7.5 Valorisation of probabilistic seismic hazard results in Finland (VALERI)

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Abstract

Probabilistic seismic hazard analysis (PSHA) is the standard method to assess seismic hazard for nuclear power plants (NPPs). In Finland, the median confidence seismic hazard at annual frequency of exceedance (AFE) 10^{-5} is used for design-basis earthquake (DBE), with a minimum threshold of the horizontal peak-ground acceleration of 0.1g. Exceptional earthquakes for design extension conditions (DEC C) are proposed with median confidence at AFE 10^{-7}/year (STUK, 2019).

In this work, we explore the possibilities of DBE being anchored to other confidence level hazards, since the use of median is the minority position in Europe. We outline PSHA as a tool for hazard calculations, and how hazards are used in risk assessment and risk-informed decision-making. We particularly focus on the treatment of uncertainties and arguments about the mean and fixed-confidence hazards. The goal is to probe if regulatory transition away from median confidence hazard is (i) desirable, (ii) possible and (iii) identify the foreseeable difficulties. We discuss possible options for DBE and DEC C, for the consideration of the different stakeholders. Since the use of median hazard has a long tradition in Finland, an update would be no trivial undertaking.

Introduction

Probabilistic seismic hazard analysis (PSHA) is a methodology to estimate the likelihood that a threshold value of the earthquake ground-motion will be exceeded at the target site or region, in a specified time interval. The methodology was introduced several decades ago (Cornell 1968). PSHA is used in Finland, among many other countries, to provide site-specific input for probabilistic risk assessment (PRA) of nuclear power plants (NPPs). PSHA was primarily developed for the vibratory ground motions triggered by earthquakes, so-called primary earthquake effects. In Northern Europe, secondary earthquake effects, such as tsunamis and landslides or other types of ground failure, are infrequent, but not unprecedented (Mäntyniemi et al. 2021a).

A complete PSHA study integrates a wide range of disciplines (i.e., seismology, geology and tectonics, geodesy, statistics, probability theory, uncertainties, decision theory, civil and geotechnical engineering). Many large-scale PSHA projects, particularly those conducted in the framework of the Senior Seismic Hazard Analysis Committee (SSHAC; Budnitz et al. 1997a, b) procedure also emphasize that cognitive psychology plays a role in making expert judgments. The primary output of PSHAs are hazard curves expressing the annual frequency of exceedance (AFE) of the selected ground-motion measures.

When a single threshold of seismic load is needed for instance in engineering work, two decisions must be made to obtain values for design: which AFE should be adopted, and from which hazard curve should the ground-motion value be read. The current regulatory status in Finland, given in the guide YVL B.7 (STUK, 2019), is that the median confidence seismic hazard at AFE 10^{-5} is used to substantiate the seismic design-basis earthquake (DBE) for NPPs with minimum horizontal PGA value as 0.1g.

Evidently, the DBE may be exceeded. Global examples of exceedance of the DBE ground motion include the Niigataken-Chūetsu-Oki earthquake (M6.6) in the Niigata Prefecture of Japan on 16 July 2007. The ground motion caused by the shallow earthquake at the site of the Kashiwazaki-Kariwa NPP (KKNPP) exceeded the plant's DBE ground motion by a significant amount, and all the seven reactors of the plant were shut down for an extended period (Johnson et al. 2017). The KKNPP units performed well in this situation, but a post-earthquake analysis concluded that similar performance cannot be assured for other NPPs given the same loading conditions. The KKNPP restart experience demonstrated the need for formulating specific and detailed criteria for addressing situations in which seismic events trigger ground shaking that exceeds the original design or evaluation basis. The International Atomic Energy Agency (IAEA) provided guidance to operating organizations (IAEA 2011). New definitions of the design basis were implemented in some cases.

