RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

APR1400 Design Certification

Korea Electric Power Corporation / Korea Hydro & Nuclear Power Co., LTD

Docket No. 52-046

RAI No.:	**182-8160**
SRP Section:	**03.07.01 – Seismic Design Parameters**
Application Section:	**3.7.1**
Date of RAI Issue:	**08/31/2015**

Question No. 03.07.01-3

10 CFR 50 Appendix S requires that the safety functions of structures, systems, and components (SSCs) must be assured during and after the vibratory ground motion associated with the safe shutdown earthquake (SSE) ground motion through design, testing, or qualification methods. In accordance with 10 CFR 50 Appendix S, the staff reviewed the adequacy of the method to estimate the power spectral density (PSD) functions for the acceleration time histories for the certified seismic design response spectra (CSDRS) and the hard rock high frequency (HRHF) response spectra (RS). In order for the staff to understand whether the PSD functions were estimated using a method consistent with the guidance of SRP Appendices A and B, the applicant is requested to provide the following additional information.

a) Explain the method used to estimate PSD for the CSDRS time histories

In DCD Section 3.7.1.1.2, the PSDs of the design acceleration time histories are compared to the corresponding target PSD. However, the method to estimate the PSD from an acceleration time history is not provided. Therefore, the applicant is requested to provide a description of the method for the PSD estimation and justify any difference of the method as compared to the guidance provided in SRP 3.7.1. The provided information should include the definition of the strong motion duration, portion of the time history used to compute the Fourier spectra, PSD smoothing, and any normalization parameters used in Fourier transform and PSD calculation.

b) Justification of the method used to estimate PSD for the HRHF time histories

Section 3.5.3 of APR1400-E-S-NR-14004-P, Rev. 1, “Evaluation of Effects of HRHF Response Spectra on SSCs,” describes the method used to calculate the PSD function from an acceleration time history. It utilizes an “equivalent stationary strong-motion duration” as the strong motion duration. The equivalent stationary strong motion is defined as the time for a P1-to-P2 rise of the cumulative Arias intensity, divided by (P2-P1). The applicant stated, “the equivalent stationary duration Tis for the entire time histories as determined from Eq. (3-3) is the duration over which the total energy of the time history is built up from 0 to 100 percent with the constant slope S." In this statement, the parameters P1, P2, and S are not defined. As such, the applicant is requested to provide these three parameters for the three HRHF acceleration time histories. In addition, it appears that the PSD estimate is very sensitive to the choice of P1 and P2; for example a P1=0 and P2=100% will lead to an equivalent stationary strong-motion duration Ts equal to the total duration of the time history. As such, the applicant is also requested to provide a justification for the values of P1 and P2.

Eq. (3-4) is described in Section 3.5.3 as the one-sided PSD, but it appears to be the two-sided PSD formula. Please confirm the validity of Eq. (3-4) and explain how this equation is implemented in the development of target PSDs and in estimating the PSD function for each time history (i.e., one-sided vs two-sided).

Eq. (3-5), the amplitude of the Fourier spectrum, is provided in terms of continuous time *t* and the integration is performed over the entire time history. Please provide the corresponding equation for the discrete Fourier transform implemented for the APR1400.

Appendices A and B of SRP 3.7.1 indicate that PSD should be estimated based on the strong motion duration. Therefore, the staff requests that the applicant provide a justification for the use of equivalent stationary strong-motion duration. Similarly, the applicant is requested to explain why the entire time histories were used in the Fourier transform. The use of the equivalent stationary strong-motion duration, which is shorter than the entire duration as shown in Figure 3-27 of APR1400-E-S-NR-14004-P, Rev. 1, together with the entire time history used in the Fourier transform, may overestimate the PSD for those frequencies that have very low magnitude but span the entire time history

Response

(a) The method for computing the PSD of an acceleration time history is in accordance with the guidance in SRP 3.7.1, Revision 4, supplemented with the additional guidance provided in NUREG/CR-5347, Appendix A (January 1989), Page A-5. The summary for computing the PSD of an acceleration time history is described below.

The one-sided PSD, $s_i(f)$ of time history $a_i(f)$ using following equation.

$$S_i\,(f) = \frac{2|A_i\,(f)|^2}{T_S^i} \quad (1)$$

where $|A_i\,(f)|$ is the amplitude of the Fourier spectrum obtained from the following equation:

$$A_i\,(f) = \int_0^{T_i} a_i\,(t)e^{-i2\pi f t}\,dt \quad (2)$$

where T_i is the total duration of the time history $a_i(t)$.

Equation (2) is a symbolic mathematical equation. In actual numerical calculation, the discrete Fourier spectrum is computed using the Fast Fourier Transform algorithm.

The one-sided PSD $S_i\,(f)$ as given by Equation (1) is in the PSD unit of (in^2/sec^4/Hz) and the frequency unit of f associated with Equation (1) is cycle/second (Hz).

If, in Equation (1), the PSD $S_i\,(f)$ is to be computed in the PSD unit of ($in^2/sec^4/rps$), where the frequency unit is in radian/second (rps), then Equation (1) should be replaced by the following equation:

$$S_i\,(f) = \frac{2|A_i\,(f)|^2}{2\pi\,T_S^i} \quad (1a)$$

When PSD is computed using Equation (1a), the frequency unit must be in rps (radian/sec), which is commonly expressed using the frequency symbol ω. Using the symbol ω with the frequency unit of rps, Equation (1a) would be more appropriately expressed as follows:

$$S_i\,(\omega) = \frac{2|A_i\,(\omega)|^2}{2\pi\,T_S^i} \quad (1a)$$

and Equation (2) would be more appropriately expressed as:

$$A_i\,(\omega) = \int_0^{T_i} a_i\,(t) e^{-i\omega t}\,dt \quad (2a)$$

The difference of Equation (1) and Equation (1a) is discussed in NUREG/CR-5347, Appendix A (January 1989), Page A-5.

The discrete form of the mathematical Equation (2a) is computed using the following discrete equation:

$$|A_i(\omega_n)| = \Delta t \left| \sum_{j=0}^{N-1} a_i\,(t_j) e^{-2\pi i (nj/N)} \right| \quad (2b)$$

where $\omega_n = n\Delta\omega = 2\pi n\Delta f = \frac{2\pi n}{(N\Delta t)}; n = 0, 1, \ldots, N/2$ and $t_j = j\Delta t, j = 0, 1, \ldots, N-1$.

The time history PSD $S_i\,(f)$ computed using Equation (1) or (1a) is smoothed using the moving average technique over a ±20 percent frequency bandwidth centered at the frequency f in accordance with the guidelines in SRP 3.7.1, Revision 4, which refers to NUREG/CR-5347, Appendix A (January 1989).

The definition of strong motion duration is described below.

The full time histories are the time histories of full duration from 0 to 20.48 seconds. The truncated time histories are the time histories truncated from the time $T_{5\%}$ to the time $T_{75\%}$ of the Arias Intensity plots. Using these definitions, the 5% to 75% truncated equivalent stationary duration designated as $T_{(75\%-5\%)}$ is computed as $T_{(75\%-5\%)} = T_{75\%} - T_{5\%}$. Similarly, the 0% to 100% extended equivalent stationary duration designated as $T_{(100\%-0\%)}$ is computed as $T_{(100\%-0\%)} = T_{100\%} - T_{0\%} = (T_{75\%} - T_{5\%})/ (75\%-5\%) = T_{(75\%-5\%)}/0.7$. The time histories, the Fourier amplitudes, PSD and smoothed PSD for time histories of full duration and truncated time histories are shown in Figures 1 through 18, respectively. The comparisons of PSDs for CSDRS compatible time histories between full duration and truncated duration are shown in Figures 19 through 21.

