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Probabilistic seismic hazard assessment (horizontal PGA) for Sweden, Finland and Denmark using different logic tree approaches

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Abstract

Recent methods of probabilistic seismic hazard assessment allow multiple values to be assigned to the various input parameters. Each combination of values (branch) gives an output hazard estimate. From all combinations (logic tree), percentile hazard estimates can be obtained. In the present application, values of the annual rate of horizontal peak ground acceleration (PGA) are derived for a grid of sites, spaced at 18 longitude by 0.58 latitude, covering Sweden, Finland and Denmark. The computation is based on two different sets of calculated moment magnitudes, M_w . Two different approaches of hazard assessment are used, one based on source regionalisation models selected from seismicity distribution and/or seismotectonic criteria, and the other independent of regionalisation. Each approach applies the same two attenuation functions. In the first approach, three regionalisation models with a total of 87 source regions are introduced, and completeness tables, seismicity rates and β -values, five focal depths and four maximum expected magnitudes are assigned to each of two gross zones (land and sea areas). Seismicity rates and β -values are also assigned to each source region. In the second approach, the seismicity rate is derived for spatial windows of the size 58 longitude by 2.58 latitude. Instead of different regionalisation models, two sets of data completeness criteria are applied to each gross zone.

From each approach, a map of median hazard values for 90% probability of non-exceedence in 50 years is plotted. For the sites with the highest median hazard values at this probability level, full fractile hazard curves are given. The highest calculated horizontal peak ground acceleration from each approach and for 90% probability of non-exceedence in 50, 100, 500 and 1000 years, corresponding to return periods of 475, 950, 4745 and 9490 years, are 0.3/0.3 (regionalisation approach at 17.08E, 68.08N/non-regionalisation approach at 14.08E, 64.58N), 0.5/0.5, 1.1/1.3 and 1.6/1.9 m/s², respectively. There are some dissimilarities in the geographical distribution of the hazard obtained from the two approaches. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Fennoscandia; Seismic hazard; Logic tree; Regionalisation and non-regionalisation

1. Introduction

An important practical aspect of regional seismicity is its potential of structural damage. Although Fennoscandia is characterized by fairly low and spatially scattered seismicity, the seismic hazard has to be considered for sensitive structures like dams, mines, nuclear power plants, under-ground depositories for radioactive waste, oil platforms, etc. In Fennoscandia, only Norway has until now been the object of probabilistic seismic hazard calculation using modern techniques (the only published study by *NFR/NORSAR and NGI* [1]). One of the main purposes with the present study is to produce consistent hazard calculations also for Sweden, Finland and Denmark. Another purpose is to apply two different approaches in seismic hazard assessment, using regionalised and non-regionalised input data, and compare the results.

There are two main hypotheses as to the cause of earth-quakes in Fennoscandia: (1) release of stresses built up and propagated from the North Atlantic Ridge and (2) stress adjustment connected to the postglacial land uplift [2]. Occasional large earthquakes have occurred, notably in 1759 in Kattegat, $M_S = 5.6$; and 1819, 1866 and 1904 in Norway, $M_S = 5.8, 5.7$ and 5.4 , respectively (magnitudes from *NFR/NORSAR and NGI* [1]), all causing damage and being felt at distances several hundred km from the epicentre. A typical intraplate region, fault mapping and tectonic understanding of seismicity patterns are incomplete. To account for this, source regions are specified in different regionalisation models (first approach), but a regionalisation-independent model is also used (second approach).

Using the method of *Kijko and Sellevoll* [3,4], *Kijko et al.* [5] have estimated the average seismic hazard of Sweden and *Mäntyniemi et al.* [6] of Fennoscandia and adjacent waters. This is a probabilistic approach based on an incomplete catalogue part for historical earthquakes and complete parts above dif-

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ferent threshold magnitudes for more recent data. The resulting areal distribution of hazard is confined to certain large regions, whereas the present study gives a significantly improved, continuous areal distribution.

An early Norwegian approach on seismic hazard estimation for the offshore area (continental shelf) has been made by *Bungum and Dahle* [7]. As part of the Global Seismic Hazard Assessment Program (GSHAP), *Lindholm et al.* [8] have produced probabilistic seismic hazard estimates of peak ground acceleration (PGA) in Fennoscandia. They use a modified Cornell-McGuire technique developed at NOR-SAR. *NFR/NORSAR and NGI* [1] have performed a detailed regionalisation of Norway and its offshore area, including detailed hazard maps for different levels of non-exceedence.