The Tōhoku-Oki earthquake of 11 March 2011 was a megathrust event (M9.0) that generated very violent ground shaking, moved the Honshu Island 3.6 m to the east, shifted Earth's axis by 25 cm and accelerated its rotation by 1.8 microseconds (Norio et al. 2011). The 11 NPPs in Northeastern Japan stopped operating their reactors automatically, and the ground shaking did not significantly damage the safety-related structures, systems, and components of NPPs (Johnson et al. 2017), but the impact of the tsunami stopped the cooling system of three of the Fukushima Dai-ichi reactors, which, consequently, led to three core meltdowns. The earthquake-tsunami induced nuclear crisis drew attention to extreme events and large-scale disaster risks (e.g., Wong 2014). Upgrades were implemented to meet new definitions of the requirements for beyond DBE ground motion. The guide YVL B.7 (STUK, 2019) states that *"exceptional external events and conditions with an estimated frequency of occurrence less than 10^{-5}/year shall be considered design extension conditions (DEC C) events"*.

The aim of this work is to explore the seismic hazard and confidence levels that are relevant for NPPs in Finland, including comparisons and interdependences between DBE and DEC C. We draw specifically on the outcomes of the SENSEI

(SENsitivity study of SEIsmic hazard prediction in Finland) project, conducted 2019–2020 (Mäntyniemi et al. 2021b, Fülöp et al. 2022).

PSHA as tool to estimate seismic hazard

Probabilistic modelling of seismic hazard incorporates *aleatory variability* and *epistemic uncertainty*. Aleatory variability is inherent randomness to the phenomena or its representation with a certain model (i.e., apparent aleatory variability), while epistemic uncertainty is the lack of understanding of the models, the distributions of earthquake magnitude, location, etc. The specific terms were introduced into PSHA by Budnitz et al. (1997a, b), but were understood much earlier including the contested nature of the separation between the two types of uncertainties (Marzocchi and Jordan 2014).

Aleatory variabilities are directly included in the exceedance probability calculation, while epistemic uncertainties are handled by assembling a set of alternative PSHA models, each providing a hazard result. Epistemic uncertainty can, in concept, be reduced by collecting new observations and developing modelling. Improved datasets clearly advocate updating PSHA models. If the logic tree covered all the mutually exclusive and completely exhaustive (MECE) and appropriately weighted future earthquake scenarios, the result could be interpreted as the true hazard distribution (Bommer and Scherbaum 2008). In practice, logic trees also document and display in a transparent fashion the state of seismotectonic data and knowledge in the target region.

Seismic hazard in risk assessment and decision making

The obtained hazard results must be placed in the context of their practical application. In the nuclear framework, they serve as input for assessment, deterministic or probabilistic, of earthquake consequences. For instance, seismic probabilistic risk analysis (SPRA) is used to compute the risks posted by earthquakes, expressed as annual frequency of unacceptable performance of the NPP. This is obtained by integrating the seismic hazards with the plant fragility, over the relevant range of intensity measure levels. SPRA incorporates the entire range of uncertainties in seismic hazard, structural response, and capacity of the NPP components. The general procedure is shown in Figure 1, reproduced from Huang et al. (2011). Figure 1a represents a mean confidence fragility curve of core melt, while Figure 1b is the mean confidence hazard curve. The mean core melt probability for PGA in the range 0.45–0.55g is approximately 0.5, and the annual frequency of PGA between these two limits is about 0.0011. Their product is the annual frequency of core melt contributed by PGAs between 0.45–0.55g, and the contributions from all PGAs can be calculated by integrating over the entire range of PGAs (Huang et al., 2011).

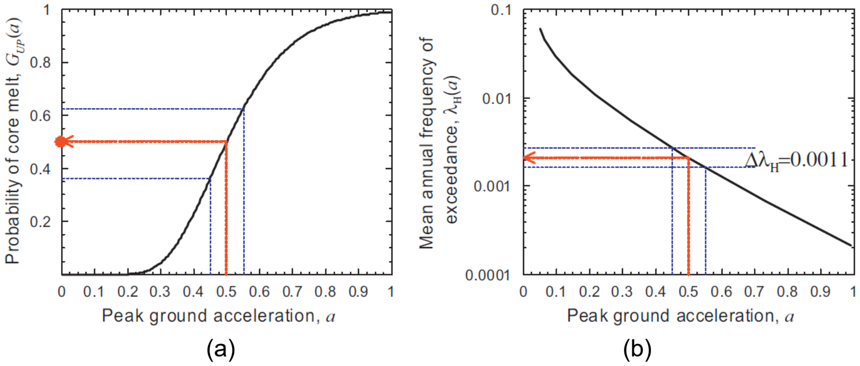


Figure 1. Generic mean core-melt fragility curve and mean hazard curve. The X-axis is commonly the peak-ground acceleration (PGA). Reproduced from Huang et al. (2011).

