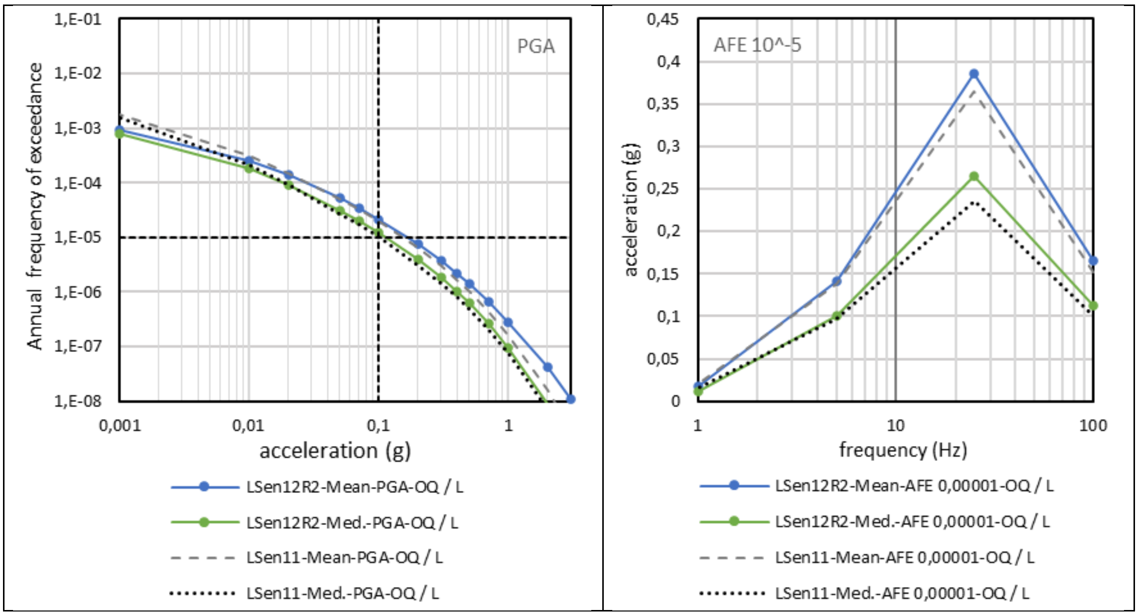


Fig. 4-30. LSen11&12: In addition to the branches from LSen10, the M_{max} uncertainty is included for LSen11. The M_{max} distribution in SENSEI is based on the Bayesian method. The median M_{max} is M_w6.64, not far from M_w6.5 used in earlier models. For LSen12, the NGA East GMPE is branched to the 17 branches and the central estimate of ergodic σ is also branched to “high”, “central” and “low” predictions. Mean hazard increasingly exceeds the median hazard.

For Olkiluoto, branching of λ and β is modelled in OSen6, branching of Mmax in OSen7, and branching of GMPE in OSen8. Because the median Mmax does not differ much between models OSen6 and OSen7, the difference between the models is not large. The hazard is slightly larger in OSen8 than in OSen7.

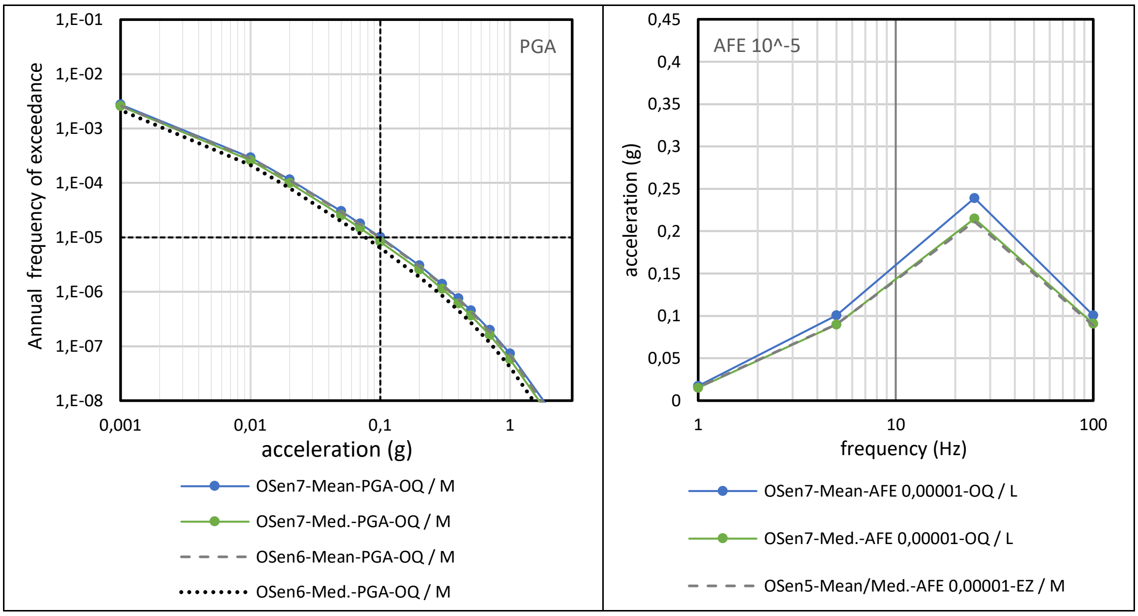


Fig. 4-31. In addition to the branches from OSen6, the M_{max} uncertainty is included. The M_{max} distribution proposed in SENSEI is based on the Bayesian method as described in chapter 3.5.1.2. The median M_{max} is M_w6.64, not very far from the M_w6.5 used in earlier models. Mean hazard increasingly exceeds the median hazard.

