13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2800

GENERATION OF SYNTHETIC GROUND MOTION FOR EXTREME EVENTS IN SOUTHERN FINLAND USING EVOLUTIONARY SPECTRUM APPROACH

Pentti Varpasuo[1]

SUMMARY

This paper describes the simulation of the extreme seismic ground motion in southern Finland. The ground motion is specified with the aid of evolutionary spectrum with modulating function specified as piecewise linear function of time and frequency. A simulated ground motion with evolutionary spectrum is described by power spectrum density function and by the time-frequency dependent modulating function. The power spectrum density function defines the overall frequency content of the ground motion, whereas the modulating function describes the evolutionary behavior in both time and frequency domain.

The generated ground motion time histories are fitted to be compatible with the Finnish YVL 2.6 – guide response spectra for the design of nuclear power plants. The spectra are generated to fulfill the criteria of the standard "Seismic Analysis of Safety-Related Nuclear Structures" (ASCE 4-98). The end result of the study is the ground motion definition presented as one three component set of statistically independent time histories of the duration of 15 seconds generated by numerical simulation approach described above.

GROUND MOTION SIMULATION USING EVOLUTIONARY SPECTRUM APPROACH

The references used in developing the formulations used in this paper are the following: Gasparini [1], Kennedy [2], Xu [3], der Kiureghian [4]. Any periodic function can be expanded into a series of sinusoidal waves:

Equation 1 $x(t) = \Sigma C_i \cos(\omega_i t + \phi_i)$

A_i is the amplitude and ϕ_i is the phase angle of the ith contributing sinusoid. By fixing an array of amplitudes and then generating different arrays of phase angles, different motions which are similar in general appearance (i.e., in frequency content) but different in the local details, can be generated. The computer uses a "random number generator" subroutine to produce strings of

[1] Fortum Nuclear Services Ltd
Rajatorpantie 8, Vantaa, 00048 Fortum
e-mail: pentti.varpasuo@fortum.com

phase angles with a uniform distribution in the range between 0 and 2π. The summation index i in Equation 1 goes from 1 to n.

The coefficient C_i in Equation 5 is of form

Equation 2 $\quad C_i = A_i(\omega_i , t)(2\Phi(\omega_i)\Delta \omega)^{1/2}$

In Equation 2 $A_i(\omega_i , t)$ is called time and frequency dependent modulation function and this the feature that includes the evolutionary effect in the simulation.

In this simulation task the time and frequency dependent modulation function is used in the form depicted in Figures 1 and 2:

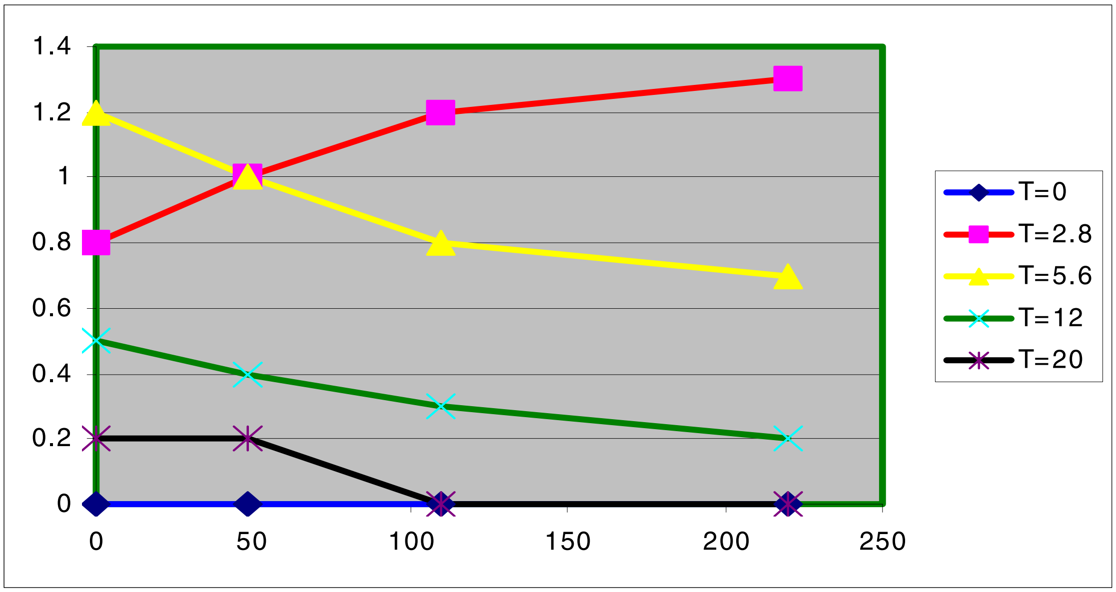

Figure 1 Frequency envelopes of the modulation function

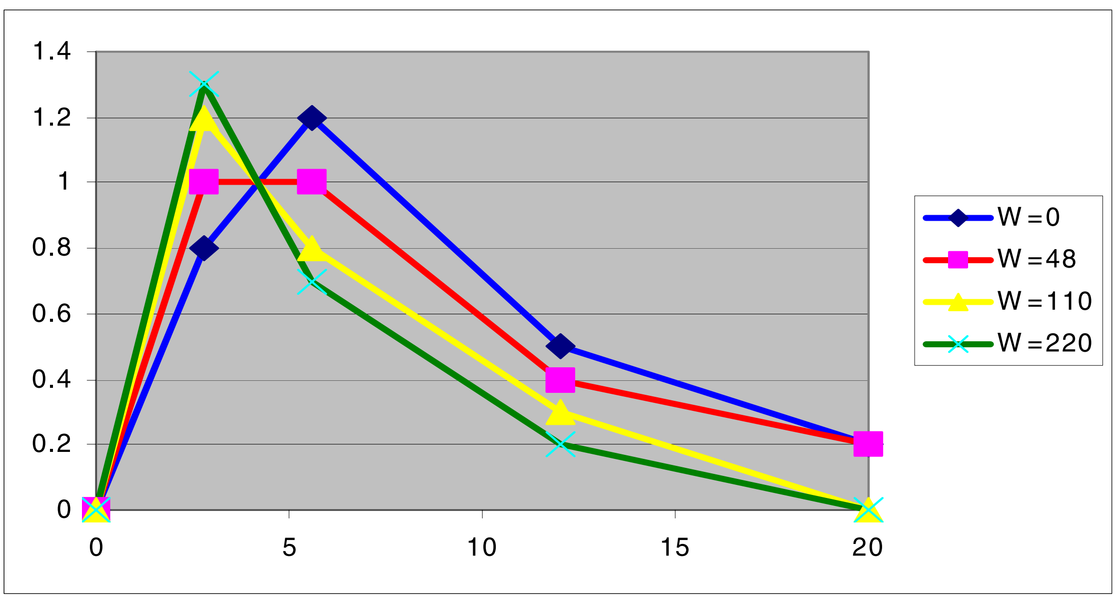

Figure 2 Time envelopes of the modulation function

The iterative correction procedure for the PSD function utilized in this work corrects the PSD ordinates with the square of the quotient between target response spectrum value and the response spectrum value of the simulated motion for each frequency value used for discretation of piecewise linear PSD function. In this work 75 frequency point were used between 0.2 and 34 Hz.

DEFINITION OF SEISMIC MOTION

The seismic motion for the analysis of the fifth nuclear unit to be constructed in Finland will be defined by the acceleration response spectrum described in the document YVL 2.6 "Seismic Analysis and Design of Nuclear Power Plants," approved 19.12. 2001 by Finnish Centre of Nuclear Protection (STUK).

The spectral shape to be used to define this motion corresponds to a median (50 percentile) spectrum with the return period of 100 000 years developed for hard rock sites. The horizontal peak ground acceleration will be assumed equal to 0.1g. The vertical spectrum will be assumed equal to 2/3 of the horizontal spectrum. The horizontal spectrum is shown in Figure 3.