Mean and fixed-fractile hazards

McGuire (1993) emphasized that probabilistic hazard results should be reported by several fractiles and the mean hazard, to allow risk mitigation decision-makers to consider uncertainties in an appropriate manner. If a single result is needed, the mean should be selected, primarily because it is sensitive to all scenarios, including the extreme ones that drive the hazard at low AFEs. McGuire (1993) also argued that, in the decision-theoretic sense, the mean hazard allows target safety goals to be met over all sites.

An opposing opinion to using mean hazard was presented by Abrahamson and Bommer (2005). Their opinion note focused on low AFEs, and was argued from the point of view of critical infrastructure (i.e. NPPs and repository for high-level radioactive waste at Yucca Mountain). They remarked on the mean hazard curve increasing over high fractiles at low AFEs (this behavior is most noticeable in Figure 3), although they admitted that it is not alone a valid reason for adopting a different hazard curve. They based their argumentation on the interpretation of the branch weights, which in their view are confidence levels rather than probabilities, and on the instability of the mean hazard curve.

In their reply, McGuire et al. (2005) maintain that it is preferable to use the mean hazard, even from the risk calculation point of view. Their core argument relates to the widespread distinction used in PSHA between aleatory variability and epistemic uncertainty. McGuire et al. (2005) pointed out that mean hazard is stable against this distinction within the model, while median hazard is not. They list cases in which the distinction is not trivial to make, so expert judgment would influence the median hazard, but not the mean. They also point out that risk mitigation decisions are normally not influenced by the source of the uncertainty in hazard model. McGuire et al. (2005) also point out that implausible interpretations should be screened out from the PSHA model itself or weighted with low weights. This will preclude the mean hazard to exceed larger fractiles. Choosing median may result in powerless decisions, since extreme scenarios would be completely disregarded.

Hazards in NPP regulations

Information about up-to-date PSHA practices in member countries of the Organization for Economic Co-operation and Development (OECD) was collected by a questionnaire sent to the representatives of countries participating in the OECD, Nuclear Energy Agency (OECD 2019; Okko et al. 2019). The questionnaire concerned details of the PSHA practice in the nuclear field, such as data collection, seismic source zones, logic trees, GMPE, ground condition, treatment of uncertainties, and the use of PSHA outputs. The respondent countries were situated in different tectonic environments and hazards are presented to AFEs in the range of 10^{-5}…10^{-9}, depending on the seismicity of the site. Very detailed PSHA output was given by Switzerland, where results for mean, median, and the 5th, 16th, 84th and 95th fractile hazard curves are normally reported. The common choice for single hazard definition is the mean hazard at AFE 10^{-4} or 10^{-5} (Table 1).

Table 1. AFE and confidence level used for the definition of SSE (i.e. similar to DBE in Finland) in nine European countries.

Country	PGA for SSE (m/s^2)	Fractile for SSE	AFE of SSE
Belgium	0.99–1.39	mean	10^{-4}
Finland	1	median	10^{-5}
France	0.5–1.5	-	-
Germany	North	84%	10^{-5}
	South	median	10^{-5}
Spain	-	-	10^{-4}-10^{-5}
The Netherlands	0.6	-	10^{-4}
Sweden	1.1	-	10^{-5}
Switzerland	3–3.9	mean	10^{-4}
United Kingdom	1.4–2.5	mean	10^{-3}-10^{-4}

Recent hazard results in Finland

The SENSEI project aimed at exploring the sensitivity of the PSHA models used in Finland (Mäntyniemi et al., 2021b, Fülöp et al. 2022). Figure 2 illustrates the mean and median hazard curves of the spectral frequencies of 1Hz, 5Hz, 25Hz, and PGA at the target sites. It shows how the mean hazard exceeds the median hazard in all cases. This is expected, because peak ground motion parameters, such as the PGA, are generally assumed to be skewed towards large values. The spectral amplitude (SA) at 5Hz is approximately equal to the PGA. The 25Hz amplitude is above the PGA amplitude whereas the 1Hz spectral amplitude is below it.