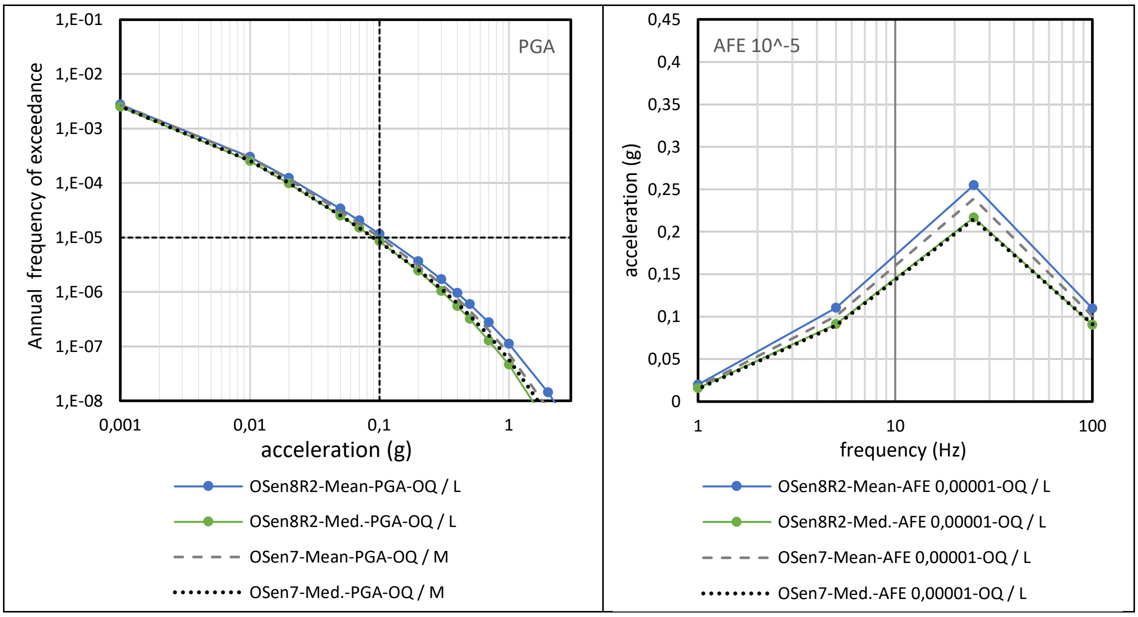


Fig. 4-32. The NGA East weighted average GMPE is branched at the 17 branches of the NGA-East GMPE. The central estimate of ergodic σ is also branched to “high”, “central” and “low” predictions. Mean hazard increasingly exceeds the median hazard.

For Hanhikivi, similar studies were made in models HSen7 (Mmax), HSen8 to HSen11 (λ and β) and HSen12 (NGA-East). The results are presented in figures 4-33 to 4-38.

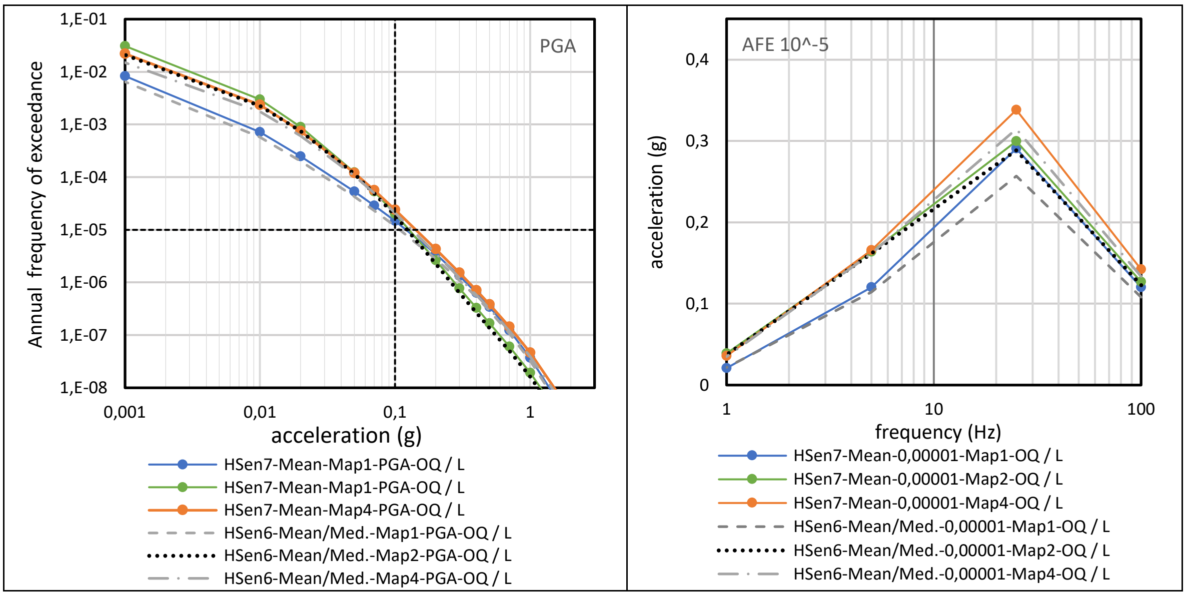


Fig. 4-33. HSen7&6: M_{max} uncertainty is included. The M_{max} distribution proposed in SENSEI is based on the Bayesian method. The median M_{max} is M_w 6.64, not very far from the M_w 6.5 used in earlier models. Mean hazard exceeds the median hazard. Largest increase at 5Hz spectra.