The latter study at hand, the present study is limited to the derivation of detailed hazard maps for the rest of Fennoscandia, i.e. Sweden, Finland and Denmark, using modern computational algorithms. Horizontal PGA is calculated for a grid of 433 points covering Sweden, Finland and Denmark with adjacent water areas. The grid density is 18 longitude by 0.58 latitude and only the land areas are mapped. In the regionalisation approach, the investigated area and its surroundings are divided into different source regions, based on presumed seismic and/or geological homogeneity. Three such regionalisation models are used, a revised version of the model by *Lindholm et al.* [8] for GSHAP and two models developed for the present study. The non-regionalisation approach uses different event size criteria instead of seismotectonic regionalisation.

The applied computer program, FRISK88M [9], has a logic tree approach to account for uncertainties in the various input parameters, i.e. the data set (magnitudes), regionalisation model (first approach) or completeness criteria (second approach), attenuation function, earthquake recurrence relation, focal depth and maximum expected magnitude, M_{max} . The combination of magnitude sets with regionalisation models or completeness criteria make up "global alternatives". Two attenuation functions, and a set of discrete values for each seismicity parameter and source region, are used. Further flexibility is obtained by assigning weights to the different global alternatives, attenuation functions and seismicity parameters. The algorithms of FRISK88M input parameter setting facilitate the merging of competing scientific hypotheses in one hazard calculation.

2. Catalogue data: M_w conversion and spatio-temporal completeness

FENCAT is a continuously updated data bank of earthquakes in Northern Europe compiled at the Insti-

tute of Seismology, University of Helsinki [10]. It is the database used to calculate values of the required input seismicity parameters, i.e. M_{max} , recurrence parameters and focal depth distribution. To comply with the applied attenuation functions (see below), the moment magnitude M_w is used. *FENCAT* contains a variety of magnitude types, and although a vast majority of the events in Sweden, Finland and Denmark have local magnitudes M_L (UPP) [11], many events have other types of magnitudes. A full homogenisation is not a trivial task. *NFR/NORSAR and NGI* [1] present hazard results for Norway based on an attempted homogenised catalogue (not *FENCAT*). This catalogue covers only in part the area of interest in the present study.

Two different sets of M_w magnitudes are used. The backbone of this approach is the relationship between seismic moment and M_L (UPP) magnitude for earthquakes in the Fennoscandian shield in the magnitude range 2-5 derived by *Kim et al.* [12]. Their data contain only a few events with magnitude above 4. Motivated by the non-linear behaviour of the moment-magnitude relation at magnitudes 4-5 found in several North American studies [13-15], a second-order regression based on the *Kim et al.* [12] data set is made and combined with the M_w "definition" by *Hanks and Kanamori* [16] to give:

$$M_w = 1.2 + 0.28 M_L \text{ (UPP)} + 0.06 M_L \text{ (UPP)}^2 \quad (1)$$

In the first input set (a), all magnitudes, irrespective of type, are converted to M_w using Eq. (1). The large difference between M_L (UPP) and M_w in Eq. (1) is of no concern - a similar relation has been obtained by Hasegawa for magnitudes up to about $M_L = 4$; e.g. M_L (Eastern Canada) = 4 corresponds to $M_w = 3.5$ and M_L (UPP) = 4 to $M_w = 3.3$ - but of importance is that the conversion to M_w is adequate.

Although giving higher values than the original *Kim et al.* [12] relation for magnitudes beyond the upper limit of the calibrating data set, Eq. (1) would still underestimate M_w for large earthquakes. Large historical earthquakes in *FENCAT* are often assigned M_S magnitudes, converted from macroseismic data. For some earthquakes, m_b magnitudes have been calculated. Average global relations of seismic moment vs surface wave and body wave magnitudes for intracontinental earthquakes presented by *Johnston* [17] are combined with the relation by *Hanks and Kanamori* [16] to give:

$$M_w = 4.28 - 0.27 M_S + 0.09 M_S^2 \quad (2)$$

$$M_w = 4.85 - 0.85 m_b + 0.18 m_b^2 \quad (3)$$

In the second input set (b), Eqs. (2) and (3) are applied where M_S and m_b are given, Eq. (1) elsewhere, i.e. the latter values remain the same as in set (a). Set (b) con-

Figure 1. Seismicity from FENCAT. Land and sea gross zones.

tains high-end magnitudes significantly larger than in set (a), resulting in smaller recurrence slopes for several source regions. The “anomalous” high-end magnitudes cause non-linear recurrence relations in many cases and in the hazard processing the set (b) is played

down by weighting set (a) at 0.75 and set (b) at 0.25. The difference in maximum M_w magnitudes between the two sets for many source regions is considered in the assignments of M_{max} (see below).

