

Characterization of Seismic Ground Motions for Probabilistic Safety Analyses of Nuclear Facilities in Sweden

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METHODS

In 1986 the Swedish Nuclear Power Inspectorate and concerned power utilities initiated the study project SEISMIC SAFETY, aiming at a deepened seismic risk assessment for the nuclear facilities in Sweden. In order to establish a reliable basis for structural response calculations and subsequent risk evaluations, a methodology was outlined for probabilistic assessments of seismic ground motions (GM) at the plant sites. This methodology, though it contains established elements, is partly novel. Improvements are envisaged, and international responses are welcomed.

METHODS AND RESULTS

Basically, the applied methodology can be structured in the form of the following tasks, further commented below.

- (1) to assess the joint occurrence frequencies for all significant events, grouped in discrete classes and characterized by the fundamental source and wave path parameters,
- (2) to establish "Event-specific Response spectra" for generalized hard rock site conditions, the spectral ordinates being expressed as functions of the most important seismic source and wave path parameters,
- (3) to assess the spread of spectral ordinates around the averages,
- (4) to determine, on the basis of results from the above, the exceedance rates for the spectral ordinates and to construct "Envelope Response Spectra" for various selected probability levels ("uniform risk spectra"),
- (5) to generate synthetic GM time-histories corresponding to the Envelope Spectra,
- (6) to characterize, on the basis of the outcome of the above, site-specific ground motions, considering effects of local rock and soil strata (not dealt with in this report).

The outcome of the above tasks has been presented in a series of working reports, from which certain parts, judged to be of general interest, are summarized in the present report.

(1) Occurrence frequency distributions of seismic events

* Over the entire range of significant sizes and locations historic earthquakes were categorized in respect of the seismic moment M_0 and the focal distance R . The widths of the classes were determined to be approximately equal in respect of the ratios between GM values at the upper and lower boundaries of each class.

* Large scale seismicity zoning and seismotectonic considerations resulted in the choice of an average Fennoscandian function of epicentral density, directly applicable to at least two nuclear plant sites and, without major modifications, to the other plants (Figure 1). The epicentral density function was derived from available catalogues, covering stronger earthquakes in Fennoscandia during a period of almost 500 years.

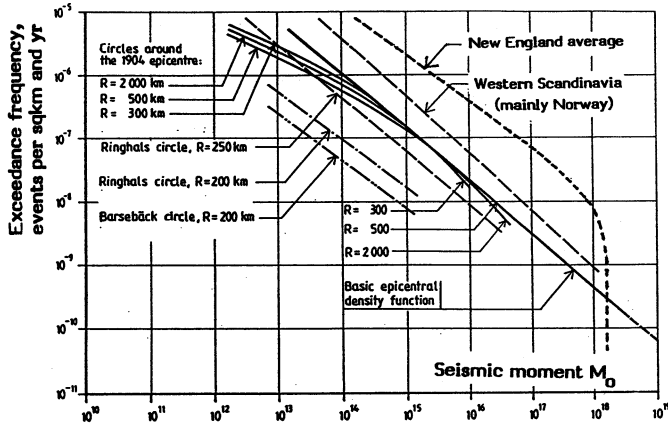


Figure 1: The "average Fennoscandian epicentral density function", compared with local seismicity functions from Scandinavia and Eastern US (the latter is an approximate average of various experts' predictions for the New England region).

* For each volume element of the crustal model (Figure 2), the occurrence rates of the various classes of events were determined on the basis of the epicentral density function and the probability density distribution of focal depths. The result of this first step of the probabilistic assessment was a matrix of occurrence frequency values for each selected class of events.