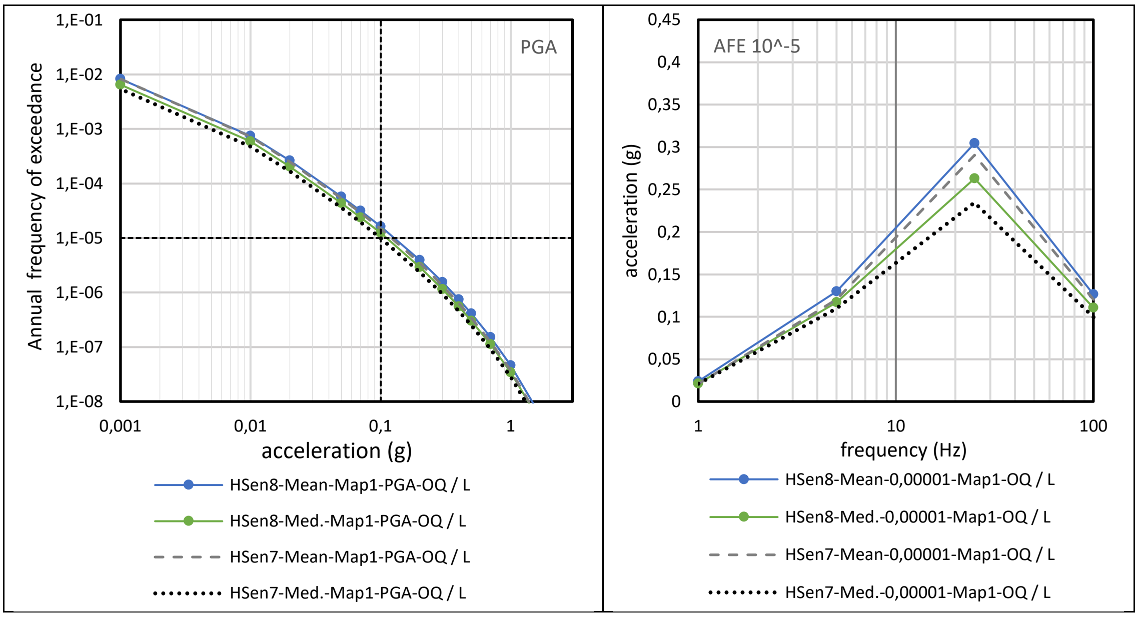


Fig. 4-34. HSen8&7: Uncertainty in β and λ, for SSA1.13 (Map1) included in (i.e., 9 branches). Mean and median hazards increase.

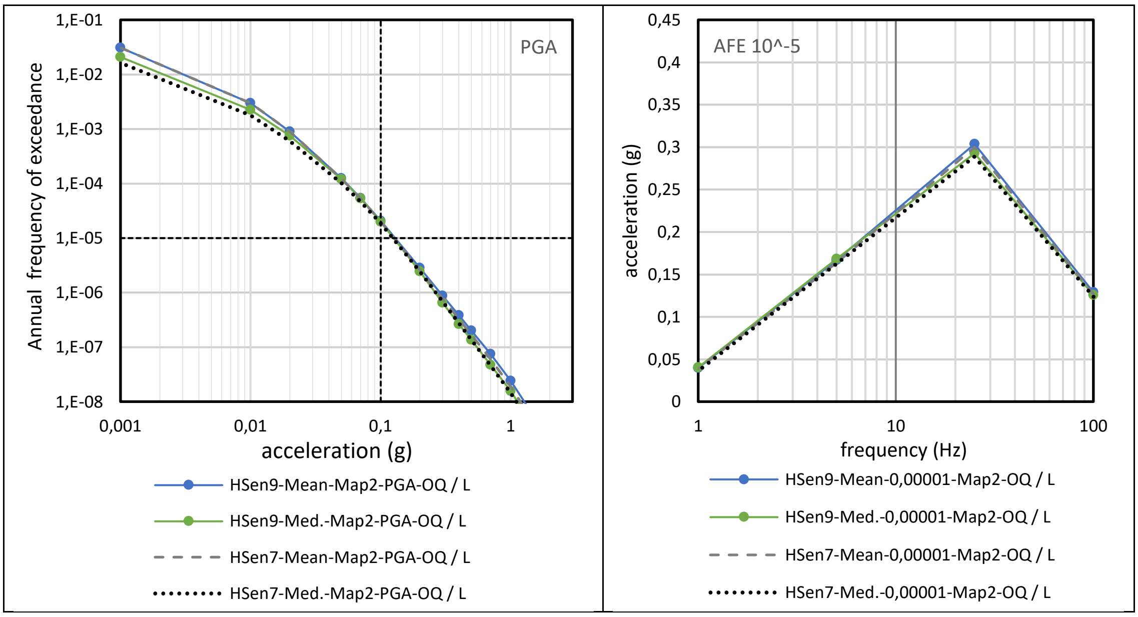


Fig. 4-35. HSen9&7: Uncertainty in β and λ, for SSA2.11 (Map2) included (i.e., 9 branches).