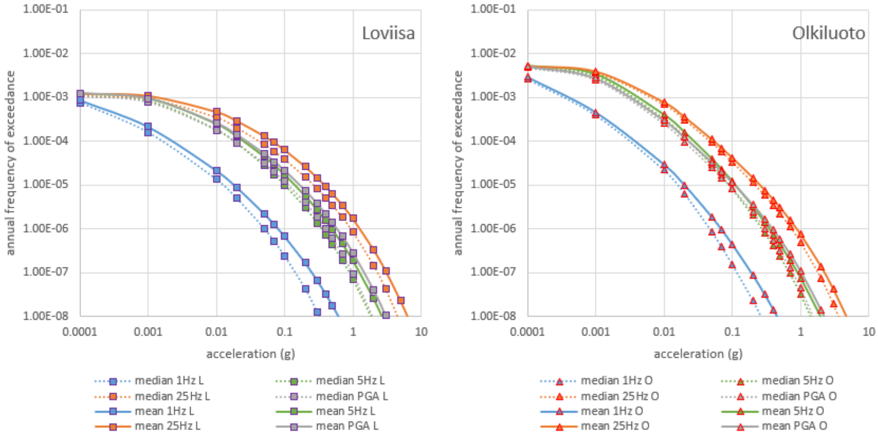
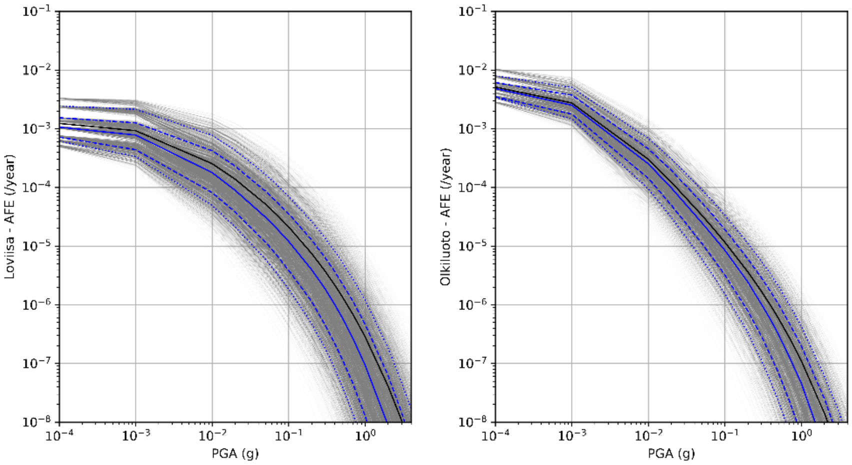


Figure 2. Median (dashed line) and mean (solid line) hazard curves for 1Hz (blue), 5Hz (green), 25Hz (orange), and PGA (gray) at Loviisa (L, purple square), Olkiluoto (O, red triangle).

A complete representation of the individual hazard curves for PGA is given in Figure 3. It shows that the mean estimate is very close to the median for higher AFEs. However, at lower AFEs the mean shifts towards the 84th percentile curves. The range of the hazard estimates is broadest at Loviisa for PGA, perhaps due to the use of two seismic source zonings for Loviisa and a single zoning for Olkiluoto. At very low PGA values, the hazard curves converge to the total activity level of the zones in the models. The uncertainties at very low PGA can be attributed to the effects of the zoning and Gutenberg-Richter parameters.

Properties of the distribution of AFEs extracted for PGA 0.0001g, 0.01g and 0.1g are given in Table 2. These can be interpreted as vertical cuts in Figure 2 at the given PGAs. The interesting quantities are the ratio of mean to median AFE. As expected, the mean AFE is higher, and the difference increases with larger PGAs. The coefficient of variation (COV) also increases with larger PGAs, and the observed trend that dispersion of the results is highest for Loviisa is quantified by the larger COV for this site. In addition, the Loviisa COV is larger for PGA 0.0001g, which is pointing at zonation as the source of the dispersion.



(a) (b)

Figure 3. Range of hazard for the sites of (a) Loviisa and (b) Olkiluoto for PGA. The gray lines are the individual hazard curves, with intensity depending on the weight of the logic-tree branch producing them. Hence the more extreme (i.e. low and high) estimates are less visible. The black line is the mean, the continuous blue the median hazard. The dashed blue lines are 16th and 84th percentile, and the dotted blue lines the 5th and 95th percentile bounds.