The results that the time-history PSDs computed using the full-duration time histories and the corresponding 0% to 100% extended equivalent stationary duration $T_{(100\%-0\%)}$

are very consistent and comparable with the time-history PSDs computed from the 5% to 75% truncated time histories and the corresponding truncated 5% to 75% equivalent stationary duration $T_{(75\%-5\%)}$ for the frequency range from about 2 to 50 Hz. These results validate the procedure of using the full-duration time histories and the corresponding 0% to 100% extended equivalent stationary duration $T_{(100\%-0\%)} = T_{(75\%-5\%)}/0.7$ to compute the time-history PSDs, giving the resulting PSDs so computed being very equivalent and comparable to the time-history PSDs computed using the 5% to 75% truncated time histories and the corresponding truncated 5% to 75% equivalent stationary duration $T_{(75\%-5\%)}$ for the frequency range from 2 to 50 Hz.

For the lower frequency range below about 2 Hz, i.e., for the low frequency range from 0.2 to 2 Hz, the time-history PSDs computed using the full-duration time histories and the 0% to 100% extended equivalent stationary duration $T_{(100\%-0\%)} = T_{(75\%-5\%)}/0.7$ deviate from the time-history PSDs computed using the 5% to 75% truncated time histories and the corresponding 5% to 75% equivalent stationary duration $T_{(75\%-5\%)}$ because the truncation of the full-duration time histories to a shorter-duration time histories affects the long-period (low-frequency) motion contents and amplitudes as indicated by the comparisons of the time-history response spectra for the full-duration and truncated time histories. The longer the truncated time-history duration the lower the validity frequency range of the computed truncated time-history PSDs. As shown in Figures 22 through 24, the response spectra of the truncated time histories fall below the corresponding full-duration time-history response spectra, which also fall below the corresponding target CSDRS in the low frequency range from 0.2 to 2 Hz as also indicated from the comparisons of the computed PSDs in the same low frequency range as shown in Figures 19 through 21.

From the results shown in above, it can be concluded that the use of full-duration time history and the corresponding 0% to 100% extended equivalent stationary duration $T_{(100\%-0\%)} = T_{(75\%-5\%)}/0.7$ to compute the time-history PSD is a convenient and valid procedure to generate the time-history PSDs and the results so obtained are valid for a wider frequency range from the low frequency of 0.2 Hz to the high frequency of 50 Hz.

Additionally, the PSDs for the CSDRS compatible time histories are computed in accordance with Appendix B of SRP 3.7.1, Rev. 4. The strong motion durations for the CSDRS compatible time histories are defined as shown in Figures 25 through 27. Using the truncated time histories and the corresponding the strong motion duration, the PSDs for the CSDRS compatible time histories are computed as shown in Figures 28 through 36. The PSDs for the CSDRS compatible time histories envelop 70% of target PSD as shown in Figures 30, 33, and 36. Therefore the PSDs for the CSDRS compatible time histories satisfy the requirement of Appendix B of SRP 3.7.1, Rev. 4.