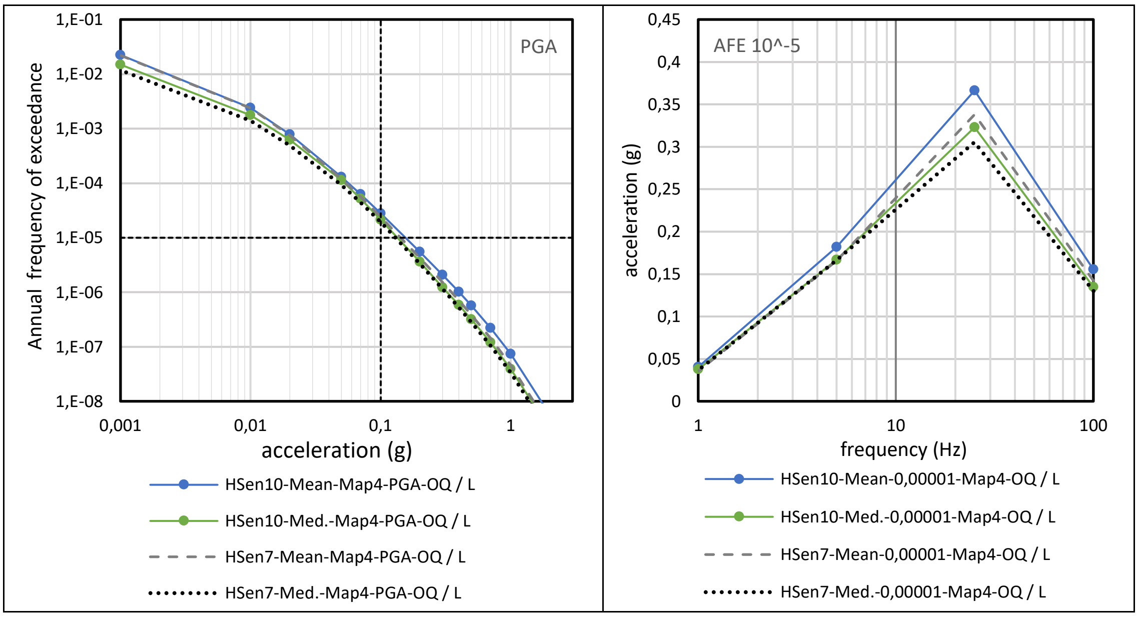


Fig. 4-36. HSen10&7: Uncertainty in β and λ, for SSA#8 (Map4) included (i.e., 9 branches). Mean and median hazards increase.

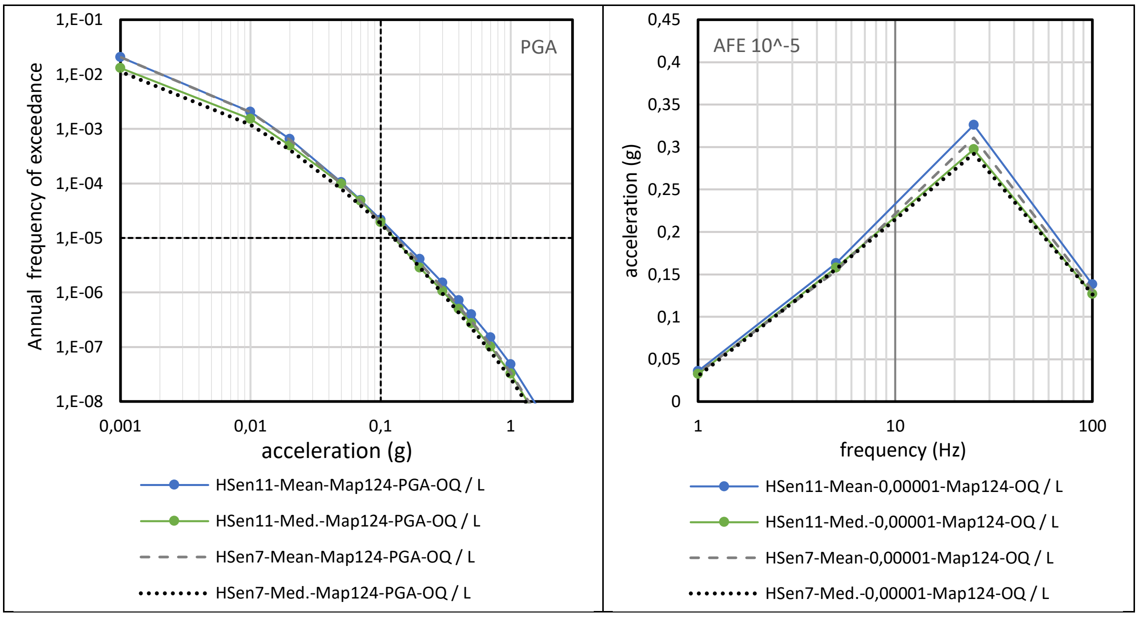


Fig. 4-37. HSen11&7: All three source area models used as logic tree branches with equal weight. Mean and median hazard are slightly decreased.

