Spectrum-Compatible Time Histories for ACR™ Nuclear Power Plant in Eastern North America

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1 ABSTRACT

The Advanced CANDU Reactor™ (ACR-1000™) standard design is developed by Atomic Energy of Canada Limited (AECL™) to be the next step in the evolution of the CANDU™ product line. It is based on the proven CANDU technology and incorporates advanced design technologies.

In recent years, it has been established that ground motions occurring in Eastern North America (ENA) are richer in high frequency content than those occurring in Western North America. This is due to the impact of smaller earthquakes at shorter distances that govern the seismic hazard of rock sites in the Eastern North America region. This phenomenon is particularly relevant for the seismic qualification of safety related structures, systems and components, which are sensitive to these high frequencies.

The ACR-1000 standard design takes this phenomenon into account by using a design ground response spectrum characterizing the richness of high-frequency in ENA ground motions, in addition to the traditional design ground response spectra defined for soil and rock sites per the Canadian Standards Association (CSA). A set of three time histories has been developed using the spectral matching technique to represent the ENA design ground response spectrum.

This paper presents the approach followed in generating the time histories compatible with the ENA design ground response spectra. In addition, the paper presents the results of the analyses performed to ensure that the generated time histories meet both Canadian and international acceptance criteria.

2 INTRODUCTION

Three design ground response spectra are defined for the seismic design of the ACR-10001 standard plant, Figure 1. Two design ground response spectra are based on the Canadian Standard CSA/CAN3-N289.3. These are the CSA-based design ground response spectra for rock and soil sites. The CSA-based rock and soil design spectra are based on the traditional Newmark spectrum, with the rock spectrum being richer in high frequency content. The third design ground response spectrum is based on a typical response spectrum developed for ENA rock sites, (Atkinson and Elgohary 2007), and is labeled the ‘ENA-based spectrum.’

To complement two sets of ground time-histories that are compatible with the CSA-based rock and soil spectra, an additional set of ground time histories that is compatible with the ENA-based spectrum is needed. Three groups of time histories were developed using different techniques, and are termed: the tightly-matched set, the seismologically-simulated set, and the lightly-modified set. The methodology used for developing the tightly-matched set was the spectral-matching technique (McGuire et al. 2001) that modifies the response spectrum of a candidate recorded time-history to closely match that of a target response spectrum. The stochastic finite fault simulation algorithm of Motazedian and Atkinson (2005) was used in developing the seismologically-simulated set. The approach makes use of a seismological model of the source, path and site parameters for Eastern Canada that have been calibrated using recordings from past large earthquakes and seismographic recordings of small-to-moderate quakes. The lightly-modified set comprises a group of multiple time-history sets that are developed using a frequency-dependent scaling

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1 ACR-1000 is a trade-mark of Atomic Energy of Canada Limited (AECL).
procedure to match the target response spectrum on average. The frequency-dependent scaling factors are computed as the ratio of the target spectral ordinate to the spectral ordinate of a polynomial fitted to the average of the various time-history spectra. In contrast with the tightly-modified set, each time-history maintains its characteristic peaks and troughs, but put together, matches the target spectrum on average.

The tightly-matched set was chosen to be used as the ENA spectrum-compatible design ground time-history.

![Graph showing design ground response spectra](image)

**Figure 1.** ACR-1000 Design Ground Response Spectra

### 3 REGULATORY ACCEPTANCE CRITERIA

Figure 2 shows the horizontal and vertical ENA-based design ground response spectra. The vertical spectrum is obtained by applying a frequency-dependent factor that is representative of ENA ground motions to the horizontal spectrum. The factor ranges from 1.0 (frequencies ≤ 0.25 Hz) to 0.71 (frequencies ≥ 10 Hz), (Siddiqqi and Atkinson 2002).

![Graph showing horizontal and vertical ENA-based response spectra](image)

**Figure 2.** Horizontal and Vertical ENA-based Design Ground Response Spectra

To be acceptable, the developed time-histories must meet the time-history acceptability requirements of Canadian and international regulatory bodies. In this case, the requirements of the US Nuclear Regulatory Commission Standard Review Plan (USNRC 2007) are chosen as representative of international requirements. Table 1 presents a list of both the CSA and USNRC requirements.

**Table 1.** CSA and USNRC Time-History Requirements
One three-component modified record set, or an artificial record set could be used.

To meet spectrum enveloping requirements, no more than 6% of the total number of points used to generate the spectrum, shall fall below the target design spectrum, and by not more than 10%.

The duration of the time-history shall be a minimum of 15 seconds.

The three-component time-histories must be statistically independent.

Either one three-component record set or multiple sets of three-component records (≥ 4) could be used. For linear analysis, the time-histories should be artificial or based on recorded seed motions. For nonlinear analysis multiple sets of real records should be used.