Table 3 shows the ratio of the AFE 10^{-7} and AFE 10^{-5} amplitudes in terms of median and mean confidence. These numbers indicate how many times the hazard is larger at AFE 10^{-7} in comparison with AFE 10^{-5}. The ratios are in the range of 4.8–14. They are highest for low frequencies at Loviisa and lowest for low frequencies at Hanhikivi.

Table 2. Properties of the AFE distribution at PGA 0.0001g, 0.01g and 0.1g for the three sites.

Site	PGA (g)	Median AFE	Mean AFE	STD	COV	Mean / Median AFE
Loviisa	0.0001	1.06E-03	1.23E-03	6.47E-04	0.53	1.16
	0.01	1.79E-04	2.54E-04	2.31E-04	0.91	1.42
	0.1	1.21E-05	2.13E-05	2.77E-05	1.30	1.76
Olkiluoto	0.0001	4.84E-03	5.14E-03	1.67E-03	0.32	1.06
	0.01	2.53E-04	3.01E-04	1.92E-04	0.64	1.19
	0.1	8.52E-06	1.16E-05	1.13E-05	0.97	1.37
Hanhikivi	0.0001	2.13E-02	2.13E-02	8.17E-03	0.38	1.00
	0.01	1.52E-03	1.64E-03	1.01E-03	0.62	1.08
	0.1	1.80E-05	2.95E-05	3.37E-05	1.14	1.64

Table 3. Ratio of intensity measure (IM) at AFE 10^{-7} and AFE 10^{-5} for the sites.

Site	Confidence level	$IM_{AFE\ 10\text{-}7} / IM_{AFE\ 10\text{-}5}$			
		PGA	25Hz	5Hz	1Hz
Loviisa	Mean	8.8	8.1	8.8	13.9
	Median	8.7	8.6	8.8	11.7
Olkiluoto	Mean	9.5	8.8	8.2	9.5
	Median	8.4	8.3	7.6	7.6
Hahikivi	Mean	6.2	6.0	5.2	6.2
	Median	5.5	7.4	4.8	4.7

Finally, we present the mean AFEs that would give the same hazard as the currently used AFE 10^{-5} and 10^{-7} median values. Since, mean hazard always exceeds median, it is expectable that these *mean-equivalent* AFEs are larger than the current targets of 10^{-5} and 10^{-7}, for DBE and DEC C respectively. We calculated the AFE for hypothetical *mean-equivalent* and *84^th^ percentile-equivalent* hazard definitions. It can be noted that for DBE mean equivalent, AFE would be above 10^{-5} in the range of $2 \cdot 10^{-5}$ in most cases. However, the values depend on the site and spectral frequency. For 84^{th} percentile equivalent DBE, AFE would be even higher in the range of AFE $3 \cdot 10^{-5}$. For the DEC C earthquake, the change would be to increase the AFE from 10^{-7} to the range of $2 \cdot 10^{-7}$ in most cases. The precise target thresholds are given in Mäntyniemi et al. (2022) for the sites.

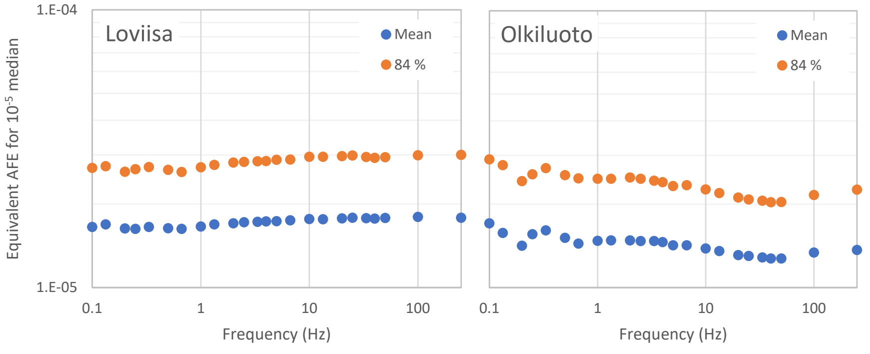


Figure 4. Target AFE for maintaining the current hazard level for DBE (i.e. 10^{-5} median), in case of a hypothetical change to mean or 84^{th} percentile confidence.