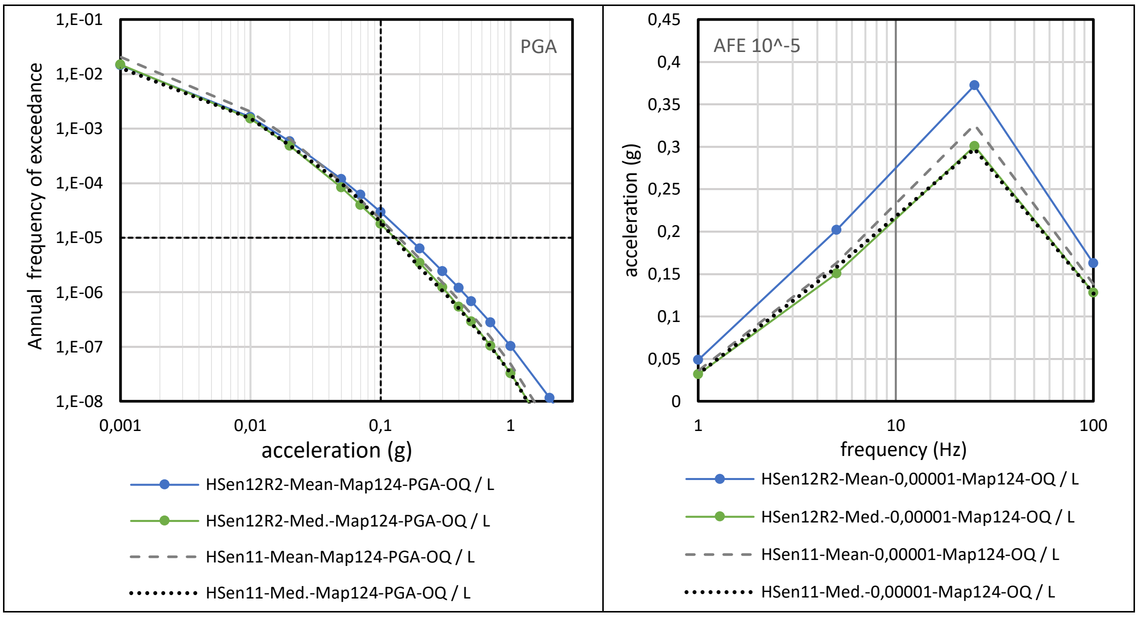


Fig. 4-38. HSen12&11: The NGA East weighted average GMPE is branched to the 17 branches of the NGA-East GMPE. The central estimate of ergodic σ is also branched to “high”, “central” and “low” predictions. The median hazard stays the same, but the mean hazard increases. The mean hazard increasingly exceeds the median hazard.

As expected, modelling of the uncertainties influences the results depending on the assumed variations of parameters. The more complex models gave information on the behaviour of the mean value, and the predicted mean value exceeded the median, which is an expected result. It may be overly conservative to have a design basis hazard based on the mean value and on the annual frequency of exceedance of 10-5. If mean values are to be used instead of median, the AFE should be re-evaluated.

4.2.8 Summary of the sensitivity of results to variation of input parameters

Some representative results have been collected into table 4-1. The range of variation of each parameter is presented as well as the effects of the variation to the hazard estimates at different AFEs and spectral accelerations.

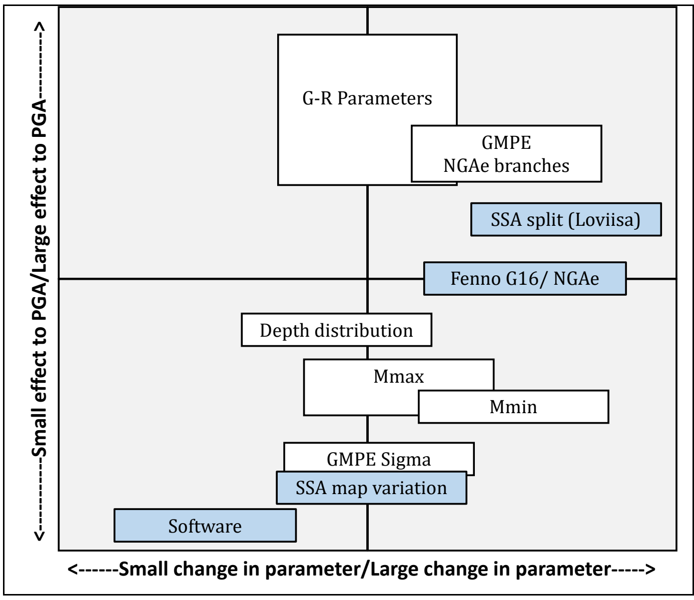
Table 4-1: Summary of the sensitivity of results to variation of input parameters in numerical form. The column "Parameter variation" indicates the how the parameters were varied to achieve the results in the columns on the right. Results marked "…" signify differences between NPP sites.