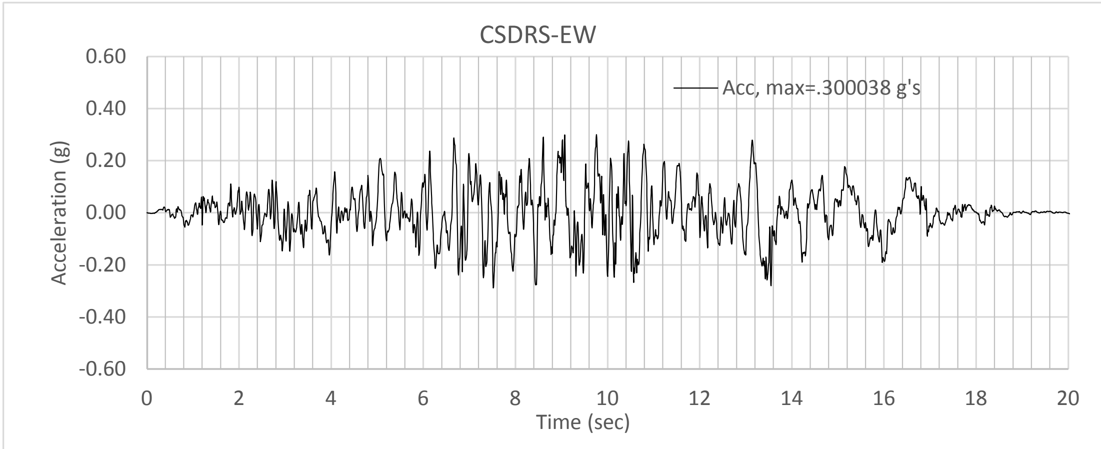

Figure 1 Time History of Full Duration for CSDRS-EW

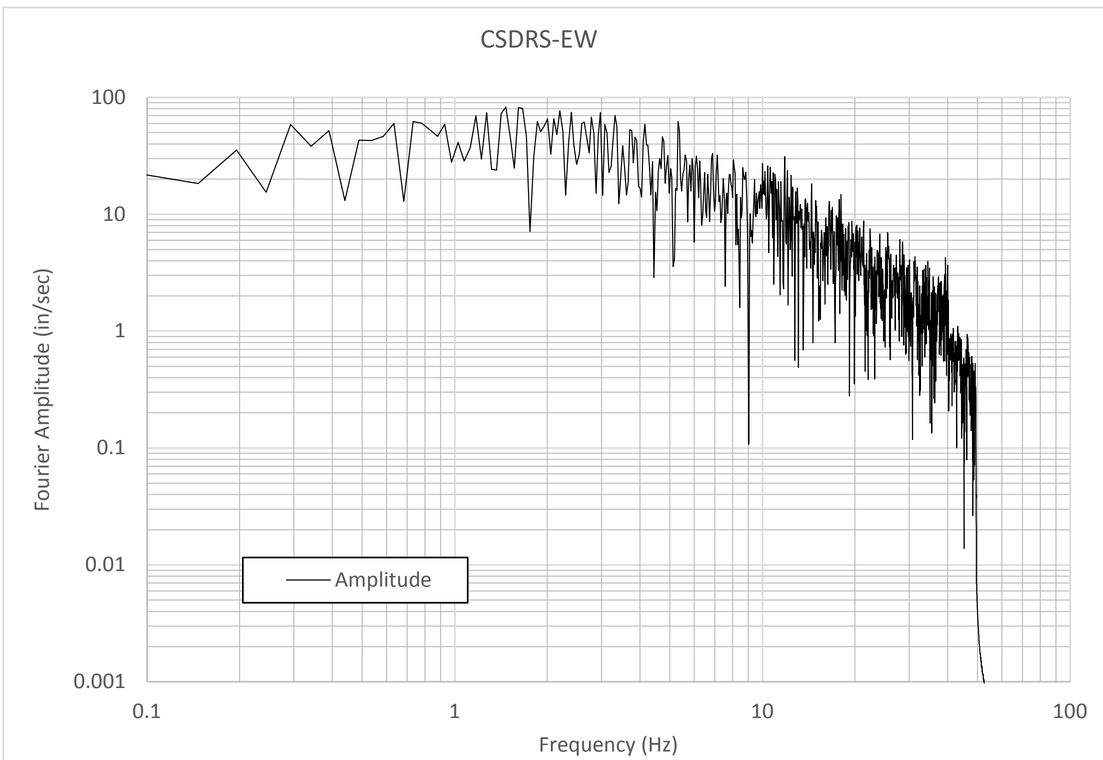

Figure 2 Fourier Amplitudes of Time History of Full Duration for CSDRS-EW

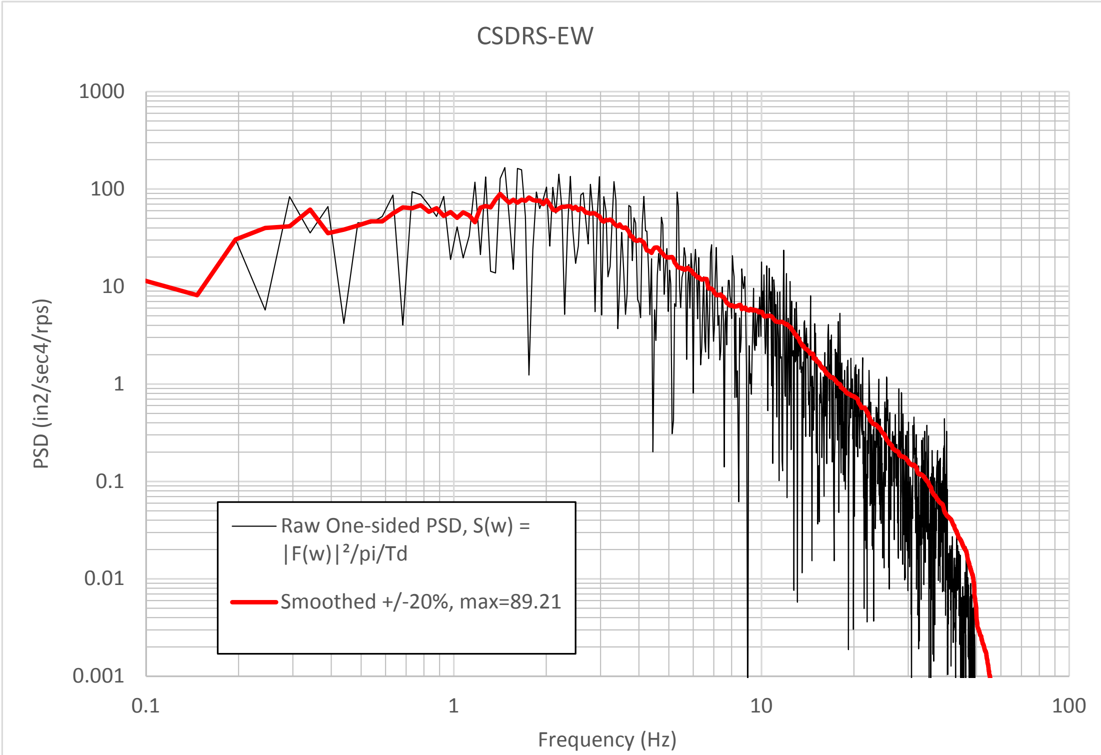

Figure 3 Raw One-sided PSD and Smoothed PSD of Time History of Full Duration for CSDRS-EW