Applications

The main application of this work is related to the definitions of seismic hazards at NPPs in Finland. One point to stress is the significant uncertainty of the hazard at all AFEs. This uncertainty is growing at lower AFEs and should be considered in PRA. Hence, we recommend that PSHA output should be reported for mean, median, and the 5th, 16th, 84th and 95th fractile hazard. The second point to stress, relates to the definition of single hazard levels for DBE and DEC C, when they are made in the future update of the YVL guide. It appears that several arguments favor the use of mean hazard curves as basis for a single definition, when needed.

Summary and conclusions

There is currently no serious contender to PSHA in sight, despite some criticism (e.g., Mulargia et al. 2017). As a future direction, the quantification and reduction of the reducible uncertainties of seismic hazard is emphasized. Ideally, new extensive datasets allow the validation of individual hazard model inputs (e.g., Daxer et al. 2022), but the limited time spans of seismicity records remain an obstacle.

The present review shows that mean hazard is the target commonly utilized for engineering design. It is in line with probabilistic risk analysis and the choice for NPPs in many OECD member countries. That the mean represents a composite of all hazards is relevant to Finland as well, since low-probability earthquake scenarios cannot be disregarded.

For example, if a future earthquake scenario, let us say a magnitude M7.0 event occurring in Finland, is considered plausible but extremely rare, it would be associated with a low weight in the logic tree. Median hazard would erase the scenario entirely, while the mean hazard would still keep it, notwithstanding some debate among the experts about the exact value of the weight. At very low AFEs, the mean hazard increases over many fractiles, but this seems not to prevent its use. A good practice is to report a number of fractiles and the mean hazard, whether the focus is on hazard mapping for the general building code (Danciu et al. 2021) or for critical infrastructure such as NPPs (Abrahamson et al. 2004).

Mean is always larger than median, so the selection of the hazard curve to read for a ground-motion value affects the adoption of the corresponding AFE. For deterministic design, mean, median or another fractile can be used and are used in existing nuclear practice. The analyses based on the SENSEI set of calculations show a variability of hazard levels at the different sites for different frequencies. We recommend that PSHA output should be reported for mean, median, and the 5th, 16th, 84th and 95th fractile hazard curves in the future to allow decision-making consider uncertainties in an appropriate manner.

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References

Abrahamson, N.A., Bommer, J.J., 2005. Probability and uncertainty in seismic hazard analysis. Earthq. Spectra 21:603–607.

Abrahamson, N.A., Coppersmith, K.J., Koller, M., Roth, P., Sprecher, C., Toro, G.R., Youngs, R., 2004. Probabilistic seismic hazard analysis for Swiss nuclear power plant sites (PEGASOS Project), Final Report, Vol. 1 (text). Retrieved from https://www.swissnuclear.ch/upload/cms/user/PEGASOSProjectReportVolume1-new.pdf

Budnitz, R. J., Apostolakis, G., Boore, D. M., Cluff, L. S., Coppersmith, K. J., Cornell, C. A., Morris, P. A., 1997a. Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on uncertainty and use of experts. NUREG/CR-6372 UCRL- ID – 122160, vol. 1.

Budnitz, R. J., Apostolakis, G., Boore, D. M., Cluff, L. S., Coppersmith, K. J., Cornell, C. A., Morris, P. A., 1997b. Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on uncertainty and use of experts. Appendices. NUREG/CR-6372 UCRL- ID – 122160, vol. 2.

Cornell, C.A., 1968. Engineering seismic risk analysis. Bulletin of the Seismological Society of America 58, 1583–1606.