Parameter	Parameter variation	PGA AFE 10^{-5}/a	PGA AFE 10^{-7}/a	25 Hz AFE 10^{-5}/a	5 Hz AFE 10^{-5}/a	1 Hz AFE 10^{-5}/a
G-R parameters: Gutenberg – Richter parameters of general seismicity (a, b) (Figs. 4-5, 4-6)	Median to +σ	100% … 300%	70%	N/A	N/A	50% … 300%
GMPE, NGA East, variation in logic tree (Figs. 4-5, 4-6)	Median to highest of 17 branches of NGAe	100%	100%	N/A	N/A	100%
SSA Map variation (Figs. 4-5, 4-6)	Median to maximum	15%	15%	N/A	N/A	25%
SSA, special case of splitting the host SSA in Loviisa (Fig. 4-7)	Original SSA to split host SSA	80%	50%	75%	50%	50%
GMPE, NGA East / Fenno-G16 (Figs. 4-26, 4-27, 4-28)	NGA-East to Fenno-G16	50%	30%	50…65%	65…100 %	50%
Depth distribution (Figs. 4-14, 4-15)	0-35 km to 0-13 km	40%	40%	40%	30%	20%
M_{max} (Figs. 4-17- 4-19)	5,5 to 6,5	15%…30 %	15%…30 %	15%…40%	<30% … 70%	<5% … 200%
M_{min} (Figs. 4-20 – 4-23)	2 to 4	-5% … -15%	-5% … -10%	-10% … -20%	0… -5%	0… -5%
NGAe σ parameter (Figs. 4-5, 4-6)	low to high GMPE σ	10%	20%	N/A	N/A	10%
Software	EZFrisk to OpenQuake	minor numerical effects				

Summarizing Table 4-1 further and looking at the PGA results at AFE 10^{-5}/a, it can be concluded that

- Gutenberg-Richter (G-R) parameters were varied within a range of -σ to +σ and the results presented are from the median to +σ, which leads a rise of 100 to 300% in the acceleration estimate depending on the NPP site.
- Variation between the different branches of NGA-East GMPEs produce a 100% rise from the median to the highest branches.
- The effect of seismic source areas (SSAs) was analysed for the Hanhikivi site using 3 different source area maps. The variation in PGAs was of the order of 15 – 20%.
- Splitting the host SSA of the Loviisa NPP to consider the uneven distribution of recorded earthquakes led to an 80% rise in accelerations.
- Fenno-G16 on average gives 50% higher PGA estimations compared to NGA-East GMPEs.
- A uniform depth distribution between 0-13 km compared to a uniform distribution of 0-35 km gives 40% higher estimation at Loviisa and Olkiluoto.
- M_{max} magnitude variation from 5,5 to 6,5 increases the PGA estimation about 15% to 30% and the increase from 6,5 to 7,5 is much smaller at 5% to 10%.
- M_{min} magnitude variation from 2 to 4 decreases the PGA estimation about 5% at Hanhikivi and 30% at Loviisa and Olkiluoto. It can be also seen that the effects are smaller at the lower frequencies.
- Choosing a high sigma instead of a low sigma NGA-East GMPE raised the PGA estimate about 10%. It can be also seen that effect is little higher, 20% for PGA at AFE 10^{-7}/a.

The information above is presented in a graphical form in Fig. 4-39. Fig. 4-39 attempts to visualise the numerical effects of parameter variation on PGA at AFE 10^{-5}/a, and at AFE 10^{-7}/a as well as on acceleration response levels at 25, 5 and 1 Hz at AFE 10^{-5}/a in Table 4-1.



Parameters affecting the seismic hazard PGA at an AFE level of 10^{-5}:

- G-R parameters [+σ] effect 100 to 300%
- GMPE [NGAe branches] effect 100%
- SSA map variation [med.-max.] effect 10%
- SSA [Local zone split for Loviisa] effect 80%
- GMPE [Fenno-G16 / NGAe] effect 50%
- Depth distribution [0-35km / 0-13km] 40%
- Mmax [5,5…6,5] effect 15 to 30%
- Mmin [2…4] effect -15%
- GMPE sigma [+σ] effect 10%
- Software [OpenQuake / EZFrisk] effect is minor

Fig. 4-39. An indicative summary of the sensitivity results. The horizontal axis of the chart represents a normalized, to a standard deviation (if possible), change in input parameter and the vertical axis represents the parameters' effect on the PGA at 10^{-5} AFE. A white background denotes a quantitative input value, and a blue background denotes a qualitative input or choice. (GMPE sigma represents the uncertainty of the GMPE's fitting to measurement data, SSA split of the host area includes recalculation of the G-R parameters)

The results of the SENSEI project help to understand the quantitative effect of input parameter uncertainties on the results of the PSHA. An important contribution by the international experts was the identification of the input parameters to be varied and the estimation of relevant ranges of variation. The four-field matrix in Fig. 4-39 illustrates how changes in parameters affect seismic hazard estimation. The field "small change in parameter" and "large effect to PGA" represents highest sensitivity. Such pure cases were not identified, which is a reassuring result. The results do not indicate any completely new significant effects of the input parameter uncertainties on the results. Changes in G-R parameters caused the largest effects. The uncertainty of the G-R parameters depends on the properties of the catalogue, e.g., completeness, declustering and homogenization of the magnitudes.