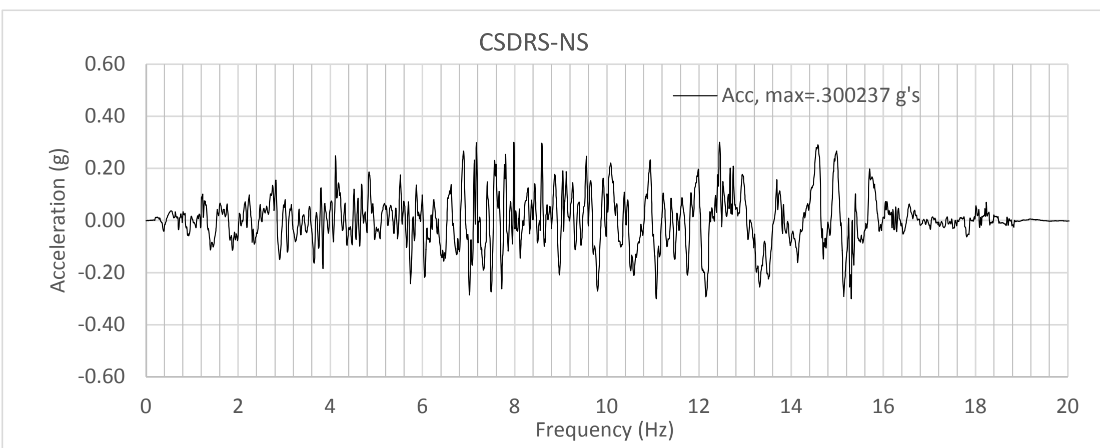

Figure 4 Time History of Full Duration for CSDRS-NS

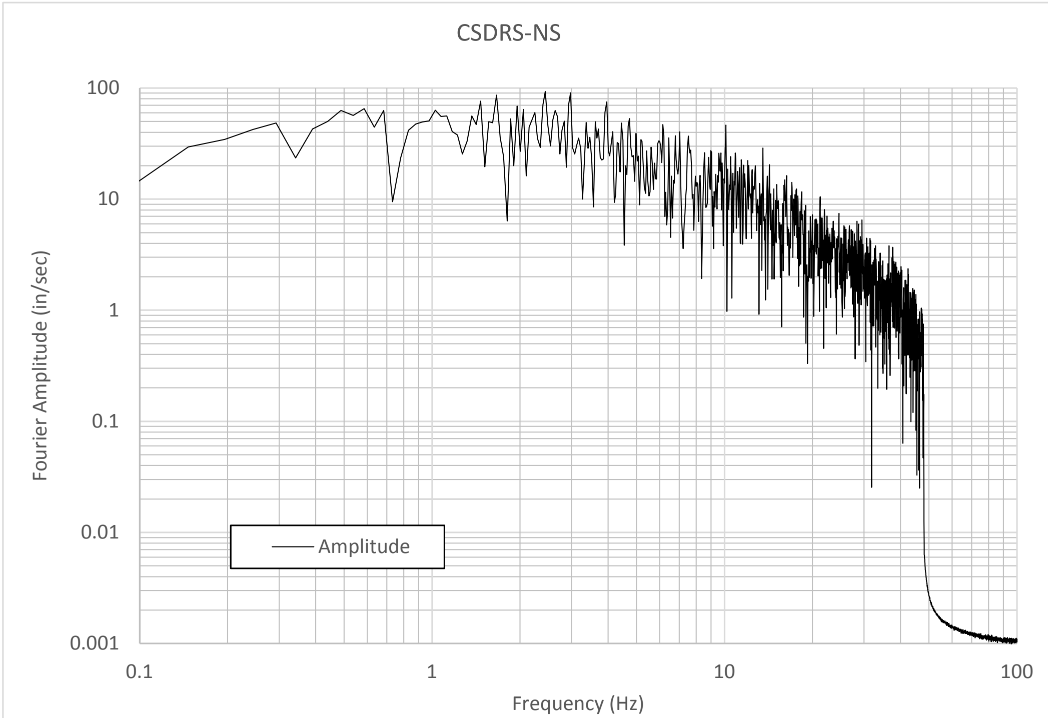

Figure 5 Fourier Amplitudes of Time History of Full Duration for CSDRS-NS

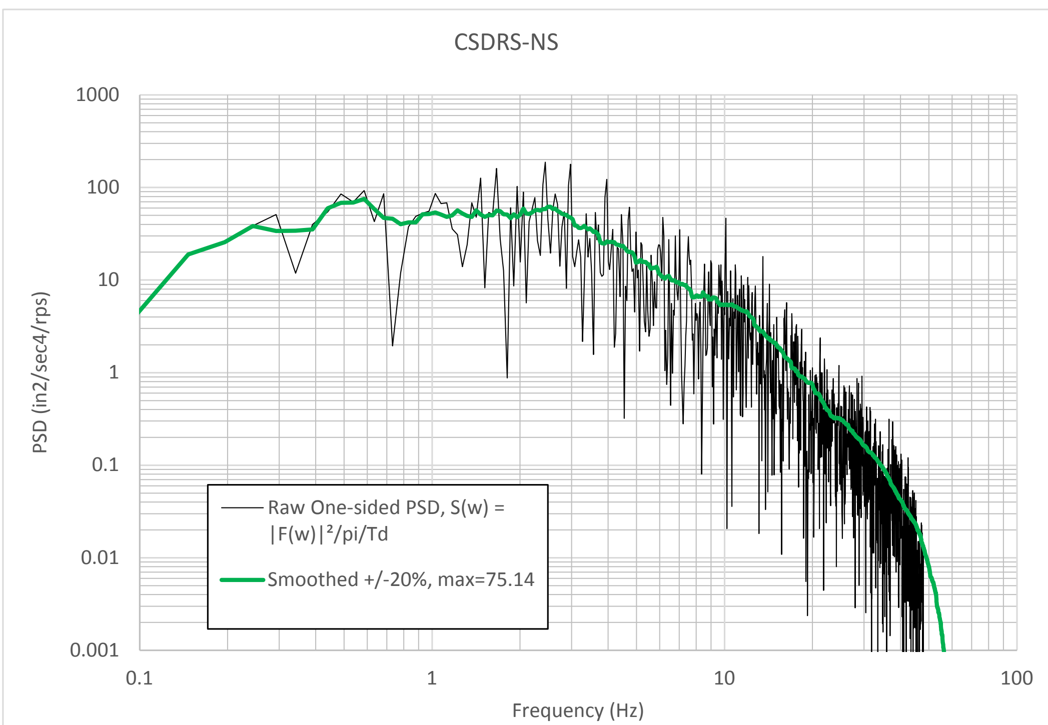

Figure 6 Raw One-sided PSD and Smoothed PSD of Time History of Full Duration for CSDRS-NS