Epicentres of earthquakes in FENCAT are plotted in Fig. 1. Two selection criteria are imposed on the data:

Table 1

Threshold magnitudes for different combinations of gross zones and M_w sets

M_w set	Gross zone	Threshold M_w^a		Year of completeness
		Reg	Non-reg	
(a)	Land	4.8	4.8	1810
		2.8	3.3	1880
		2.3		1980
(a)	Sea	3.8	3.8	1890
		3.3	3.3	1955
		2.8		1978
(b)	Land	2.3		1986
		5.3	5.3	1750
		2.8	3.3	1880
(b)	Sea	2.3		1980
		4.8	4.8	1890
		4.3	4.3	1955
		2.8	3.3	1978
		2.3		1986

^a The regionalisation approach uses threshold values of the first column; the non-regionalisation approach those of both columns.

1. *Event independence.* For earthquake sequences, only one shock (main) is included in order to keep the assumption of a Poissonian distribution in time required by the probabilistic approach.

2. *Catalogue completeness.* Threshold magnitudes are specified for two sets of M_w magnitudes, two gross zones and various time periods. $M_w = 2.3$ is the smallest accepted magnitude. In the non-regionalisation approach, $M_w = 3.3$ is used as an additional lower magnitude limit. Details are given below and in Table 1.

The completeness levels of the catalogue differ not only in time but also in space. Although the southern and coastal parts of Fennoscandia are more densely

Figure 2. Source regionalization models and source regions: (A) *Lindholm et al.* [8] model, revised. (B) New seismicity based model developed for this study. (C) New geology based model developed for this study combined with part of the *NFR/NORSAR and NGI* [1] model.

populated than other areas, a too detailed spatial separation is not desirable considering the rather scarce overall data. For each of the two M_w sets, threshold magnitudes are thus calculated, based on linearity discrepancies in frequency-time diagrams at different magnitude levels, for a land gross zone and a sea gross zone (Fig. 1). The former zone includes also offshore areas in the vicinity of land and the latter a practically aseismic part of the southeastern Baltic Sea. The completeness values are given in the column "Reg" of Table 1.

3. Attenuation functions

There exist very little recorded ground acceleration data from earthquakes in Fennoscandia. For a compilation of attenuation functions for southern and south-eastern Europe, see Ref. [18]. In the present study, two relations developed for hard rock conditions, i.e.

suitable for the Fennoscandian shield where most of the currently investigated area is located, are selected:

$$\ln(A) = -2.143 + 0.751 M_w - 1.04 \times 10^{-3} r - 0.815 \ln(r) \quad (4)$$

$$\ln(A) = -1.79 + 0.298 (M_w - 6) - 5.36 \times 10^{-2} (M_w - 6)^2 + 1.35 \times 10^{-3} r - \log(r) \quad (5)$$

where Eq. (4) is from *Ambraseys et al.* [19] with M_S converted to M_w using the *Hanks and Kanamori* [16] M_w definition and a regression of seismic moment on M_S for Central European data (GeoForschungs-Zentrum Potsdam, unpublished), and Eq. (5) is from *Atkinson and Boore* [20]. Eq. (4) was derived from European data and Eq. (5) from data in eastern North America, structurally similar to Fennoscandia. In both equations, A is horizontal PGA (m/s^2) and r is hypocentral distance (km). Following *Ambraseys et al.* [19], the standard deviation of the normal distribution

Figure 2. (continued)

of $\ln(A)$ is 0.576 for Eq. (4), corresponding to 0.25 for a $\log(A)$ relation, which is the value assigned to Eq. (5). In the FRISK88M runs, Eqs. (4) and (5) are equally weighted at 0.5.