4.3 Discussion on the connection of the hazard to nuclear safety

Based on hazard studies the site response spectra are defined and used as input for the dynamic analysis of buildings leading to floor response spectra. The floor response spectra and the fragility curve of a system, structure or component (SSC) used to calculate the total seismic risk to that SSC. Based on the results of the previous chapter, e.g., the variation of the G-R parameters reveal the PGA could increase to the range studied in the example below.

The relevance of the seismic hazard is dependent on the fragilities of safety significant SSCs. The fragility of an SSC is typically given by a fragility curve. Figure 4-40 presents examples of fragility curves for typical SSCs representing 1) normal SSC, 2) seismically sensitive SSC and 3) seismically very sensitive SSC. The component HCLPF (High Confidence of Low Probability of Failure) corresponds to a 1% probability of unacceptable performance on a mean fragility curve in terms of a specified ground motion parameter, which in this case is PGA.

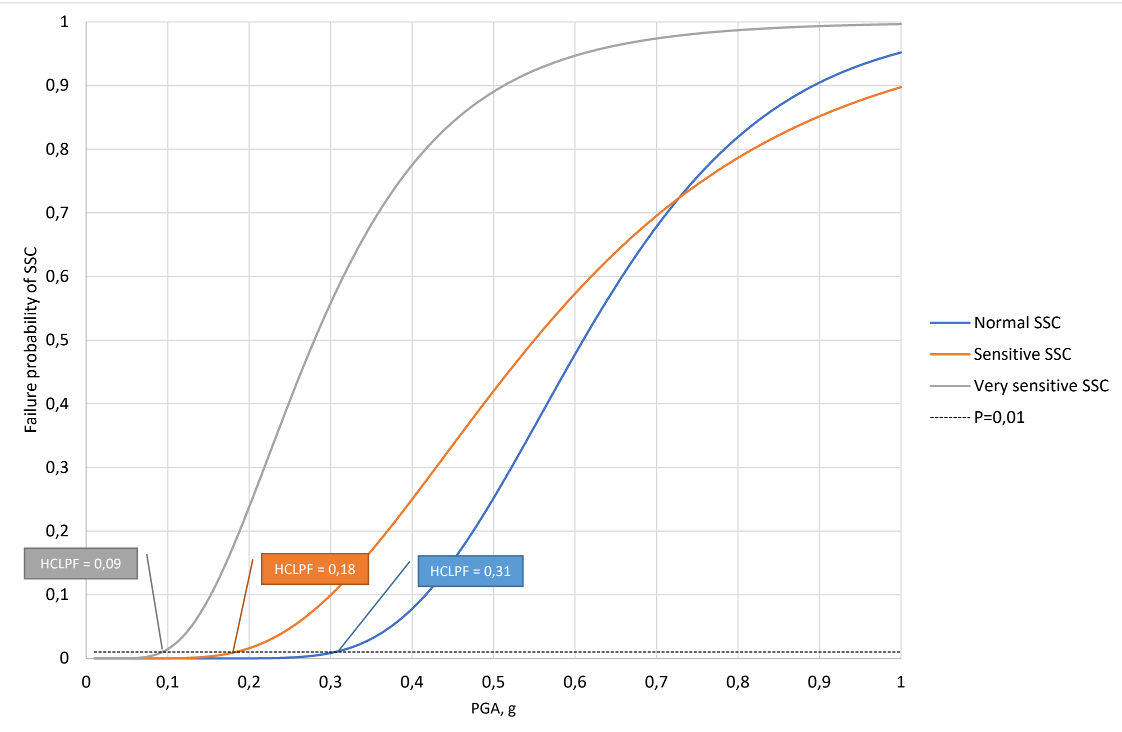


Fig. 4-40. Example fragility curves for three SSCs with different fragility parameters, representing 1) normal SSC, 2) seismically sensitive SSC and 3) seismically very sensitive SSC.

Appendix 1 presents an example where a simplified PRA model has been constructed to study how sensitive the seismic core damage frequency is when various seismic hazards and SSC fragilities are assumed. The assumed seismic hazards are within the range of hazards studied in SENSEI. The postulated fragilities correspond with the examples in Figure 4-40. It was no point to include seismically strong SSCs in the study. The assumed conditional core damage probabilities (CCDP) given failure of SSC were from 0,04 to 1. In typical seismic PRAs, most SSCs have CCDP lower than 0,04. Four sensitivity studies are performed:

1. Variation of fragilities — CCDP values are equal
2. Variation of CCDP values — fragilities are equal
3. Mixed variation of fragilities and CCDP values
4. Variation of seismic hazards — mixed variation of fragilities and CCDP values

It was found that seismic events around PGA 0,2 to 0,6 g are the most important regarding seismic risk. They have AFE in the range of 10^{-7}/a to 10^{-6}/a. Core damage frequency values 10^{-7} per year of this example are low and typically would not contribute much to the overall core damage risk of an NPP. However, in the seismic scenarios, the conditional probability of large or early release can be high. From the external release risk assessment point of view (level 2 PRA), it can even be meaningful to put effort in the estimation of seismic hazards at PGA levels 0,5 or above.

5 Conclusions

The results of the sensitivity studies can be used to identify the most important topics for additional research in the field of seismic safety. Several findings, recommendations and new points of view arose in the SENSEI project based on the experience of the expert group and results of technical calculation group. In some cases, it turned out that there are no simple solutions to the problems encountered in the PSHAs for the Finnish NPP sites. The conclusions will be taken into consideration in the review of the latest PSHAs and development of new PSHAs for the Finnish NPP sites.