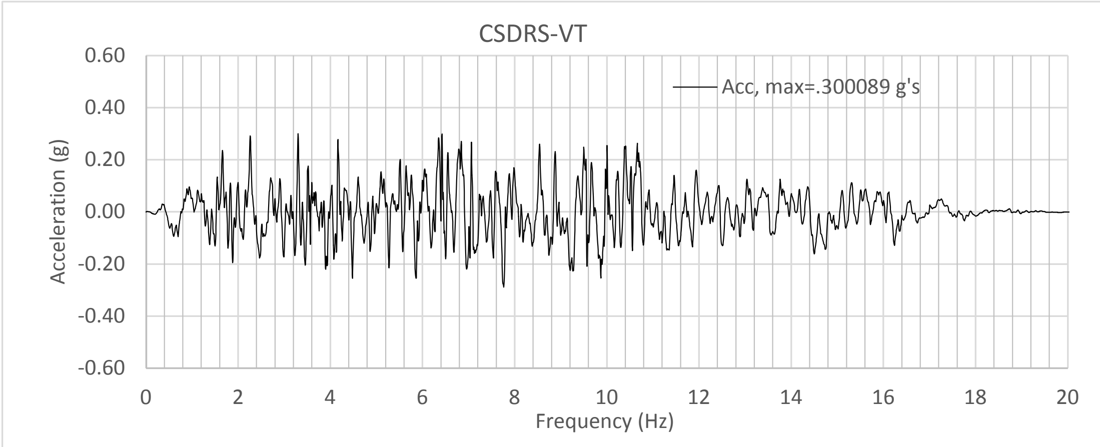

Figure 7 Time History of Full Duration for CSDRS-VT

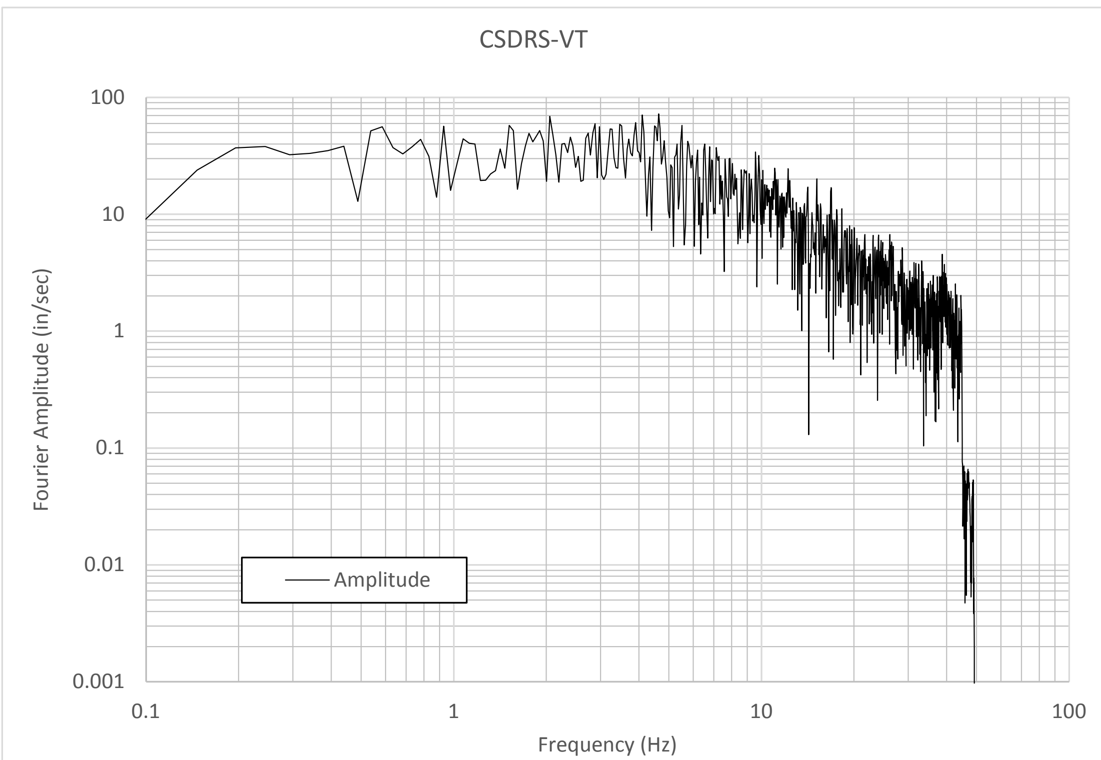

Figure 8 Fourier Amplitudes of Time History of Full Duration for CSDRS-VT

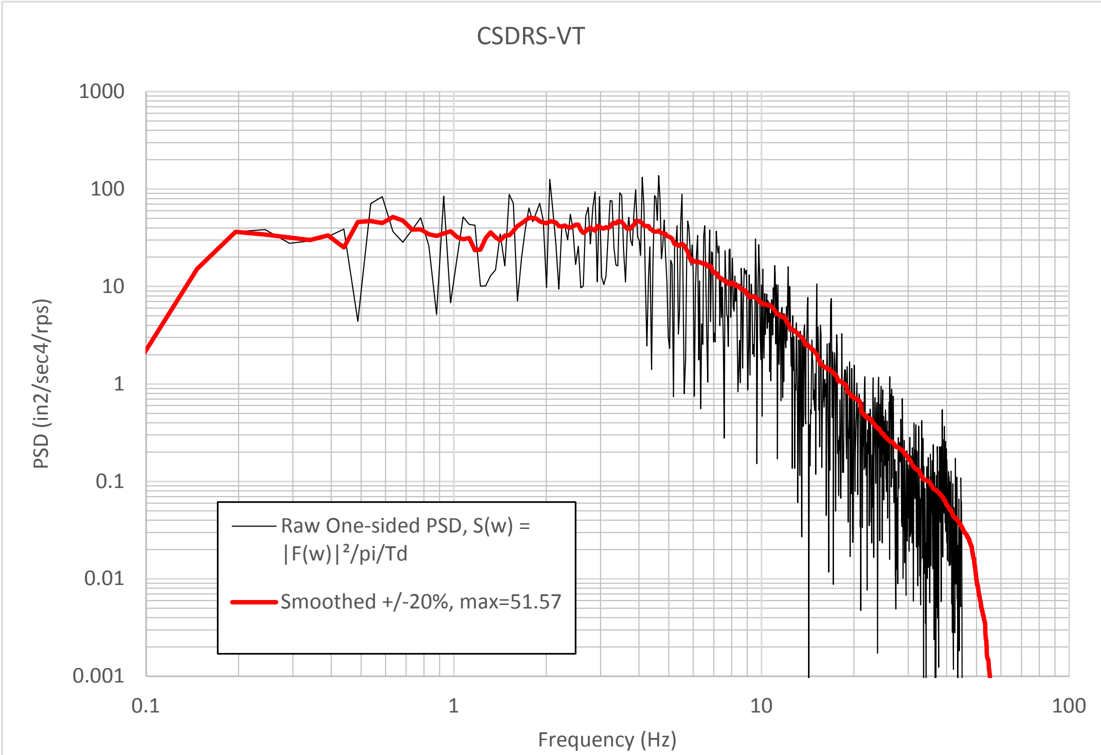

Figure 9 Raw One-sided PSD and Smoothed PSD of Time History of Full Duration for CSDRS-VT