4. Hazard calculation approaches

4.1. Regionalisation

4.1.1. Regionalisation models and source regions

The FRISK88M program is based on a division into source regions of the area of potential threat to the investigated site or, as in the present case, a grid of sites. A source region should be in some respect seismically homogeneous, but this does not necessarily imply an approximately even distribution of recorded earthquakes. A good regionalisation model could be based on geological units in each of which there is reason to believe that the seismic potential is constant in the long term, although the existing seismic record may be insufficient to show this (Ref. [21]). An out-

line of the tectonic features and recent history of Fennoscandia is given by e.g. Muir Wood [22]. Although tectonic maps of the three countries are steadily improving, the regionalisation is far from straightforward and three different models are used in this study (Fig. 2):

(A) A revised version of Lindholm *et al.* [8] used for GSHAP, 31 source regions. The revision mainly concerns the inclusion of additional regions to the southeast.

(B) A new model with 21 source regions based on the seismicity distribution.

(C) A new model with 14 source regions based mainly on tectonic maps of Sweden [23], Finland [24] and Denmark [25], in addition to 21 regions for Norway and its offshore area from the NFR/NORSAR and NGI [1] model.

For each source region, FENCAT earthquakes are selected from the specified independence and completeness criteria. Each region is assigned a gross zone characteristic, land or sea, determining the complete-

Figure 2. (continued)

ness table and the applicable seismicity parameters. In cases where the border between the land and sea gross zones cuts through a source region, the gross zone containing most of the seismicity of the region is selected.

Each of the M_w sets (a) and (b) is combined with each of the three regionalisation models to make up six global alternatives in the FRISK88M input. The regionalisation models (A) and (B) are each weighted 0.25 and the geology based model (C) is weighted 0.5.

Table 2
 β -values, focal depths and maximum magnitudes for different combinations of gross zones and M_w sets

M_w set	Gross zone	β	Focal depths km	M_{max}^a
(a)	Land	3.42	4, 8, 12, 17, 30	5.65, 6.10, 6.40, 6.85
(a)	Sea	3.33	4, 11, 14, 21, 34	5.40, 5.95, 6.55, 7.20
(b)	Land	2.05	4, 8, 12, 17, 30	5.80, 6.05, 6.35, 6.75
(b)	Sea	2.10	4, 11, 14, 21, 34	6.10, 6.30, 6.65, 7.25

^a For source regions covered by the small part of the sea gross zone, M_{max} values from the land gross zone are used.

The model (C) is established from the most recent geological and seismic data which is the reason for its higher assigned weight.

4.1.2. Seismicity parameters

4.1.2.1. Seismicity rate and frequency-magnitude relation. Values of ν and β - ν is the annual rate of earthquakes with the selected minimum magnitude, $M_w = 4.0$, or larger and $-\beta$ is the $\ln(\text{frequency})$ vs cumulative M_w slope - are calculated for each source region. If there are less than 40 events in a region, data from one or more neighbouring regions are included in the calculation of b . b -values are also obtained for the gross zones (Table 2) and kept fixed to calculate an alternative set of ν -values for the regions. A weight of 0.5 is assigned to each of the regional value and the gross zone value.

4.1.2.2. Focal depth. The largest known earthquakes in Fennoscandia date to historical time and have poorly estimated focal depth from macroseismic data. The net of seismograph stations in Fennoscandia has been

sparse until recent years and the focal depth is often not well constrained. The uncertainty in the depth determinations is accounted for by calculating the depth distribution in each of the two gross zones instead of in the individual source regions. For the land zone, the depth distribution is calculated from events with $M_w \geq 2.8$; for the sea zone, this limitation gives insufficient data and events down to $M_w = 2.3$ are included.

FRISK88M requires fixed weights, common for all regions, for each input seismicity parameter. As for the recurrence parameters and the maximum expected magnitude (see below), focal depths have to be assigned to predetermined weights, not vice versa. Five equally weighted (0.2) depths are derived from the distribution in each gross zone (Table 2). In this case, no distinction is made between the two M_w sets. The appropriate set of depth values is then used for each source region.

4.1.2.3. Minimum magnitude. One entry in the FRISK88M input, which is kept at a fixed value throughout the computation is the minimum magnitude thought to cause structural damage. It is set at $M_w = 4.0$ in this study, the same for sets (a) and (b) and for all source regions. According to Eq. (1), this corresponds to $M_L(\text{UPP}) = 4.9$. The choice of this value has impact on the hazard at shorter return periods (see Section 7).

