Ground Motion Attenuation Uncertainties for Intraplate Earthquakes with an Application to Southern Finland.

Pentti Varpasuo, Yrjö Nikkari
IVO Power Engineering Ltd., Vantaa, Finland

Pieter van Gelder
Subfaculty of Civil Engineering, Delft University of Technology, The Netherlands

ABSTRACT: The purpose of the present work is the estimation of seismic hazard in the territory of Finland in the possible area of the atomic power station in Olkiluoto. Because there are no registered acceleration recordings of earthquakes in Finland, the earthquake recordings from the Saguenay and Newcastle regions from Canada and Australia respectively were taken as sources of initial data because of their geological and tectonical similarity to Finland. Theoretical bases of determination of seismic hazard, questions of seismicity of the southern part of Finland, initial data on earthquakes and techniques of their processing, are considered in this paper.

1 INRODUCTION

Finland is situated on the Baltic shield, which is the one of the seismically quietest areas in the world. The source mechanisms of earthquakes in Finland are considered to be the uplift of ground after glacial compression and tectonic plate movements.

Earthquake recurrence rates in Fennoscandia are very low if compared with plate boundary regions worldwide. In fact, stable continental regions like Fennoscandia account for less than one per cent of global moment release rate. Nonetheless, Fennoscandia is an active seismic region, albeit at low earthquake recurrence rates and with low historical maximum magnitudes.

Although instrumental earthquake observations started in Finland in the 1920's, local short period recordings started in 1956. Given the low earthquake recurrence rates and small magnitudes of the Fennoscandian shield region, the catalog is not likely to be complete and completeness varies geographically. Local high gain seismic recording stations would be needed to record the small events that characterize most of the regional seismicity.

For the purpose of computing the probabilistic seismic hazard of the Olkiluoto Nuclear Power Plant site (south-west Finland), a catalog of all earthquakes within 500 km of the site was compiled. This catalog encompasses the whole of Fennoscandia and includes all documented historical events in the region including magnitudes assigned on the basis of macroseismic felt area information. Most of the earthquakes in the catalog are very small and well below the threshold of engineering concern. There are only few magnitude 5 events documented within 500 kilometers of the site. Only a few historical events were significantly felt (see Figure 1).

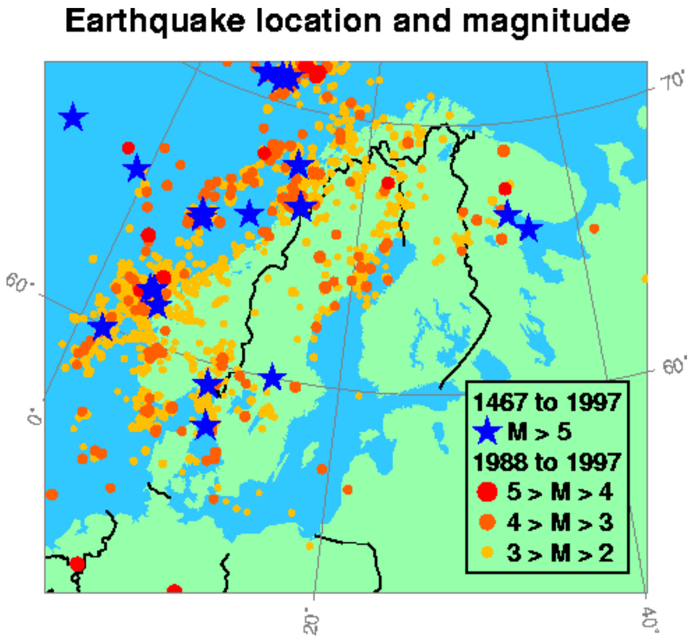

Figure 1: Seismicity Map of Fennoscandia (Wu, et.al., 1999).

The spatial distribution of the catalog epicenters gives some indication of the geographical pattern of seismic activity in the vicinity of the site, but the inhomogeneity in seismological detection thresholds is very marked. Instrumental detection is better for

Sweden than it is for Finland and instrumental detection is worse in Baltian countries than it is for Finland. Dr. J. Saari carried out the actual compilation of the seismicity used in this study and the results of his work are described in his doctoral thesis (Saari, 1998).