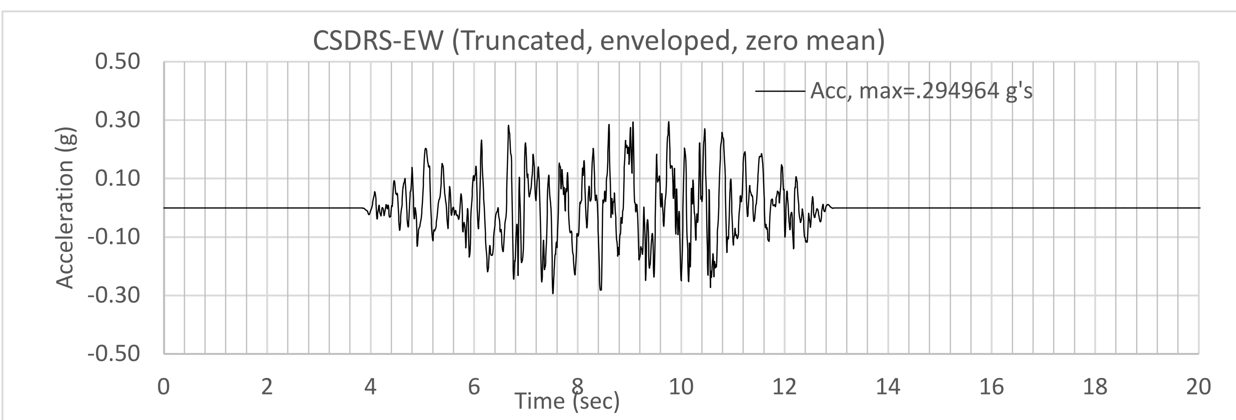

Figure 10 Time History of Truncated Duration for CSDRS-EW

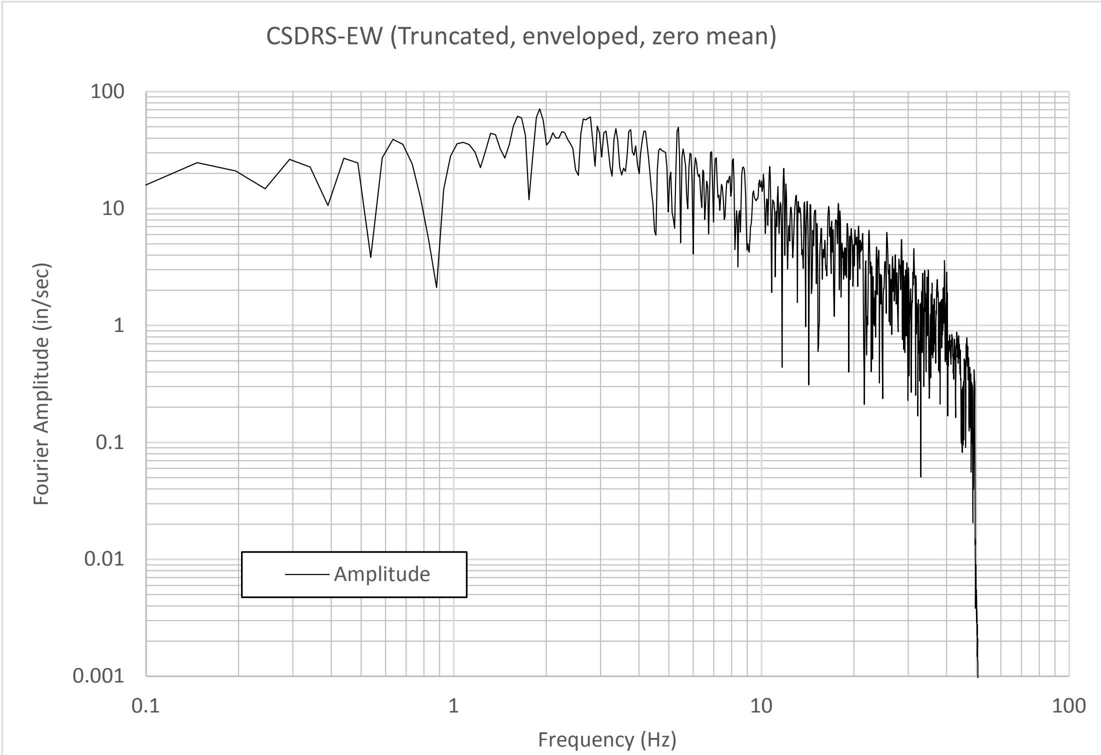

Figure 11 Fourier Amplitudes of Time History of Truncated Duration for CSDRS-EW

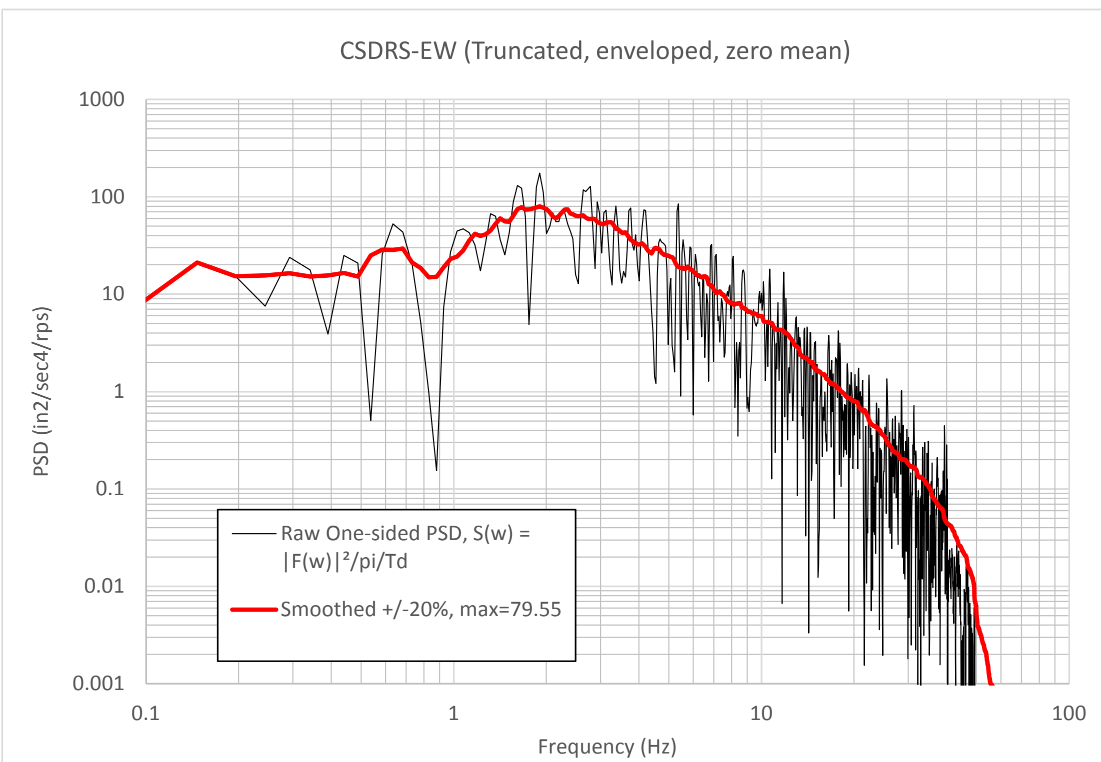

Figure 12 PSD and Smoothed PSD of Time History of Truncated Duration for CSDRS-EW