4.1.2.4. Maximum magnitude. Following the approach by Cornell [26] and Coppersmith [27], normal distribution functions of maximum magnitudes in intracontinental regions globally, of extended crust and non-extended crust, respectively, are multiplied with likelihood functions based on the maximum observed M_w and the number of recorded large earthquakes regionally. In the present study, four resulting posterior distributions are distinguished by combining the two M_w sets with the two gross zones. The calculations are made in a qualitative way and from each posterior distribution four representative M_{max} values (Table 2) are given a weight of 0.25 each. All source regions belonging to the land gross zone and the small sea gross zone are accounted as non-extended crust and those belonging to the large sea gross zone as extended crust (cf. Ref. [28]), and the M_{max} values are accordingly assigned to each source region.

The arrangement of all parameter settings can be illustrated in a logic tree, as explained in a forthcoming section.

4.2. Non-regionalisation

For regions where the seismotectonics are not fully understood, the specification of source regions is to a certain degree arbitrary. To some extent, this is counteracted by the use of several regionalisation models,

as in the approach above. Techniques avoiding regionalisation have been suggested, e.g. by Frankel [29], Rüttener [30] and Woo [31]. Frankel [29] combines different event size classes and, with some exception, applies the same seismicity parameters, except the seismicity rate for part of the classification, to the whole investigated area (central and eastern North America). In a similar approach, two new input data sets are created in this study by restraining events in the M_w sets (a) and (b) to magnitudes, $M_w \geq 3.3$; corresponding to $M_w(\text{UPP}) \geq 4.0$. The change of threshold magnitudes is analogous to changing the completeness tables (column "Non-reg" of Table 1). In addition, the sets (a) and (b) are used as before, i.e. events with magnitudes $M_w \geq 2.3$ (column "Reg" of Table 1). The investigated area is divided into spatial windows of the size 5° longitude by 2.5° latitude. For each window and each of the four global alternatives (combinations of M_w sets with completeness tables), the annual seismicity rate of $M_w \geq 4.0$ events v is calculated from the gross zone β after specifying the window as "land" or "sea" depending on in which gross zone most of its seismicity falls. This is the only $\{v, \beta\}$ set used in the non-regionalisation approach. In the FRISK88M runs, the M_w sets are equally weighted (0.5 each) as are the completeness tables. The two attenuation functions and their weights, the sets of values and weights of focal depths and M_{max} , and the minimum magnitude assumed to cause damage, $M_w = 4.0$, are all the same as in the regionalisation approach.

5. Logic trees

The combination of all input parameters to FRISK88M, with their weights, can be illustrated in a logic tree. In practical applications, there must be a balance in the assignment and weighting of parameters between the generous input options of the program algorithm and a caution to stick to simple and realistic values. The number of values for any parameter must be the same for all regions within a global alternative, but the values themselves may vary. A seismicity parameter can be combined with the same setting (dependence) or every setting (independence) of this parameter for all source regions.

The number of solutions, i.e. branches on the logic tree, for each global alternative is $AM^SB^SH^S$, where A is the number of attenuation functions, M maximum expected magnitudes (or intensities), B $\{v, \beta\}$ values and H focal depth values, and S is 1 if a parameter (M , B , H) is dependent and is equal to the number of source regions if it is independent. A is always dependent. In cases with a large number of source regions, there is evidently a drastic increase in the number of branches (and computer time) when independent parameters are used instead of dependent. Tests made on small samples show that the range of output

Figure 3. Logic trees of input parameters with assigned weights. (a) Regionalisation approach. (b) Non-regionalisation approach.

hazard values does not change significantly if dependent parameters are used instead of independent. In the present study, M , B and H are all dependent.

The logic tree for the regionalisation approach is shown in Fig. 3a. The number of branches of the tree is 480 (2 M_w sets, 3 regionalisation models, 2 attenuation functions, 4 M_{max} values, 2 $\{\nu, \beta\}$ sets, 5 focal depths). The corresponding set of output hazard values determines the distribution of the fractiles. The logic tree for the non-regionalisation approach (Fig. 3b) consists of 160 branches (2 M_w sets, 2 M_w thresh-

olds, 2 attenuation functions, 4 M_{max} values, 1 $\{\nu, \beta\}$ set, 5 focal depths).