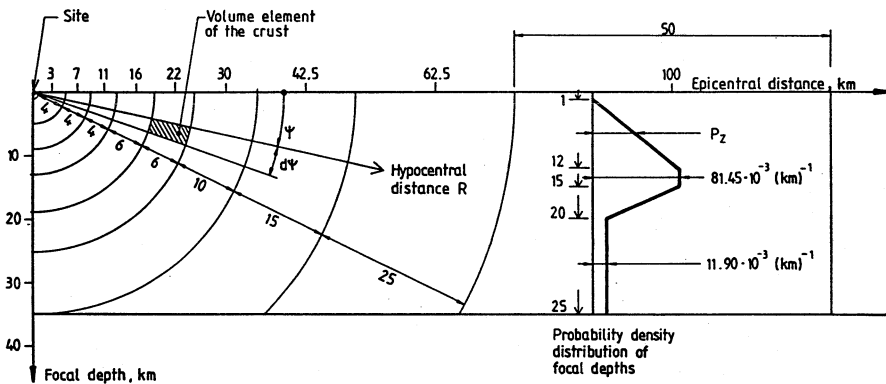


Figure 2: The basic seismicity model: Geometry and distribution of focal depths

(2) Ground response spectra for each class of $M_0 - R$

* The model used for the development of "event-specific" ground response spectra is based on the processing of empirical data from more seismic regions to suit the typical conditions in Sweden. The main rationales for the choice of this approach are the obvious lack of sufficient local strong motion data corresponding to the extremely low probability levels considered in the risk analysis of nuclear facilities, and the observation that effects of differential geological and seismological conditions have a moderate influence on the shapes of the ground response spectra. The fairly comprehensive and well-defined database given in Ref. 1-3 in the form of empirical ground response spectra, mainly from Japan, was taken as the basis for the first approach of a spectral characterization.

* The characteristic response spectra for Swedish hard rock conditions were thus obtained by modifications of the corresponding Japanese spectra with respect to the influence factors that are expected to affect the spectra differently. These factors are associated with differences of source parameters such as stress drop and fault area, and of wave propagation effects such as anelastic attenuation. Since the resulting differences are moderate, the transformation of the Japanese spectra could be based on generalized, best-estimate values of the influence factors. The following spectral formulae, (based on Aki, 1967) constituted the basis for the transformation.

$$F_d = \text{Const} \cdot F_{d0} \cdot (1 + (f/f_c)^{2n})^{-1/2} \cdot A(f,R)$$

where the displacement wave amplitude F_d is a function of the "zero frequency amplitude" F_{d0} , the "corner frequency" f_c and the "anelastic attenuation" function $A(f,R)$. Since these parameters can be related to other source and wave path parameters, viz. stress drop, fault displacement area, seismic moment, fault distance and shear modulus, the effects of differential conditions in Sweden and Japan could be assessed based on generalized empirical relationships. The Japanese spectra for each selected class of magnitudes and focal distances, were thus modified to account for

- differential (characteristic) stress drop,
- differential (average) fault area and strong motion duration,
- differential rock quality, rock stiffness and anelastic attenuation.

* The results of the transformation of a Japanese "Standard spectrum" are demonstrated in Figure 3 and compared with spectra based on observations of an earthquake in the Eastern US, where the geological conditions are similar to those prevailing in Sweden.

* It appeared that the influence of the differential properties was moderate, but significant, for frequencies exceeding 1 Hz, whereas, for the lower-frequency range, the effects of differential stress drop and differential duration balanced each other. For the spectral range of higher frequencies, the higher stress drop and lower attenuation significantly increases the spectral ordinates of near-field earthquakes in Sweden compared with Japanese earthquakes of corresponding magnitudes and focal distances.

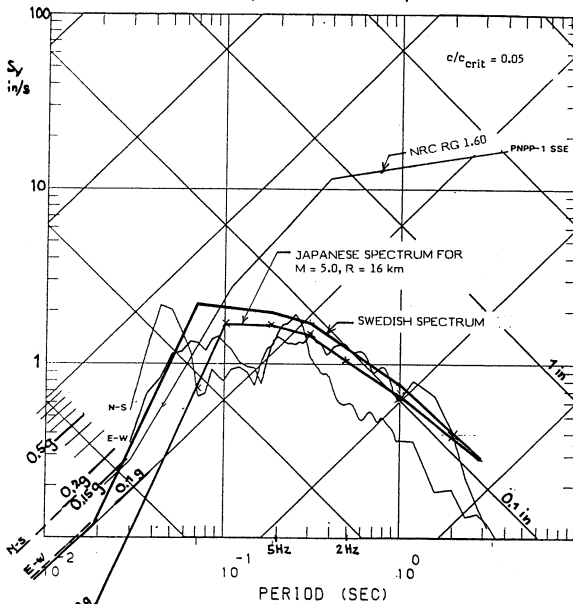


Figure 3:
A Japanese standard response spectrum and the corr. Swedish spectrum for the Japanese magnitude $M=5$ (est. $M_0 = 5 \times 10^{16}$ Nm) and hypocentral dist. $R=16$ km, comp. with data from the Leroy main shock, recorded at the Perry NPP, Jan. 31, 1986 ($m_b=4.9$, $R=16$ km, $M_0=10^{16}$ Nm, approx.)