In Sadigh et.al., 1997, attenuation relationships are presented for peak acceleration and response spectral accelerations from shallow earthquakes. The relationships are based on strong motion data primarily from California earthquakes. Relationships are presented for strike-slip and reverse faulting earthquakes, rock and deep soil deposits, earthquakes of moment magnitude M 4 to 8+, and distances up to 100 km. Due to the low seismicity in stable continental regions, there are very few strong motion data available for this tectonic regime. As a result, attenuation relationships for this region are usually based on numerically simulated ground motions instead of recorded ground motions. Atkinson-Boore (1997) use a stochastic point source model to generate a synthetic data base of strong ground motions. They then perform regression analyses to develop simplified equations that describe the attenuation of the data in the synthetic data sets.

The Atkinson-Boore is a very welcome alternative to the applied attenuation model in Van Gelder and Varpasuo's study (1997) and can be used as a tool in trying to quantify the uncertainty in attenuation which is the most important source of uncertainty in a seismic hazard analysis. In this paper the attenuation model will be directly fitted on the Saguenay and Newcastle databases. The approach is to use the Saguenay from Eastern Canada and the Newcastle data from Australia as a substitute for lacking suitable recordings from Finland. The Eastern Canada and Australian plain area suit for this purpose very nicely since the level of seismicity is the same and the geological conditions are quite similar as in Finland. The Saguanay and Newcastle database have enough data for an accurate evaluation of the logarithmic standard deviation for the attenuation equation.

2 THEORETICAL BASES OF THE DETERMINATION OF SEISMIC HAZARD

In this paper the seismic hazard assessment methodology described in McCuire, 1976 was used. It can be submitted in the basic form as the Theorem of total probability:

$$\mathbf{P\,[A] = \iint P\,[A \mid S\ and\ R]\, f_s(S)\, f_r(R)\, dsdr,} \quad \mathbf{(1)}$$

where P indicates the specified probability, A is the event whose probability is sought, S and R are continuos independent random variables that have an effect on the value of A.

Variables s and r represent earthquake size in used measure and distance from the site of interest. Random size and random location of the events are taken into account in the method.

As an estimation of the continuous probability of the logarithm of the ground acceleration, exceeding some value i, at the given station, the normal distribution is assumed (Esteva, 1970). The average size of the continuous distribution of the logarithm of the ground acceleration is defined as:

$$\mathbf{M_I\,(S, R) = C_1 + C_2 * S + C_3 * \ln(R + h),} \qquad \mathbf{(2)}$$

where C_1 , C_2, C_3 are constant factors, S is the size of earthquake and R is the epicentral distance in km; h is the depth of a seismic source in km. This equation is called the attenuation equation of ground motion.

By means of a slight modification of (2), one can handle mean logarithmic acceleration attenuations of the form:

$$\mathbf{m_I\,(S,R) = C_1 + C_2 *S + C_3 *\ln(R+h) + C_4 *(R+h)} \qquad \mathbf{(3)}$$

The standard deviation of logarithm of ground acceleration σ_I is generally constant and independent from S and R.

Applying the normal distribution in (1), we have:

$$\mathbf{P\,[A \mid S\ and\ R] = P\,[I > i \mid S\ and\ R] =}$$

$$\mathbf{= \Phi^* ((i - C_1 - C_2 * S - C_3 * \ln(R + h)) / \sigma_I)} \qquad \mathbf{(4)}$$

where Φ^* is the cumulative standard normal distribution. When peak ground motion values or spectral velocity values are used as measures of the ground motion intensity these variables are generally assumed to be lognormally distributed. Thus the logarithms of these variables are normally distributed. This assumption of normality is the corner stone of the methodology. The mean of peak ground acceleration or spectral acceleration A_g as a function of M and R is described in many cases with the following equation:

$$\mathbf{M_{Ag}\,(M, R) = C_1{}' * e^{C2\,M}\,(R + h)^{C3}} \qquad \mathbf{(5)}$$

In this case the logarithm of ground acceleration can be found as the natural logarithm from A_g, S is equivalent to M, and (2) turns out by logarithmic transformations from (5). Parameter σ_I is now the standard deviation of the logarithm of the maximal acceleration of the ground. If C_1, C_2 and C_3 are determined by least-squares approximation of the logarithm of the ground motion, C_1' is called the antilogarithm of C_1. Consequently, C_1 can be calculated from the following equation:

$$C_1' = \exp(C_1 + \sigma_I^2/2), \qquad (6)$$

from which the value C_1 can be found. Equation (6) gives a smaller unilateral estimation for C_1' in comparison with application of only the antilogarithm C_1.