6. Results

Hazard values are calculated for the selected grid of sites in Sweden, Finland and Denmark, with points spaced at 1° longitude by 0.5° latitude. Fig. 4 shows the annual probability of exceedence of horizontal PGA for the point of the selected grid, which has the

Figure 4. Curves of annual seismic hazard, P : 16, 37, 50, 63 and 84% fractiles for the grid point with the highest median hazard resulting from each approach.

highest hazard median values obtained from each approach. The points occur at different locations, 17.0°E, 68.0°N (regionalisation approach) and 14.0°E, 64.5°N (non-regionalisation approach). The 16, 37, 50, 63 and 84% fractiles of each set of solutions are plotted. They correspond to deviations from the median of 21s, 20.5s, 0, 10.5s and 11s, respectively. The median can be considered the best estimate from the given input parameter values and the 84% fractile a solid conservative estimate [32]. The 90% probability of non-exceedence in 50, 100, 500 and 1000 years, corresponding to return periods of 475, 950, 4745 and 9490 years, occurs at ground accelerations of 0.3/0.3 m/s² (regionalisation/non-regionalisation), 0.5/0.5 m/s², 1.1/1.3 m/s² and 1.6/1.9 m/s², at the respective highest hazard grid points.

Fig. 5 presents maps of the 90% probability of

non-exceedence level in 50 years (median values) for the whole investigated area resulting from both approaches.

There are some differences in the geographical distribution of the seismic hazard obtained from the two approaches (see Section 7).

For the site with the highest calculated median hazard levels from each approach, the contribution to the seismic hazard, at a selected PGA level of 1 m/s², of earthquakes with different magnitude-distance combinations is shown in Fig. 6 (cf. Ref. [33]). The FRISK88M output data representing the seismic hazard in Fig. 6 are mean hazard values.

Figure 5. Maps of 90% probability of non-exceedence of horizontal PGA (m/s^2) in 50 years, corresponding to a return period of 475 years. Regionalisation approach left, non-regionalisation approach, right; median hazard values.

7. Discussion

The obtained hazard maps for a return period of 475 years (Fig. 5) can be compared internally and with the preliminary map of *Lindholm et al.* [8]. Fig. 5 shows that the regionalisation approach gives higher hazard for northern Fennoscandia, southern Sweden and most of Denmark; the non-regionalisation approach gives higher values for south-western Finland and the areas on both sides of the northern Gulf of Bothnia. Geographical discrepancies are also found between the corresponding hazard sets for longer return periods. The preliminary results of *Lindholm et al.* [8] show significantly higher hazard than obtained in the present study, also if recognizing that they present mean hazard values. Along the border to Norway, a comparison can be made with the results from *NFR/NORSAR and NGI* [1]. The agreement of the corresponding maps on the opposite sides of the border is generally good, again considering that mean hazard values have been used in the Norwegian study. The two areas along the Swedish-Norwegian border with the highest hazard values according to the Norwegian study stand out also in Fig. 5, although the northern area in the map from the non-regionalisation approach is slightly displaced southward.

Different to *Frankel* [29], no spatial filter is applied in assigning the v -values in the non-regionalisation approach. If filtering had been applied, contours of the corresponding map in Fig. 5 (previous page) would have been smoother. On the other hand, selecting smaller spatial windows would enhance local hazard features.

It should be noted that whereas median hazard values are depicted in the maps of Fig. 5, mean hazard values are used to show the magnitude/distance contributions in Fig. 6, the output from FRISK88M being so designed. The mean values approach higher fractiles for longer periods (see Ref. [34]). It is obvious from both diagrams of Fig. 6 that the main contributions to the hazard come from small earthquakes at distances in the range below 40 km, however not from the very near distances. The distance distribution is understandable from Figs. 1 and 2, showing low seismicity in the immediate vicinity of the two selected sites but high seismicity in the Norwegian and coastal areas nearby. The significance of the smallest magnitude class stems from the concentration of almost all events to this class.

There are two basic types of uncertainties in the input parameters to be considered in seismic hazard calculations. The aleatory uncertainty appears from the apparent randomness of nature, accounted for as the standard deviation in the attenuation functions, and the epistemic uncertainty is due to the lack of full knowledge in parameter assignment and regionalisation, which is accounted for by the logic tree multiple input option. The latter type of uncertainty will de-

crease with future improved knowledge of the tectonics, seismicity and ground conditions. A general survey of the uncertainty of various input parameters and assumptions in seismic hazard calculation is provided by *Bender and Perkins* [35] and *Grünthal and Wahlström* [34].