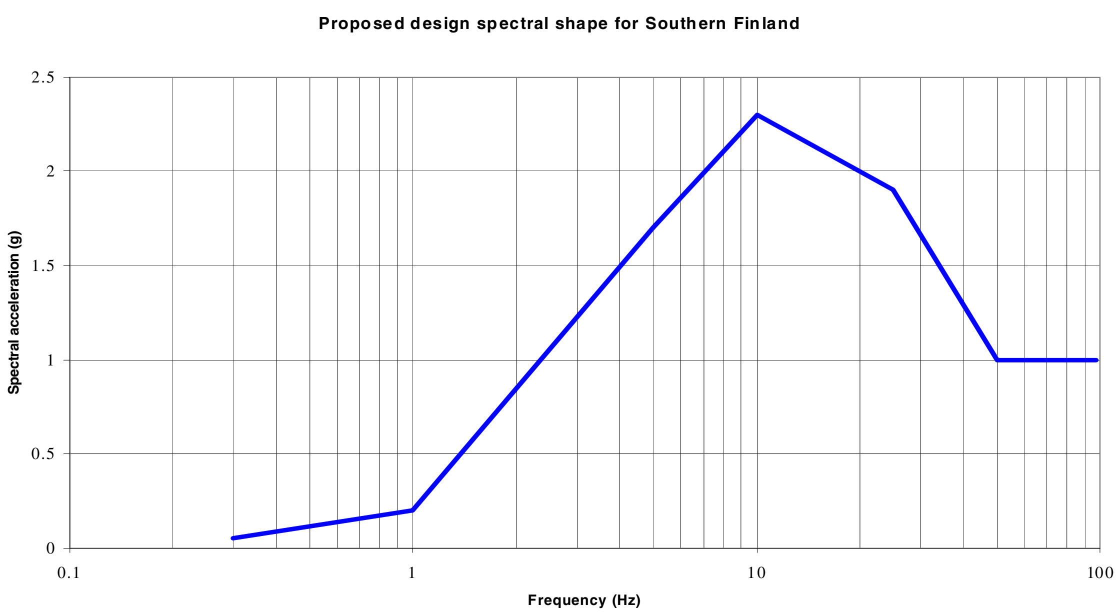

Figure 3 Design horizontal acceleration spectrum. Peak acceleration scaled to 1 g –5% damping

DEFINITION OF ACCELERATION TIME HISTORIES

The horizontal acceleration time history was developed to match the horizontal target response spectrum. The characteristics of these time histories are as follows:

Total duration = 20 seconds, Time step = 0.005 seconds. Figure 4 shows the trace of the artificial time history simulated in this task.

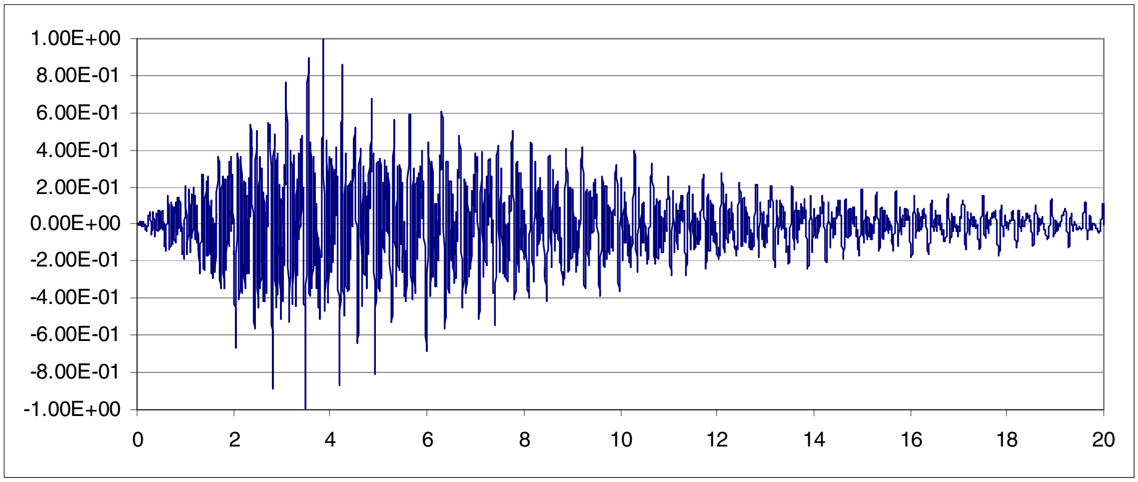

Figure 4 Acceleration time history for horizontal component x

Figure 5 shows the comparison of the acceleration response spectrum of the artificial time history to the target YVL 2.6 response spectrum.