The distribution magnitude, $f_M(m)$, is considered next. The number n_M of earthquakes having magnitude greater than M, occurring in the source area is assumed to be of the form:

$$\mathrm{Log}_{10}\, n_M = a - b * M, \qquad (7)$$

where and and b are constants describing the source area. The constant b describes relative distribution of small and large magnitude events; larger values of b indicate relatively fewer large events, and vice versa.

Assuming, that the sizes of consecutive earthquakes in the source area are independent, it follows from (7), that the cumulative distribution magnitude for each event is given by the following equation:

$$F_M(m) = k\,[1-\exp(-b\,(m-m_0))]; \quad m_0 < m < m_1, \qquad (8)$$

where m_O is the lower-bound magnitude, m_1 is the upper bound-magnitude , which can be developed from properties of the source area, constants β and k are given by:

$$\beta = b * \ln 10;\; k = [1-\exp(-\beta\,(m_1-m_o))]^{-1} \qquad (9)$$

From (8) it follows that the density function on magnitude is given by:

$$f_M(m) = \beta * k * \exp(-\beta * (m-m_o));\; m_o < m < m_1 \qquad (10)$$

We leave aside for a while the consideration of the density function on distance in (1) and we substitute (4) and (9) in (10) and equate s to m and obtain the probability that logarithmic acceleration i is exceeded at the site:

$$P[I>i] = \int_R \int_{mo}^{m1} \Phi^*((i-C_1-C_2*m-C_3*\ln(R+h))/\sigma_I)*$$
$$\beta*k*\exp(-\beta*(m-m_o))*f_R(r)\,dm\,dr \qquad (11)$$

With the aid of some algebraic manipulation, the integration on magnitude in (11) may be performed analytically in closed form and resulting equation will be as follows:

$$P[I>i] = \int_R \{(1-k)\Phi^*(z/\sigma_I) + k*\Phi^*(z'/\sigma_I) +$$
$$+ k*(r+h)^{\beta C3/C2} * \qquad (12)$$
$$\exp(-i\beta/C_2+\beta*C_1/C_2+\beta*m_0+\beta^2\sigma_I^2/2/C_2^2)*$$
$$[\Phi^*((z-\beta\sigma_I^2/C_2)/\sigma_I)-\Phi^*((z'-\beta\sigma_I^2/C_2)/\sigma_I)]\}f_R(r)dr$$

where constants z and z' are defined in Merz et.al., 1973. The attenuation relations considered here in (2) and (5) do not correspond to the actual values of ground acceleration near the epicenter and therefore the cutting distance at which the equation limited to a constant value is introduced in the program. There are two possibilities to limit the attenuation equation ordinates near the epicenter. One possibility is to describe the logarithmic acceleration as a function of magnitude with the following equation:

$$\text{maximum } m_I(S) = A_1+B_1*S \qquad (13)$$

In (13) variables A_1 and B_1 are submitted by the program user and variable S is the earthquake magnitude. In this study these variables are not used.

The second possibility to limit the ground acceleration in the vicinity of the epicenter is to use the cutting distance parameter r_1. The program is capable to use both options when variables A_1 and B_1 and r_1 are all specified in the input data file. When this is the case the cutting of ground acceleration in the vicinity of epicenter is carried according to the equation:

$$m_I = (B_1*C_1-A_1*C_2)/(B_1-C_2) +$$
$$+(B_1*C_3)/(B_1-C_2)*\ln(R+h) \qquad (14)$$

The use of parameters r_1 and A_1 and B_1 is illustrated:

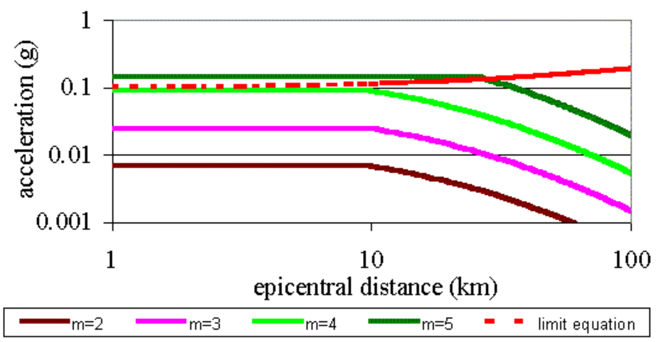

Figure 2: The effects of cutting the ground acceleration in the vicinity of the epicenter.

The values of parameters C_1, C_2 and C_3 of equation (2) which have been used in Figure 2 are 1.05, 1.29 and -2.35 ,respectively, and the coefficients A_1 and B_1 of equation (14) are -3.0 and 0.2, and the value of cutting distance r_1 is 10 km.

3 ATTENUATION OF GROUND ACCELERATION

Ground motions were estimated from an attenuation relationship of the form:

$$\ln(y) = C_1 + C_2 * M + C_3 * \ln(R + h) \qquad (15)$$

where y is the strong motion parameter of interest; M is the earthquake magnitude, R is the distance from the earthquake epicenter to the site; h is the depth of the earthquake focus; and C_1, C_2 and C_3 are regionally dependent coefficients. This form is widely used and available in software described in McCuire, 1976.

Attenuation of strong shaking is not only dependent on the distance to the source and the earthquake magnitude, but is also dependent on the type of the earthquake source and of the geologic site conditions. In this study, ground acceleration registrations were selected from those geological and tectonical regions that were judged to be similar to the investigated area. The second principle for choosing these areas was the availability of registrations. By using these principles the Saguenay region from Eastern Canada and the Newcastle region from Australia were chosen. These are both moderate seismic, intraplate regions and the registrations were observed on bed rock. In the case of Saguenay, the bed rock was of pre-cambrian formations, similar to Fennoscandia, but in the case of Newcastle the rock formations were sedimentary rocks. This difference in rock formation was the weakness of Newcastle data in respect of its similarity to Fennoscandia, but in other respects also this area was similar to Fennoscandia. The reason for selecting these similar areas as the source of basic data for attenuation is that there are no strong motion acceleration recordings available from Fennoscandia.

For the determination of the coefficients, of equation (15), the method of optimization (nonlinear curve-fitting with the aid of the least-squares methods) is used.

The initial data for the Saguenay case consists of digitized, three component acceleration registrations for eleven Saguenay events, four Miramichi events and some additional registrations for Nahanni-1 and Nahanni-2 events. The digital SMA recordings for the Newcastle events consist of four three component recordings. These events were converted to g units from the SMA recordings by conversion coefficient described in McCue, 1995. Synthesized recording for the Kelunji earthquake complemented the instrumentally recorded Newcastle events. The Kelunji synthesized recording was amplified to a magnitude level of 5.3 from the instrumentally recorded event of magnitude 2.3 by methods described in Sinadinovski et.al., 1998.

The following procedure was followed: First, the acceleration histories were plotted on the basis of the recordings. From these plots the ten-second time windows corresponding to the maximum acceleration peaks were chosen. From these acceleration plots the response spectra for the 5% damping were computed with the aid of software from Xu et.al., 1990. The spectral ordinates are calculated for longitudinal and transversal earthquake components. The investigated frequency values were 0.3, 1, 2, 5, 7, 10, 15, 20, 25 and 97 Hz. The magnitude value for the Saguenay event was 5.8, and the depth focus was 29 km. The Kelunji synthesized recording were used for spectral calculations after the scaling of the magnitude to the value of 5.3 and the distance to the value of 10 km. The magnitude scaling was carried out according to the relations given in Ahorner, 1983 and the distance scaling according to the relations given in McCue, 1995. The Miramichi recordings used for spectral calculations were scaled to the same magnitude and same depth value as the recordings of the Saguenay event with the aid of the relations of Ahorner, 1983. The Kelunji recordings were used to supplement the four Ellalong recordings that are called together the Newcastle recordings in this paper because of their vicinity to town of Newcastle in New South Wales, Australia. The two recordings of the Miramichi event were used to supplement the ten Saguenay recordings that are called Saguenay recordings in this paper after the name of the main event.