The following points regarding the PSHA studies and their input were discussed and assessed.

- Ground motion prediction equations (GMPE): The following GMPEs were reviewed and compared in the project: The VNS GMPEs used in Loviisa and Olkiluoto PSHAs, the Pezeshk and referenced Pezeshk GMPEs used in the latest Hanhikivi PSHA, the NGA East GMPEs developed recently for Central and Eastern USA, and the Fenno-G16 GMPE, based on the work of Graizer, developed for Finland by a part of technical calculation team. The NGA East and Fenno-G16 GMPEs were selected for the sensitivity studies. The Fenno-G16 equations were used in calculations which required a low minimum magnitude for hazard integration due to more limited magnitude range of NGA East equations. The VNS GMPEs were rejected because their development does not correspond to current established practices and the GMPEs based on the Pezeshk equations were rejected due to the problematic changes of form in the middle of the frequency range.

- Seismic catalogue: The review of the seismic catalogue was not a focus area in the project, but it was considered in some discussions. It was pointed out that the catalogue and the declustering and homogenization procedures should be open to external review as a part of sensitivity studies. In these SENSEI studies the pre-determined source areas and their seismic parameters were applied as such.

- Completeness of the catalogue: The completeness and homogeneity of the seismic catalogue was addressed as the length of the historic observation period of the order 250 years varied between the source zones. The annual occurrence rate is also affected by the possible inhomogeneity during the observation period. Most of the recent recordings in Fennoscandia contain low magnitude earthquakes; whereas, in the historic observations there is a threshold for perceivable events which is affected also by the depth of the earthquake. Reviewing and continuous updating and homogenising of the catalogue could be a future research item.

- Seismic source area delineation: Site-specific seismic source areas models have been delineated for the NPP sites mainly according to seismicity because seismicity does not correlate well with main geological features in Finland. There has not been a general seismic source areas model for the whole country which makes the comparisons between the NPP sites difficult. On the other hand, on the European scale Finland as a whole is a rather uniform and stable continental area and thus the local deviations mainly are due to the occurrence rate of small events.

- Gutenberg-Richter parameters: The estimation of G-R parameters for the seismic source areas contains major uncertainty in the sensitivity analysis because of the low activity rates and the catalogue. The parameters λ and β, or a and b, of the Gutenberg-Richter model describing the annual number of earthquakes above a given magnitude have significant effect on the hazard prediction. The annual occurrence rate is also affected by the possible inhomogeneity during the observation period in the seismic catalogue. The lack of large magnitude events in Fennoscandia complicates the calculation of G-R parameters, increases the uncertainty in b, and makes the estimation of M_{max} difficult.

- Magnitudes M_{min} and M_{max}: It was found that the effect of minimum and maximum magnitudes was less significant than expected based on previous PSHAs. The findings indicate that reassessing the G-R parameters would be an interesting topic for future research.

- Depth distribution: An analysis of the catalogue revealed that the depth distributions of observed earthquakes in Finland seem to differ between southern areas and the northern. Thus, two depth distributions were used in the calculations, which led to moderate effects on the hazard.

- Hazard calculation software: The widely used computer programs use similar well-established calculation methods, and the variation of results of different programs is small. However, there are differences in the user interfaces. Modern programmes include more possibilities for post-processing and combining results of calculations for individual branches of the logic tree and make the whole PSHA computational process faster also enabling sensitivity studies. The recent Finnish PSHAs have been carried out with the EZ-FRISK program but in the SENSEI project the OpenQuake program was selected for the sensitivity calculations due to its versatility and relative user-friendliness, also benefitting the quality control of calculations. OpenQuake type of software should enable in future also to implement Monte-Carlo procedure for analyses which has been practically impossible so far.

The quantitative effect of input parameter uncertainties on the results of the PSHA are illustrated in figure 4-39 and table 4-1. An important contribution by the international experts was the identification of the input parameters to be varied and the estimation of relevant ranges of variation. The four-field matrix in Fig. 4-39 illustrates how changes in parameters affect seismic hazard estimation. The results do not indicate any completely new significant effects of the input parameter uncertainties on the results. Changes in G-R parameters caused the largest effects. The uncertainty of the G-R parameters depends on the properties of the catalogue, e.g., completeness, declustering and homogenization of the magnitudes.

In addition, there was discussion on the use of the mean values for the ground response spectrum and PGA in the definition of the design basis earthquake instead of the median used in the current YVL B.7. The topic could be reconsidered in the next update of the YVL guides.

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Nuclear Reactor Regulation
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Appendices

1. Simplified PRA model
2. Calculation matrix reported by VTT and commented by other parties
3. Discussion papers received from experts:

   3.1 Benchmark cases for EZ Frisk and OpenQuake
   3.2 Seismic source areas in the Fennoscandian Shield, focusing on the Loviisa NPP
   3.3 Notes on Proposed Treatment of lambda and beta in Logic Tree
   3.4. On the depth distribution of earthquakes in Finland
   3.5 Mmax using the Bayesian approach
   3.6 Arguments for a certain range of Mmin in the PSHA sensitivity studies in Finland
   3.7 Comparative plots of GMPEs