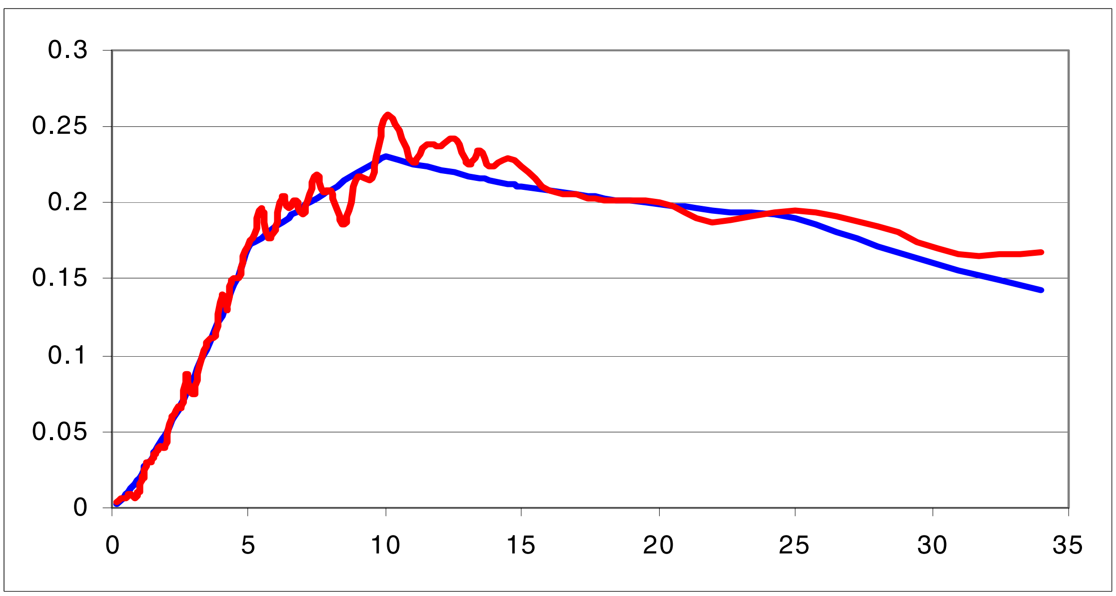

Figure 5 Horizontal component x – 5% response spectrum fit

STRONG MOTION DURATION

To estimate the strong motion duration of the artificial time histories it is necessary to calculate the variation of energy with time for each component. It is a standard practice to use the following parameter related to the energy released by the earthquake:

Equation 3 $$H(t) = \int_{o}^{t} a^2(\tau)\, d\tau$$

where t is time and $a(\tau)$ is the acceleration value at time τ. Figure 6 shows the parameter H(t) for the artificial time history. Different limits are used to define the strong motion duration T_{sm}. The most common limits to define T_{sm} are the period between the times when the parameter H reaches 5% and 95% or the parameter H reaches 5% and 75% of its maximum value. For the three components developed here, the strong duration times are approximately:

Tsm (95%-5%)	Component	Tsm (75%-5%)
11.47 sec	Horizontal x	5.805 sec

Table 1 Table for strong motion duration of generated time history component

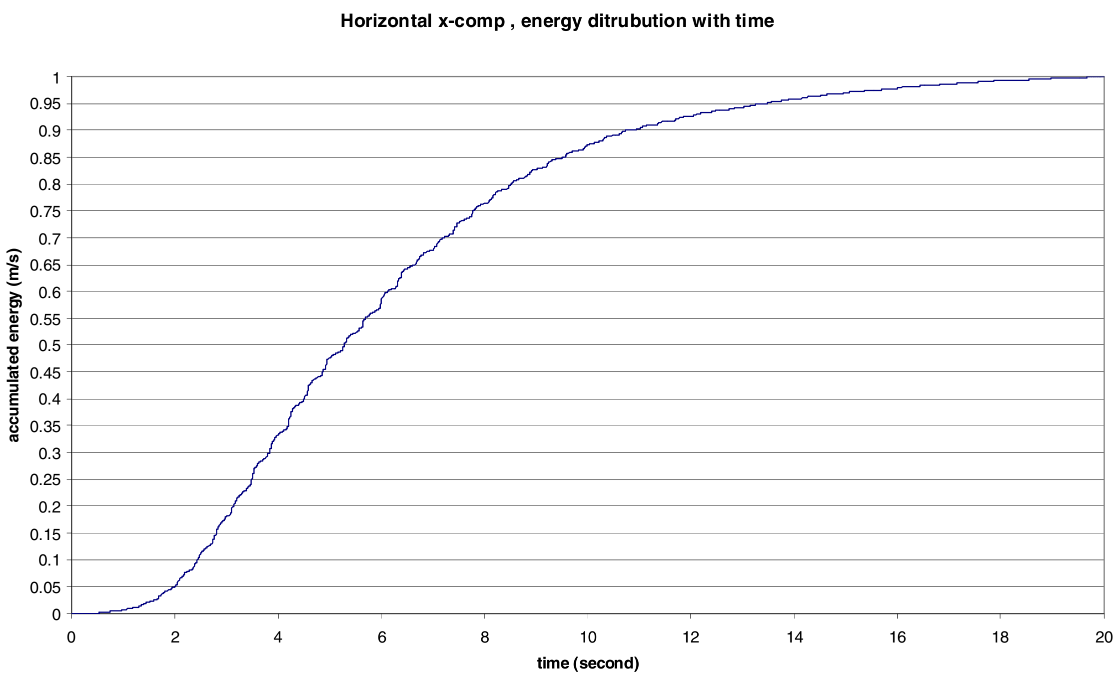

Figure 6 Horizontal x component – Husid diagram- energy distribution with time

ENERGY DISTRIBUTION WITH FREQUENCY

To demonstrate that the artificial time histories have enough energy in all the frequency ranges of interest, the common practice is to calculate the power spectral density (PSD) function of them.

For this purpose, the power spectral density could be defined as:

Equation 4 $S(\omega) = |F(\omega)|^2 / \pi T_d$

where $F(\omega)$ is the Fourier spectrum and T_d is the strong motion duration of the record.

For comparison purposes, this raw PSD is generally averaged. The window length for averaging PSD function in this study is 1Hz in frequency range. To demonstrate that the PSD function of the artificial record has the frequency characteristics of the target response spectrum, it is necessary to develop a “target” PSD function that is consistent with the target response spectrum.

A “target” PSD function can be estimated by an iterative process using the relationship between the mean of the peak response ($E[r_{max}]$) and the root-mean-square response of a stationary process ($(E[r^2])^{1/2}$). This relation can be expressed as:

$$E[r_{max}] = p(E[r^2])^{1/2} = p(\int_0^{\infty} S_r(\omega)\, d\omega)^{1/2}$$

Equation 5

where p is a peak factor, r is the response value, S_r is the PSD of the response, ω is the frequency. $E[r^2]$ is a function of the transfer function of a single degree of freedom oscillator and the PSD of the ground motion. In this task the original form power spectral density function to begin the fitting with the target response spectrum was the Kanai-Tajimi power spectral density function for filtered white noise. The power spectral density function of filtered white noise can be written in form

Equation 6 $\quad \Phi(\omega) = \Phi_0\,(1 + 4\zeta^2\omega^2/\omega_0^2)/((1-\omega^2/\omega_0^2)^2 + 4\zeta^2\omega^2/\omega_0^2)$

In Equation 6 Φ_0 is the power spectral density parameter of the white noise passing through the filter, ω_0 is the filtering frequency and is the damping parameter os the filter.

In subsequent iterations the power spectral density function was described as a piecewise linear function. The numerical values for these parameters in the last iteration using Kanai-Tajimi PSD description were 0.0002 m^2/s^3 for Φ_0, 62.8 rad/s for ω_0 and 1.2 for ζ. Figure 7 shows the three last response spectrum fits using Kanai-Tajimi PSD and Figure 8 shows the three last fits when iteration was continued with piecewise linear PSD description.