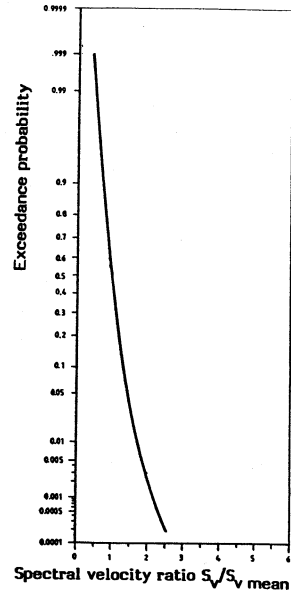


Figure 4:
Cumulative distribution of spectral ordinates around the average

(3) Assessment of the spread of spectral values

Since the various selected events and their corresponding characteristic response spectra have been classified only with respect to the "fundamental parameters" M_0 and R , it is not surprising that there is a considerable spread of spectral values around the average. This spread was assessed in a generalized way, once more on the basis of Japanese data (Ref. 4), reprocessed to suit the conditions pertaining to the Swedish model. Thus the combined effects of other parameters than M_0 and R were considered, though without identifying their individual contributions, that would not be possible at the present state-of-the-art. A considerable part of the spread is probably due to errors in the data acquisition and processing systems, including the uncertainty associated with the use of various magnitude scales and transformations between such scales. On the basis of the Japanese data a generalized distribution function, normalized to the mean spectral value as unity and independent of the frequency of vibration, was thus developed. (Figure 4)

(4) Construction of Envelope Ground Response Spectra

* On the basis of the derived occurrence frequency distributions for discrete classes of events, the event-specific spectra of these classes and the relative distribution of spectral values, the frequency of exceedance of a certain spectral value was determined for each class of events. The overall exceedance frequencies were then determined for various spectral values by adding the contributions from each class of events.

* For each selected probability level envelope spectra or so-called uniform risk spectra were finally constructed by interconnecting discrete spectral values, corresponding to the given level, obtained from the overall exceedance frequency distributions of spectral values. On the basis of empirical relationships between response spectra for various damping ratios that are also included in Ref. 2 and 3, envelope response spectra were also produced for various damping ratios other than 0.05 (Figure 5).

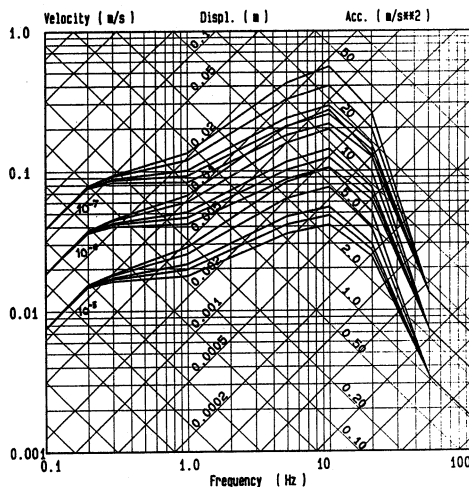


Figure 5: Envelope Ground Response Spectra for horizontal ground motions of outcropping hard rock. Annual exceedance frequencies 10^{-5} , 10^{-6} and 10^{-7} . Damping ratios 0.005, 0.02, 0.05, 0.07 and 0.10.

(5) Generation of synthetic ground motion time-histories

* Synthetic time-histories of ground acceleration, velocity and displacement were developed, corresponding to the envelope response spectra. The time-histories were produced for two perpendicular horizontal directions and for the vertical, one of the horizontal representing the primary principal axis of the ground motion.

* The spectra for 5 per cent of critical damping were selected to constitute the primary target spectra. It was possible to attain a good conformity between the response spectra of the time-histories and the target spectra, not only for 5 per cent but also for other damping ratios. Particularly, for the important range $f = 1-5$ Hz and damping ratios exceeding 0.02, the agreement is remarkably good.

* The time-histories could be given a realistic duration of the various phases of a strong motion, implying that they may be used not only for linear but also for non-linear response calculations, without causing any major deviations from a realistic response, in the form of accumulated residual strain, displacements etc.

COMMENTS

Uncertainty ranges

Although effects of the inevitable spread of parameter values from case to case are judged to be reasonably well accounted for by the introduction of a probability distribution of spectral characteristics, several averages of the parameter values were assessed only by best estimates. Therefore, some of the most important parameters or functions have been selected for examinations as regards the sensitivity of the results to parameter variations:

- The "basic seismicity function" or "epicentral density function": (A curve based on "local seismicity", representing the lower limit of likeliness as regards earthquakes in south-west Sweden, was compared with the spectrum curve based on the average Fennoscandian seismicity, in order to quantify a possible range of conservatism).
- The upper boundary ("cut-off") magnitude was increased from $M_L = 6.5$ to $M_L = 7.0$.
- The Japanese response spectrum formulation obtained from Ref. 1 was used for comparison with the (more conservative) formulation in Ref. 2 which has constituted the basis for the Swedish spectra.
- The characteristic stress drop.
- The "rock quality factor" Q_0 and the anelastic attenuation function.