Quoting the text introducing *FENCAT* [10]: “by selecting the national solutions for each earthquake, we can establish a database sufficiently consistent for seismicity studies. However, homogenisation of the different magnitudes may be needed for special studies.” The M_w sets used in the present study are not altogether homogeneous. However, all magnitudes in *FENCAT*, with the exception of a few entries based on Russian intensities, ultimately refer to the original Richter M_L definition, although indirectly for many types. In spite of the discrepancies, the different magnitude types in *FENCAT* may thus be assumed to be approximately comparable. A similar assumption is made in hazard computation for western Canada, where different magnitudes are mixed [32].

Even if great caution is taken in selecting seismological, geological and other criteria for the regionalisation, some subjectivity is inevitable. Borders between source regions are generally not sharp from the seismic activity point of view. This general problem is discussed by *Bender* [36]. Furthermore, for any area where active tectonic faults are not fully manifested, the lack of a complete understanding of the long-term tectonic processes implies an uncertainty in the specification of regional borders. The option of the logic tree approach to use several regionalisation models makes the border effect less prominent. The Canadian approach is to make hazard calculations separately for smaller regions based on seismic homogeneity and larger regions based on geological homogeneity, and use the highest of the obtained values at each site (quasi-probabilistic “robust” model [21,32]). The present study keeps a fully probabilistic approach by combining regionalisation models based on different selection criteria in one run.

Alternative hazard calculation procedures avoid regionalisation [29-31], but it is doubtful if the “objectivity” of such techniques can compensate for the deliberate omission of distinct geological and seismological knowledge. For a critical discussion of *Frankel's* [29] method, which currently is a standard procedure in USGS hazard calculations, see Ref. [37].

The attenuation functions used are derived for hard rock conditions. Loose ground conditions (stiff or soft soil) increase the PGA values. The obtained hazard values for the region south of the Tornquist Fault Zone (southernmost Sweden and most of Denmark), i.e. outside the Fennoscandian shield, may thus be somewhat low.

The two categories of β -values, based on source regions and gross zones, applied in the regionalisation approach, correspond in several studies, e.g. Refs.

Figure 6. Contribution to the seismic hazard v of earthquakes with different magnitudes and at different distances, for a horizontal PGA of 1 m/s^2 at the grid points with the highest median hazard resulting from each approach. The lowest magnitude class represents $M_w \leq 4.5$ and the highest distance class represents $r > 100 \text{ km}$. The diagrams are based on mean hazard values.

[8,32] to a “best” value and two error bounds (± 1 std in the case of *Adams et al.* [32]). β -values are often kept constant over large areas in hazard calculations ([1,8,38]). In the present study, equal weight is assigned to the gross zone values and the regional values.

The larger the minimum magnitude, the narrower the range of contributing magnitudes and thus the lower the hazard. The sensitivity is greatest at small return periods [34,35]. Assignments of the maximum expected magnitude M_{max} are uncertain in regions where the dimensions of active faults are poorly

known, as is generally the case in intraplate environments. On the other hand, the influence of M_{max} is minor if the return period is not too long. The combination of global (from tectonically similar regions) and regional information on maximum observed magnitudes is a sensible way to generate the M_{max} sets.

It is thought that paleoseismic evidence can extend observational recurrence periods for large earthquakes and influence the M_{max} setting. In northern Fennoscandia, several earthquakes estimated at magnitudes up to and above 8 (M_S) occurred at the latest phase of deglaciation some 9000 ya [39]. Whatever

the underlying cause of these events [2], their close spatial and temporal connection to a unique geological process make them occasional events not to be included in seismic hazard calculation, unless drastic geological changes, like a new glaciation-deglaciation cycle, are considered.

Only a few applications of probabilistic seismic hazard calculation using the logic tree technique have been performed in Europe so far, e.g. by *Labák et al.* [40] for a site in Slovakia and *Musson and Winter* [38] for the UK. The latter study concludes that the generous input options require great consideration in the assignments of the parameter values. Logic tree studies by *Lindholm et al.* [8] for Fennoscandia and *NFR/NORSAR and NGI* [1] for Norway and its offshore area are mentioned in previous sections.

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