Two approaches are provided to assess spectrum enveloping requirements:

**Approach 1:** The aim is to envelope the target response spectrum over the frequency range of interest. Specifically, no more than 5 points among those listed in Table 2 shall fall below the target design spectrum, and by not more than 10%.

**Approach 2:** The aim is to achieve an approximate mean-based fit to the target response spectrum. Specifically, the average of the computed to target spectral ordinate ratio over the frequency range of interest should be slightly greater than 1. The computed spectrum should also not fall below 10% of the target spectrum. The minimum recommended frequency set is 100 frequency points per frequency decade.

For any 3-component set of records, the strong motion duration (given by 5%-75% Arias Intensity), and the ratios $\frac{PGV}{PGA}$ and $\frac{(PGA \cdot PGD)}{PGV^2}$ must meet the magnitude-distance bin requirements specified in NUREG/CR-6728 (Mcquire et al. 2001). The uniformity of growth of the Arias Intensity curves is also reviewed.

Any three-component set of records must be statistically-independent, i.e., the correlation coefficient between time-histories should be less than 0.16.

Records must be shown to have sufficient power across the frequency range of interest. This is demonstrated by showing that the averaged (smoothed) time-history power spectral density (PSD) for the duration of strong motion, computed over a frequency bandwidth of ±20% centred on a particular frequency, is not less than 80% of the target PSD over the frequency range of interest. Two methods are provided to check against target PSD functions: one for RG 1.60 spectra (USNRC 1973), and the other for NUREG/CR-6728 spectra.

In lieu of these PSD requirements, the computed response spectra of the developed time history should be shown not to fall below or above the target response spectra by 10% and 30%, respectively.

For multiple time-histories, the average of the different spectra, and the average of the different PSDs should be used in Approach 2 to assess the suitability of the record set.

*(PGA: Peak ground acceleration; PGV: Peak ground velocity; PGD: Peak ground displacement)*
4 TIME-HISTORY DEVELOPMENT

Prior to spectral-matching, a suitable recorded “seed” time-history was chosen. The criteria for the selection were that the time-history should be of adequate duration, and should have sufficient energy in the frequency range of 0.2 – 50 Hz. Records representing a large regional (Magnitude 7, M7) event at approximately 30 – 50 km were judged to be good candidates. This judgment was based on the consideration of typical seismic hazard de-aggregations, and by comparison of predicted ENA-based spectra from ground motion prediction equations for rock sites in ENA (Atkinson and Boore 2006). From the catalogue of records appropriate for rock sites in ENA compiled by McGuire et al. (2002), the three-component M7.6 Chi-Chi Taiwan earthquake accelerogram recorded on rock at Station TCU, 54 km from the fault was selected. A reverse fault mechanism was responsible for the Chi-Chi earthquake, which is appropriate, since reverse faulting is considered to be the dominant faulting mechanism for the ENA stable continental interior.

The spectral-matching technique, as applied here, reduces the low-frequency content of the selected record, and boosts the high-frequency content to accommodate expected high frequency contribution from smaller events at closer distances. A key advantage of spectral-matching is that the phase characteristics of the record are not modified, and thus the resulting time-history retains the character of the original earthquake record. The procedure used for each earthquake component is as follows:
   a. Compute Fourier Transform (FFT) and response spectrum of input record.
   b. Compute the ratio of the input response spectrum amplitude to the target spectral amplitude as a function of frequency.
   c. Multiply the input Fourier amplitude spectrum by the computed ratio at each frequency (leaves phase unchanged).
   d. Reverse FFT to get modified time-history.
   e. Repeat steps 1 to 4 till the required match is obtained.
   f. Correct the modified record to remove undesirable low-frequency content.
   g. Scale the time-history by a small amount to offset its spectra just above the target in order to meet spectrum enveloping requirements.

The following points should be noted:
   a. The ENA-based spectrum is not defined below 0.2 Hz, but was arbitrarily extrapolated down to 0.1 Hz; matching was therefore performed in the frequency range of 0.2 – 50 Hz.
   b. The target power spectrum was evaluated using the least-squares minimization procedure of Park (1995). This approach is based on the approximate equality between the response spectrum and the superposition of the extreme responses of a narrowband process whose PSD function is the dirac-delta function. The Levenberg-Marquardt least-squares minimization algorithm was used.
   c. Acausal frequency domain filtering which involves the modification of the Fourier amplitude of the time-history with a high-pass filter was used to correct the time-histories. This method has been noted by NUREG/CR 6728 (McGuire et al. 2001) to be efficient and stable. The correction involves removing low frequency noise that contaminates the time-history and introduces a drift in computed displacements. Because the procedure results in the development of filter transients, a sufficient length of zero-padding at the beginning and end of the time-history was used (Boore 2005).
   d. A factor of 1.04 was used to scale the time-histories as mentioned in (g) above.