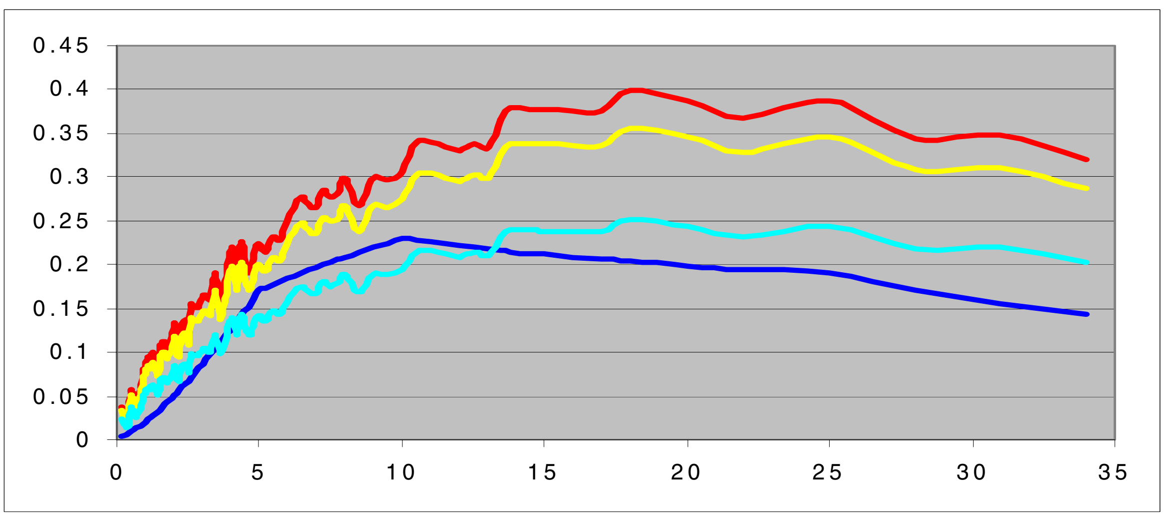

Figure 7 Three last response spectrum fits with Kanai-Tajimi PSD description

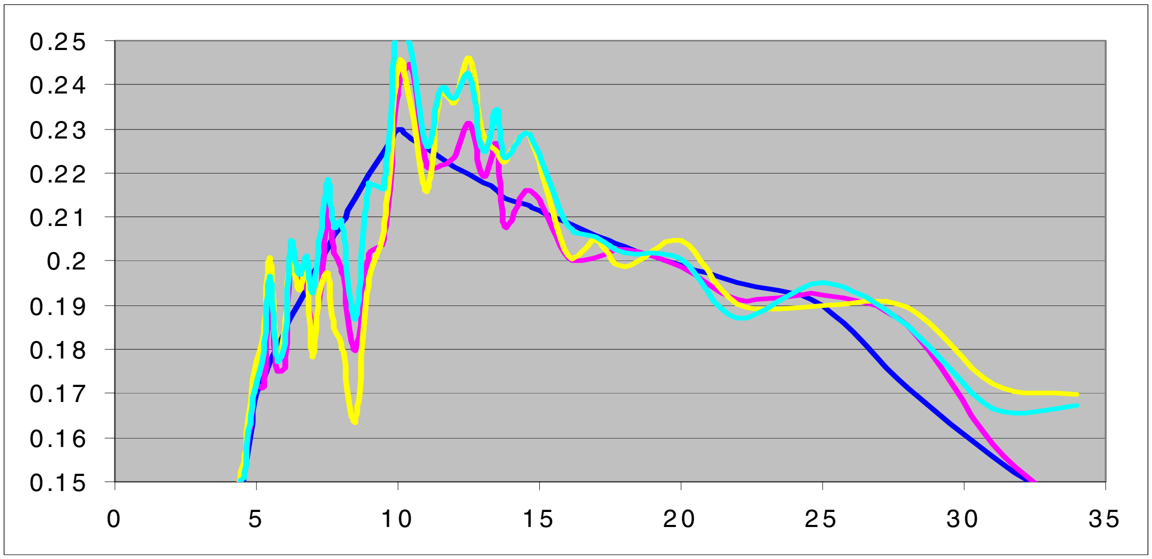

Figure 8 Three last response spectrum fits with piecewise linear PSD description

The shapes of the PSD functions using for simulating the motion during three last iterations are given in the Figure 9:

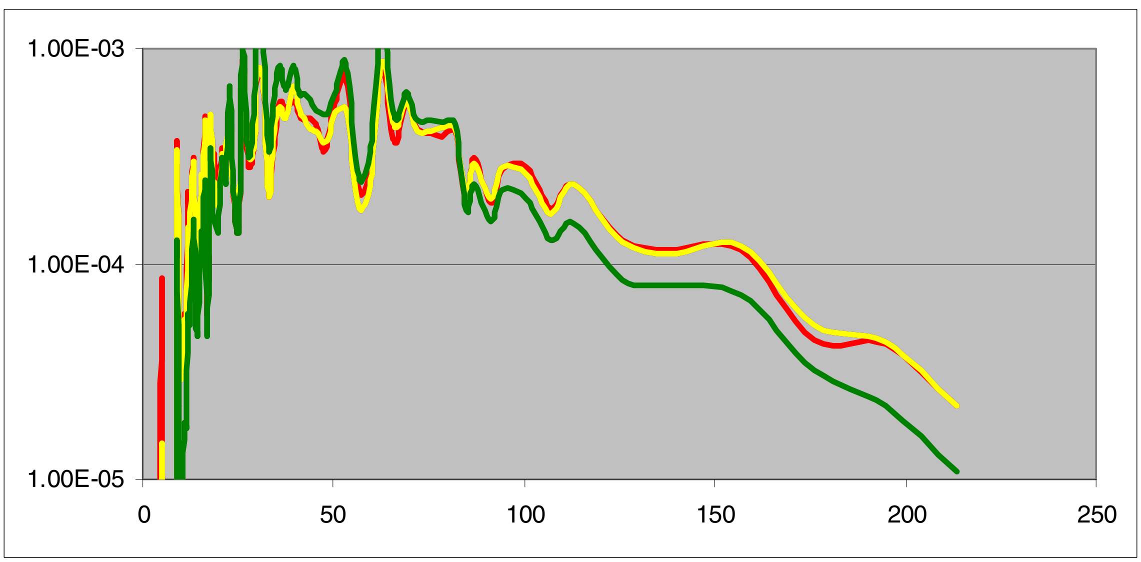

Figure 9 The PSD shapes during the three last iterations in simulation when the piecewise linear PSD description is used

DISCUSSION

To validate the histories generated above the requirements the ASCE STANDARD 4-98 is used. The requirements given of the standard are as follows:

1. One or more recorded, modified recorded or synthetic earthquake ground motion time histories may be used to calculate seismic response of safety related structures.

2. Time histories shall be so selected or developed that they reasonably represent the duration of strong shaking conditions expected for the site. For analysis shorter time segments may be used if they satisfy the conditions given below:

3. The developed time histories shall have following characteristics:

- the mean of the zero-period acceleration (ZPA) calculated from the individual time histories shall equal or exceed the design ground acceleration
- in the frequency range 0.5 to 33 Hz the average of the ratios of the mean spectrum (calculated from the individual time history spectra) to the design spectrum, where the ratios are calculated frequency by frequency shall be equal, shall be equal to or greater than 1.
- no one point of the mean spectrum (from the time histories shall be more than 10% below the design spectrum

Spectral values from the time history shall be calculated at sufficient frequency intervals to produce accurate response spectra. The following table provides suggested frequencies at which spectral ordinates may be calculated:

Frequency range (Hz)	Increment(Hz)
0.5-3.0	0.10
3.0-3.6	0.15
3.6-5.0	0.20
5.0-8.0	0.25
8.0-15.0	0.50
15.0-18.0	1.0
18.0-22.0	2.0
22.0-34.0	3.0

Table 2 Suggested frequencies for calculating of response according to ASCE Standard 4-98.

CONCLUSION

A method using the evolutionary spectrum approach for generation of simulated ground motions has been presented. The energy distribution of the generated motion in time and frequency space has been demonstrated. The validation of the motion according to ASCE Standard has been discussed.

REFERENCES

1. D. A. Gasparini, E. H. Vanmarcke, "Simulated earthquakes compatible with prescribed response spectra", Massachusetts Institute of Technology, Publication No. R76-4, Cambridge, Massachusetts, January 1976.
2. R. Kennedy et al, "Seismic Analysis of Safety Related Nuclear Structures", ASCE STANDARD 4-98, American Society of Civil Engineers, September 1998.
3. 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.
4. A. D. der Kiureghian, C. H. Wung, Stocal-II, Computer-Assisted Learning System for Stochastic Dynamic Analysis of Structutes, Part I -Theory and Development, Part II – User's Manual, Report No. UCB/SEMM-89/10, Dep. Of Civ. Eng., Univ. of California, Berkeley, California, 1989.