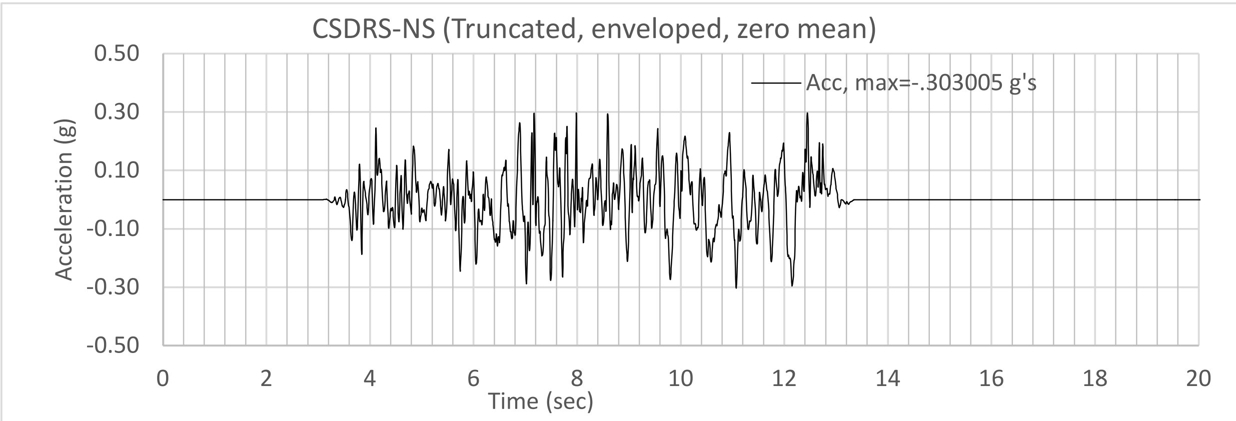

Figure 13 Time History of Truncated Duration for CSDRS-NS

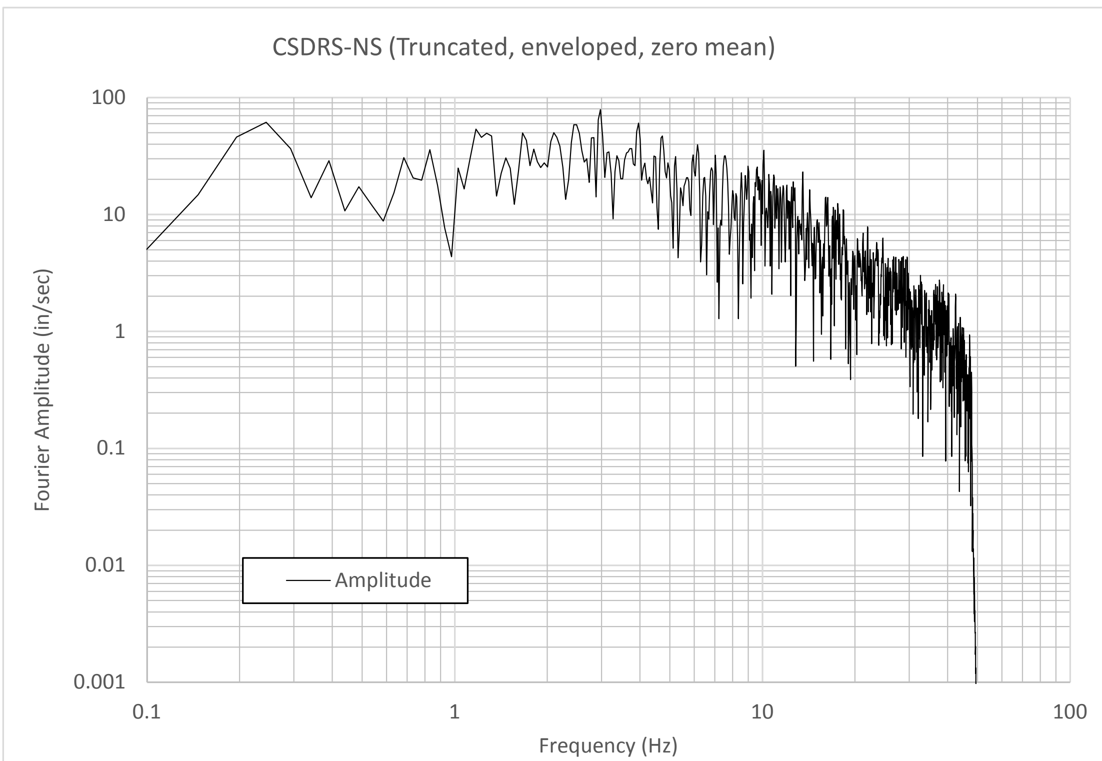

Figure 14 Fourier Amplitudes of Time History of Truncated Duration for CSDRS-NS

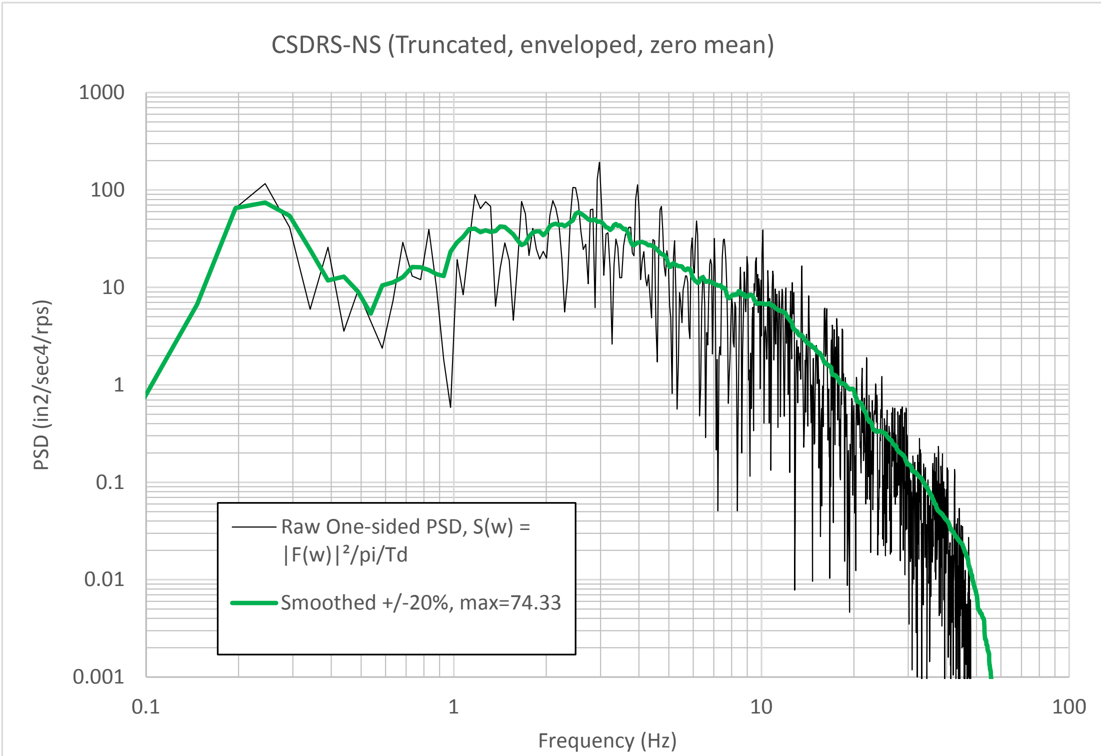

Figure 15 PSD and Smoothed PSD of Time History of Truncated Duration for CSDRS-NS