5 TIME-HISTORY ASSESSMENT

The time-histories compatible with the ENA-based ground response spectra are assessed to check their acceptability with the Canadian and international regulatory requirements.

5.1 Requirements for Response Spectrum

The response spectra of the time-histories are computed to a maximum of 100 Hz based on the frequency increment presented in Table 2. Figure 3 presents a comparison of the time-history response spectrum and that of the target design spectrum for the three components. For the three components, not more than five points can be noted to fall below the target spectrum, thus meeting both the CSA and USNRC Approach 1 spectrum enveloping requirements.
Table 2. Recommended Minimum Frequency Interval for Response Spectrum Computation

<table>
<thead>
<tr>
<th>Frequency range (Hz)</th>
<th>0.1-3.0</th>
<th>3.0-3.6</th>
<th>3.6-5.0</th>
<th>5.0-8.0</th>
<th>8.0-15.0</th>
<th>15.0-18.0</th>
<th>18.0-22.0</th>
<th>&gt;22.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incremental freq. (Hz)</td>
<td>0.10</td>
<td>0.15</td>
<td>0.20</td>
<td>0.25</td>
<td>0.50</td>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Figure 3. Target and Time-History Response Spectra

5.2 Requirements for Power Spectrum Density

Because the ENA-based spectrum is similar to recommended NUREG/CR-6728 spectra, the USNRC PSD assessment approach for NUREG/CR-6728 spectra was used. In accordance with the approach, the PSD of the records are computed using the strong motion portion of the record as the ±20% smoothed PSD. Figure 4 presents a comparison between the PSD of three records and that of the target ENA-based spectrum computed as explained in Section 3. The PSD of the three time-histories envelope the target PSD between the frequencies of 0.2 - 60 Hz, and meet the requirement of enveloping 80% of the target over the frequency range of interest. In addition, it is noted that the response spectra of the three records do not fall below the target spectrum by 10% or above the target spectrum by 30%, respectively.
5.3 Requirements for Ground Motion Characteristics

Table 3 gives a summary of the different ground motion characteristics. The strong motion duration of the three records are greater than 6 seconds and satisfy duration criteria presented in NUREG/CR 6728. The total duration is also greater than 15 seconds, thus satisfying the CSA requirement. In addition, the \( \frac{PGV}{PGA} \) and \( \frac{PGA \cdot PGD}{PGV^2} \) ratios of the individual records fall within the recommended magnitude-distance bin ratios given in NUREG/CR 6728. As shown in Figure 5, the growth of the Arias Intensity curve for all three time-histories is also satisfactory.

Table 3. Summary of Time-History Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Strong Motion Duration</th>
<th>PGA (g)</th>
<th>PGV (cm/sec)</th>
<th>PGD (cm)</th>
<th>( \frac{PGV}{PGA} ) (cm/sec)/g</th>
<th>( \frac{PGA \cdot PGD}{PGV^2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal (H1)</td>
<td>15.18</td>
<td>0.43</td>
<td>15.67</td>
<td>7.22</td>
<td>36.74</td>
<td>12.30</td>
</tr>
<tr>
<td>Horizontal (H2)</td>
<td>13.93</td>
<td>0.48</td>
<td>15.18</td>
<td>6.46</td>
<td>31.63</td>
<td>13.20</td>
</tr>
<tr>
<td>Vertical (V)</td>
<td>13.50</td>
<td>0.30</td>
<td>15.96</td>
<td>5.91</td>
<td>52.70</td>
<td>6.90</td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td>H1 &amp; H2: 3.13E-04</td>
<td>H1 &amp; V: -5.60E-02</td>
<td>H2 &amp; V: 8.07E-03</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 5. Time-History Arias Intensity Curves

5.4 Requirements for Time-History Records

The final corrected acceleration, velocity and displacement time-histories are presented in Figure 6. A 2nd order Butterworth filter with a corner frequency of 0.1 Hz was used to correct all three time-histories.

Figure 6. Acceleration, Velocity & Displacement Time-Histories: a) Horizontal Component (H1); b) Horizontal Component (H2); c) Vertical Component (V)

6 CONCLUSIONS

This paper focussed on the development of a single three-component time-history set compatible with the ENA-based design ground response spectrum. The Chi-Chi TCU Station record was selected as a suitable seed record, and the spectral-matching technique was used to modify the time-history spectrum to match that of the target. The time-histories were shown to meet both Canadian and US requirements, and are used in combination with the CSA-based design ground response spectra compatible time-histories in the seismic analysis and design of the ACR-1000 standard plant.
REFERENCES