Danciu, L., Nandan, S., Reyes, C., Basili, R., Weatherill, G., Beauval, C., Rovida, A., Vilanova, S., Sesetyan, K., Bard P.-Y., Cotton, F., Wiemer, S., Giardini, D., 2021. The 2020 update of the European Seismic Hazard Model: Model overview. EFEHR Technical Report 001, v1.0.0, doi:10.12686/a15

Daxer, C., Huang, J.-J.S., Weginger, S., Hilbe, M., Strasser, M., Moernaut, J., 2022. Validation of seismic hazard curves using a calibrated 14 ka lacustrine record in the Eastern Alps, Austria. Sci. Rep. 12:19943. https://doi.org/10.1038/s41598-022-24487-w

Fülöp, L., Mäntyniemi, P., Malm, M., Toro, G., Crespo, M.J., Schmitt, T., Burck, S., Välikangas, P., 2022. Probabilistic seismic hazard analysis in low-seismicity regions: An investigation of sensitivity with a focus on Finland. Nat. Hazards, https://doi.org/10.1007/s11069-022-05666-4

Huang, Y.-N., Whittaker, A. S., Luco, N., 2011. A probabilistic seismic risk assessment procedure for nuclear power plants: (I) Methodology. Nucl. Eng. Des. 241:3996–4003. https://doi.org/10.1016/j.nucengdes.2011.06.051

IAEA, 2011. Earthquake preparedness and response for nuclear power plants. International Atomic Energy Agency IAEA Safety Reports Series No. 66.

Johnson, J. J., Gürpinar, A., Campbell, R. D., Kammerer, A., Rivera-Lugo, R., Stovall, S., 2017. Seismic design standards and calculational methods in the United States and Japan. United States Nuclear Regulatory Commission, Report NUREG/CR-7230.

Marzocchi, W., Jordan, T. H., 2014. Testing for ontological errors in probabilistic forecasting models of natural systems. Proceedings of the National Academy of Sciences 111(33):11973–11978, https://doi.org/10.1073/pnas.1410183111.

Mäntyniemi, P., Sørensen, M.B., Tatevossian, R.E., 2021a. Testing the Environmental Seismic Intensity scale on data derived from the earthquakes of 1626, 1759, 1819, and 1904 in Fennoscandia, northern Europe. Geosciences 11, 14. https://doi.org/10.3390/geosciences11010014

Mäntyniemi, P., Malm, M., Burck, S., Okko, O., Välikangas, P., Fülöp, L., 2021b. Sensitivity of seismic hazard analysis in Finland: Overview of the SENSEI project. ATS Ydintekniikka 50(2):19–23.

Mäntyniemi, P., Malm, M., Rinne, L., Fülöp, L., 2022. Valorisation of probabilistic seismic hazard results in Finland (Research Report No. VTT-R-00978-22). VTT Technical Research Centre of Finland, Espoo.

McGuire, R.K., 1993. Computations of seismic hazard. Ann. Geofis. 36:181–200. https://doi.org/10.4401/ag-4263.

McGuire, R.K., Cornell, C.A., Toro, G.R., 2005. The case for using mean seismic hazard. Earthq. Spectra 21:879–886. https://doi.org/10.1193/1.1985447

Mulargia, F., Stark, P.B., Geller, R.J., 2017. Why is probabilistic seismic hazard analysis (PSHA) still used? Phys. Earth Planet. In. 264:63–75. https://doi.org/10.1016/j.pepi.2016.12.002

Norio, O., Ye, T., Kajitani, Y., Shi, P., Tatano, H., 2011. The 2011 Eastern Japan great earthquake disaster: overview and comments. Int. J. Disaster Risk Sci. 2:34–42. https://doi.org/10.1007/s13753-011-0004-9

OECD, 2019. Comparison of probabilistic seismic hazard analysis of nuclear power plants in areas with different levels of seismic activity. Report NEA/CSNI/R(2019)1, Organization for Economic Co-operation and Development Nuclear Energy Agency (NEA), Paris.

Okko, O., Fülöp, L., Sandberg, J., Välikangas, P., 2019. Comparison of probabilistic seismic hazard studies within the oecd countries, Proceedings of the Symposium on the Application of Geophyics to Engineering and Environmental Problems, SAGEEP 2019, Portland, United States.

STUK, 2019. Guide YVL B.7 Provisions for internal and external hazards at a nuclear facility *and Explanatory memorandum*. Radiation and Nuclear Safety Authority. Retrieved from https://www.stuklex.fi/en/YVLB.7-memo.pdf

Wong, I. G., 2014. How big, how bad, how often: are extreme events accounted for in modern seismic hazard analyses? Nat. Hazards 72:1299–1309. https://doi.org/10.1007/s11069-013-0598-x