In the following figures the attenuation relations for the logarithm of the peak ground acceleration or various spectral accelerations are given as well as the attenuation for the acceleration ordinates itself. The figures are for the longitudinal and transversal components of the Saguenay and Newcastle events, which for the purposes of this study are regarded as independent recordings.

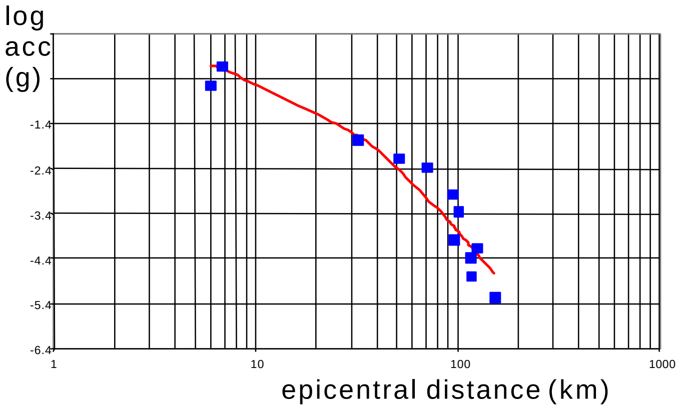

Figure 3: Fit of the attenuation (eqn. (3)) to the Saguenay transversal recordings of the logarithm of the peak ground acceleration in g.

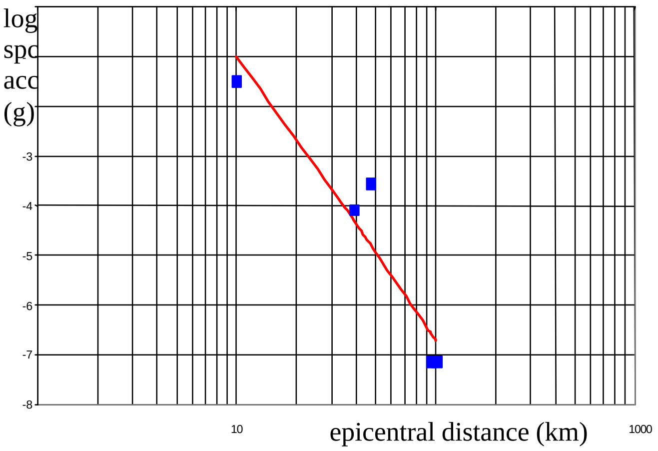

Figure 4: Fit of the attenuation to the Newcastle longitudinal recordings for the logarithm of the spectral acceleration at 0.3 Hz.

The fit of the Saguenay event is based on 12 observations; the Newcastle event only on 4 observations. Given the epicentral distance the prediction of the logarithmic accelaration is therefore involved with quite some uncertainty.

4 DISCUSSION

By preparing the initial data according to the previous section, the further analysis was carried the Seismic Risk Analysis Software described in McCuire, 1976. As a result the spectra of ground acceleration in the Olkiluoto area for two horizontal directions on the data of the seismicity of this area and on the data of the earthquakes which were having place in Canada (Saguenay) and Australia (Newcastle) could be obtained.

Assuming, that the earthquake components of the different horizontal directions are independent we will obtain four independent events: Saquenay longitudinal, Saguenay transversal, Newcastle longitudinal and Newcastle transversal. In the analysis the final results were calculated as the median value from the distribution of the four independent spectra. It was carried out as follows in detail. Acceleration values in g, obtained from the calculation of the four independent events are assumed to be the mean values of uniform random distributions. Samples are generated from these uniform probability distributions. The total number of generated sample values was thirty for the Saguenay events in each direction and for the Newcastle events in each direction twenty values were generated. So, the relative weighting factors for the Saguenay events was 3 and for the Newcastle events 2 and the sum of weights was ten. The four spectra from the initial data of the Saguenay and Newcastle events and the median spectrum for the return period of 100,000 years were calculated using the weights described above and are given in the following figure:

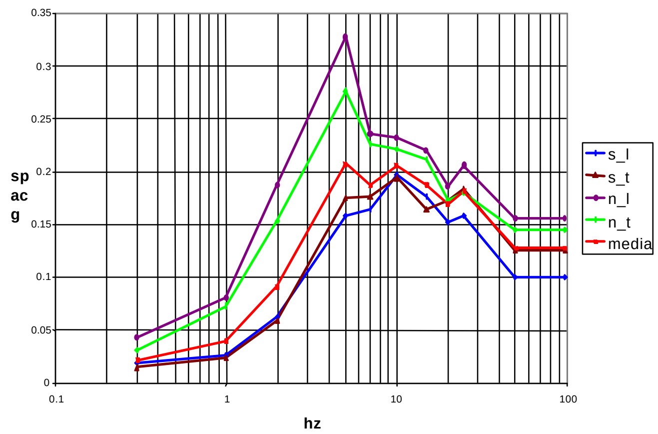

Figure 5: The resulting ground response spectra for 5% damping from four input data and the median spectrum for 100,000 years return period

5 CONCLUSION

An overview is presented of the determination of seismic hazard in a region where seismic activity is very low, but the consequences of possible damage (a nuclear disaster) are very high. Seismic data from other locations with more seismic activity could be very well used for this purpose.

6 REFERENCES

Barosh, P.J. 1969. Use of seismic logarithm of ground acceleration data to predict the effects of earthquakes and underground nuclear explosions in various geologic settings. U.S.Geological survey bulletin, 1279: 93.

Saari, Jouni. 1998. Regional and Local Seismotonic Characteristics of the Area Surrounding Loviisa Nuclear Power Plant in SE Finland.

McCuire, R.K. 1976. Fortran computer program for seismic risk analysis. pp. 1-90.

Merz, H.A. And Cornell, C.A. 1973. Seismic risk analysis based on a quadratic magnitude-frequency law. Seismol. Sos. America Bull., v. 63, no.6, pt. 1: 1999-2006.

Esteva, L. 1970. Seismic risk and seismic decisions, in Hansen, R.J., ed., Seismic design for nuclear power plants. Cambridge, Massachusetts Inst. Technology Press: 142-182.

McCue, K., Dent, V. and Jones T. The characteristics of Australian strong ground motion. Pacific Conference on Earthquake Engineering, Australia, 20-22 Nov. 1995: 71-80.

Sinadinovski, C., McCue K. F., Somerville M.Strong ground motion simulation of Australian intraplate eartquakes, 17th European Conference on Earthquake Engineering, 1998, Balkema, Rotterdam.

Xu J.,Philippacopoulas A. J., Miller, C. A., Constantino C. J., Cares (Computer Analysis for Rapid Evaluation of Structures 1.0, NUREG/CR 5588,BNL-NUREG-52241,Vol. 1-3, Brookhaven National Laboratory, May 1990.

Ludwig Ahorner, Protection of Nuclear Power Plants against Seismic Effects Reference Ground Motion: Practice Followed in European Countries (Synthesis Report), Universität Köln, European Applied Research Reports, Nuclear Science and Technology. Vol 4, No. 6, (1983) pp.1325-1422.

Gail M. Atkinson and David M. Boore , Some Comparisons Between Recent Ground Motion Relations, Seismological Research Letters, 68, January/February, 1997.

Wu, P., P. Johnston & K. Lambeck, Postglacial Rebound and Fault Instability in Fennoscandia, Geophys. J. Int., (1999) submitted.

K. Sadigh, C.-Y. Chang, J.A. Egan, F. Makdisi, and R.R. Youngs, Attenuation Relationships for Shallow Crustal Earthquakes Based on California Strong Motion Data, Seismological Research Letters, 68, January/February, 1997

P.H.A.J.M. van Gelder and P. Varpasuo, Bayesian Seismic Hazard Assessment for a Nuclear Power Plant, ESREL'98: European Safety and Reliability Conference 1998, 16 - 19 June 1998, Trondheim, Norway.

Somerville, P.G., J.P. McLaren, C.K. Saikia, and D.V. Helmberger (1990). The November 25, 1988 Saguenay, Quebec earthquake: source parameters and the attenuation of strong ground motion. Bull. Seism. Soc. Am., 80, 1118-1143.