Except for the "seismicity function", only parameter deviations tending to increase the responses were tested. The results of the sensitivity tests are summarized graphically in a spectral form in Figure 6. It appears that the sensitivity of the spectral values to parameter variations is moderate and that the proposed spectra have the appropriate position for being regarded as being the best estimates when taking all the most probable parameter variations together. Particularly, within the frequency band 2-5 Hz the sensitivity of the spectrum towards the unconservative side appears to be small.

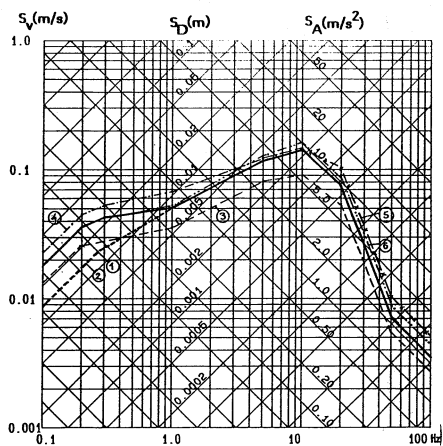


Figure 6:
Envelope Ground Response Spectrum for horizontal ground motions and damping ratio 0.05 (Curve 1), adjusted with respect to an alternative Japanese spectrum formulation (Curve 2), a possible overestimate of the seismicity (Curve 3), increased cut-off magnitude (Curve 4), increased stress-drop or spectral decay factor (Curve 5), increased rock quality factor (Curve 6).

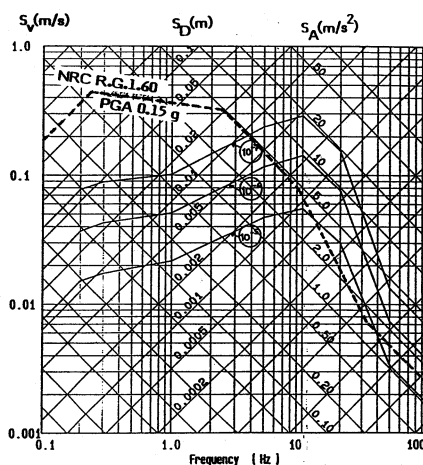


Figure 7:
The new Swedish design response spectra for horizontal GM, damping ratio 0.05 and the exceedance rates 10^{-5} , 10^{-6} and 10^{-7} , compared with the original design spectrum based on US NRC R.G.1.60

Comparison with common design spectra

* Within a region with an essentially uniform seismicity the predominant seismic hazard contribution comes from the nearfield. In terms of "uniform risk" response spectra, the near-field predominance is stronger the higher the vibration frequencies are. In intraplate regions such as Fennoscandia, the spectra are particularly up-lifted within the high-frequency range, due to the relatively low anelastic attenuation and high stress drop. This up-lift includes the peak ground acceleration, set to a large extent by the high-frequency components of the ground motions.

* The entire shapes of the "uniform risk" spectra for regions with an essentially uniform seismicity differ strongly from the shapes of commonly used envelope design spectra, such as those given in the US NRC Reg.Guide 1.60. As demonstrated in Figure 7, the original Swedish design spectrum, obtained by scaling of the NRC₅ spectrum to PGA=0.15 g and intended to represent the annual exceedance rate of 10^{-5} per year and site, greatly exaggerates the response in the low and intermediate frequency range, viz the range of major significance to the nuclear facilities. Obviously, if aiming at a "uniform risk" assessment, the NRC spectra might be used for areas with a much higher seismicity in the far-field than in the near-field but should not be used for regions with a uniform seismicity. The scaling of the spectra to PGA might be quite misleading, particularly if the choice of PGA is influenced by near-field observations. Figure 3 is also referred to with respect to this matter.

* Parameters such as the peak ground velocity which are more strongly related to the low frequency waves and thus to the fundamental fault mechanism, constitute more appropriate anchor points. The most reliable spectrum, corresponding to a certain type of events, is, however, determined on the basis of direct empirical relationships between the whole spectral function and the fundamental event-specific parameters, e.g. M_0 and R, as in the present study and in the bases for the Japanese standard spectra.

* In the long-term perspective the outline of response spectra for Swedish hard rock sites on the basis of data from interplate regions may obviously be regarded as a temporary approach, to be validated and probably improved in the light of an increasing database from intraplate regions which are similar to Fennoscandia, from a geological and seismotectonical point of view. A few near-field records from recent earthquakes in Eastern North America have already been compared with Swedish "event-specific" response spectra as demonstrated by an example indicated in Figure 3. It appears that the spectra of the North-American earthquakes do not deviate very much from the proposed Swedish spectra.

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