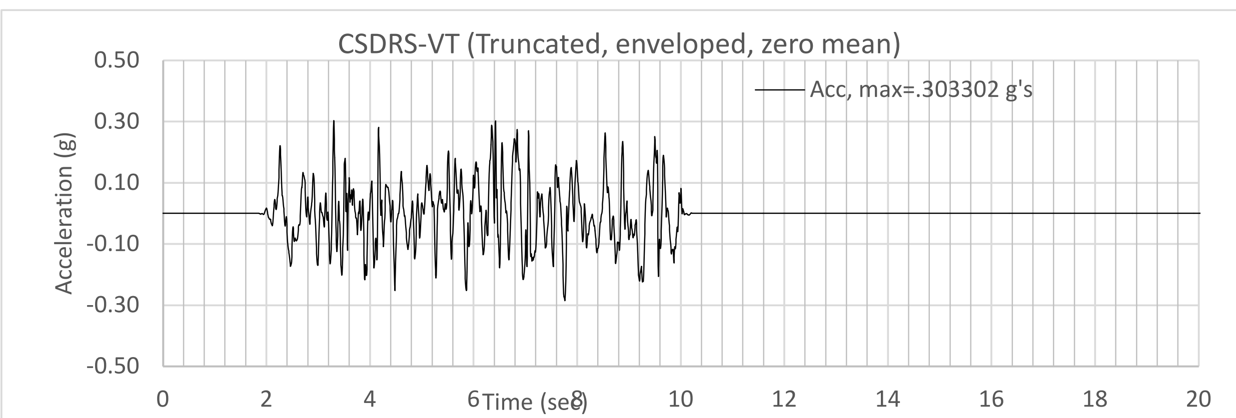

Figure 16 Time History of Truncated Duration for CSDRS-VT

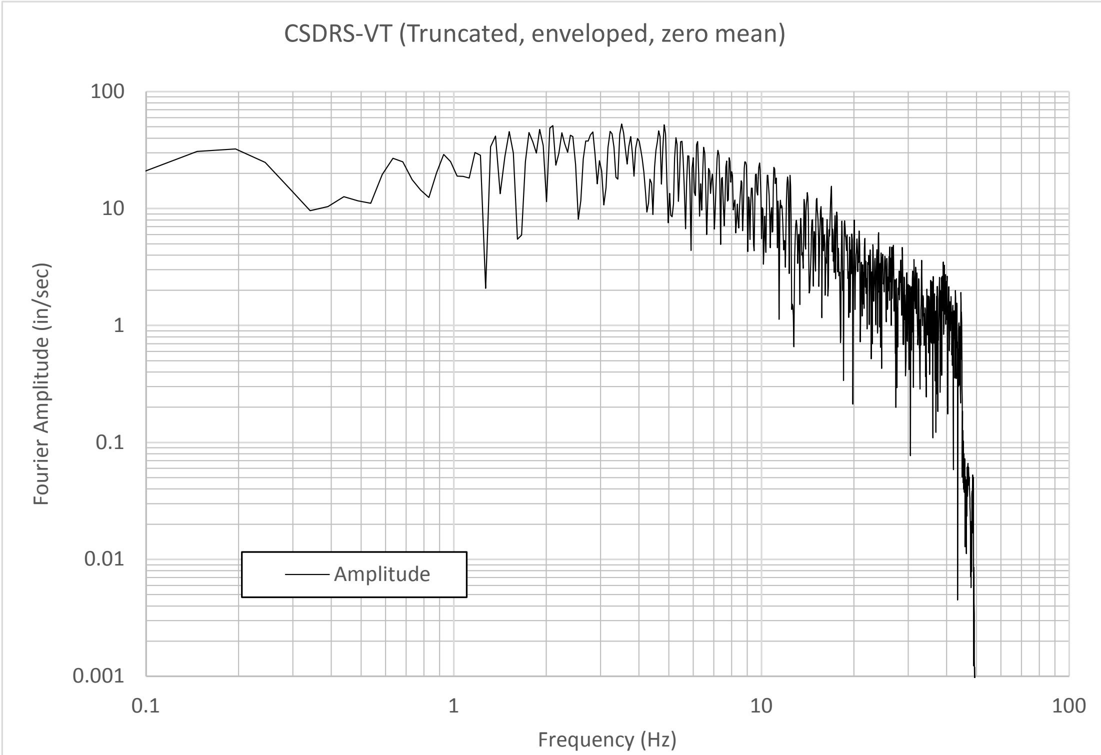

Figure 17 Fourier Amplitudes of Time History of Truncated Duration for CSDRS-VT

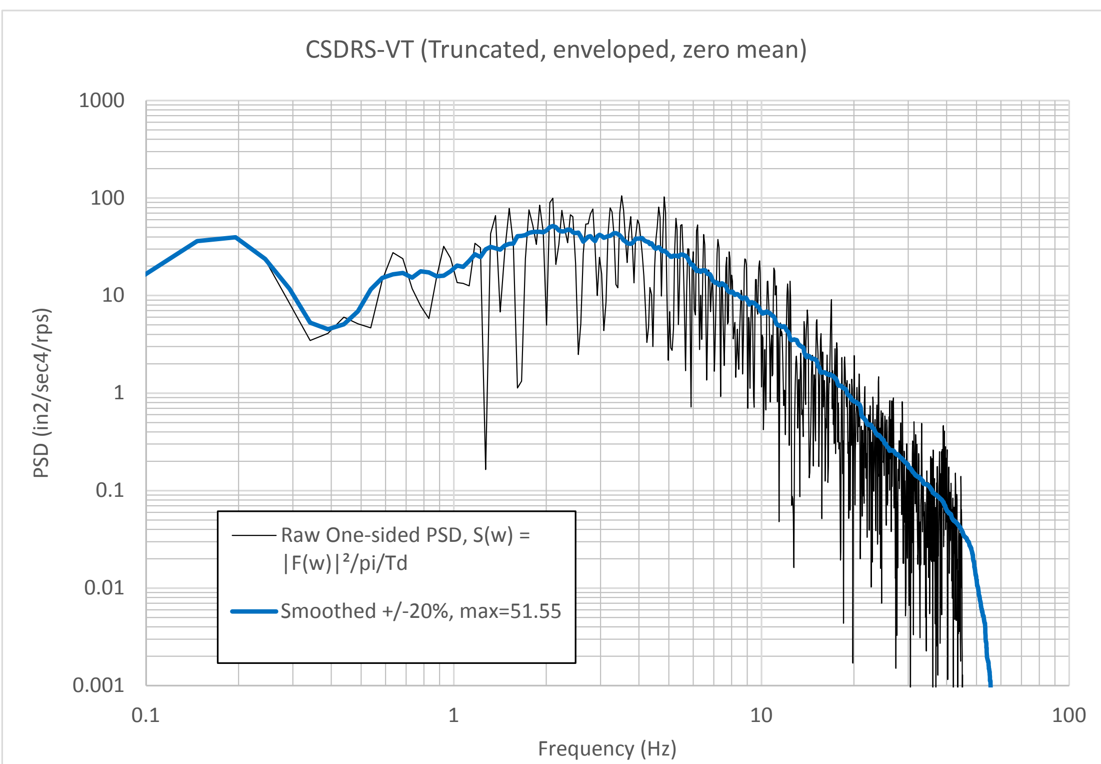

Figure 18 PSD and Smoothed PSD of Time History of Truncated Duration for CSDRS-VT

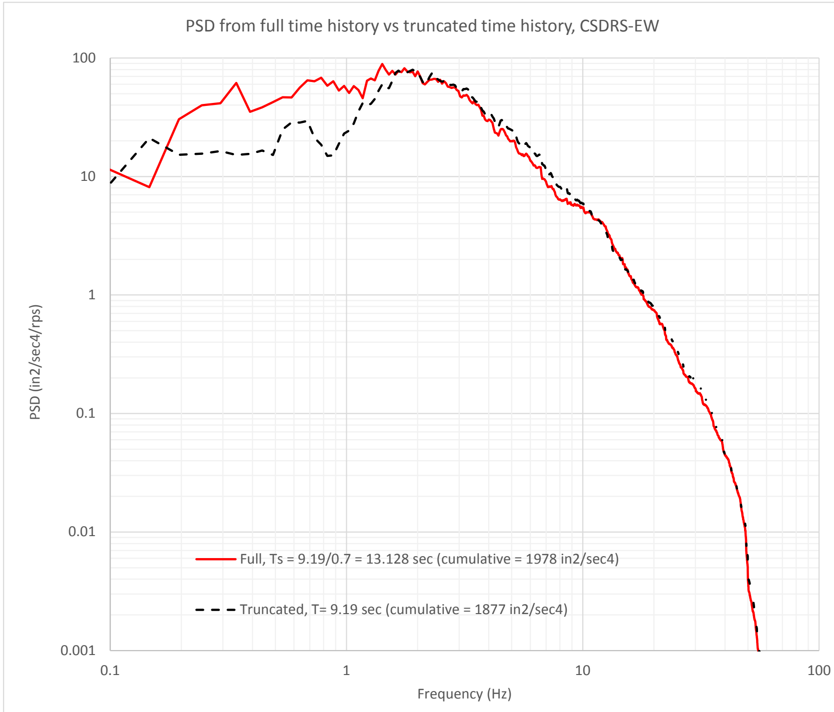

Figure 19 Comparison of PSD between Full Duration and Truncated Duration for CSDRS-EW Compatible Time History

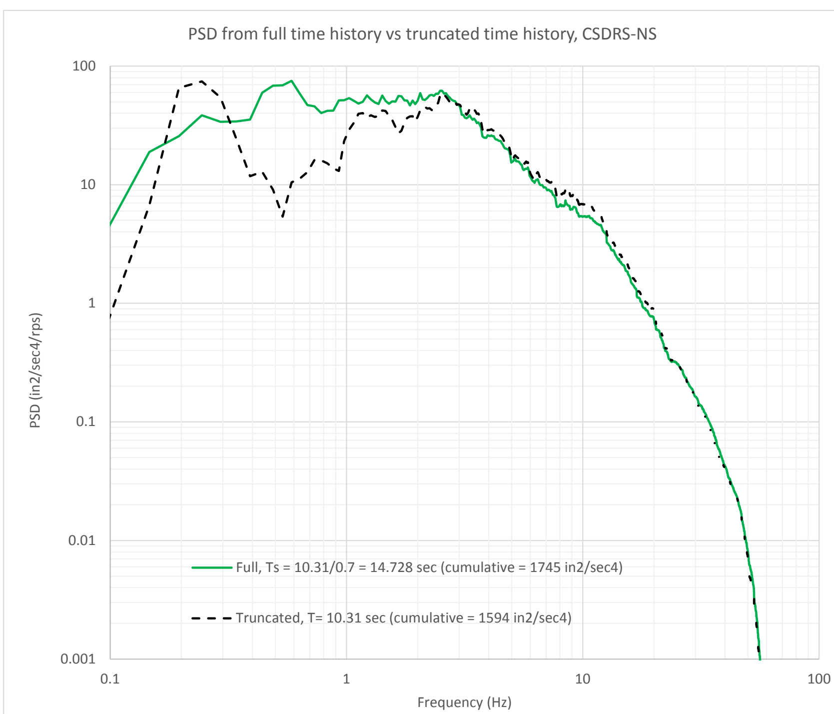

Figure 20 Comparison of PSD between Full Duration and Truncated Duration for CSDRS-NS Compatible Time History

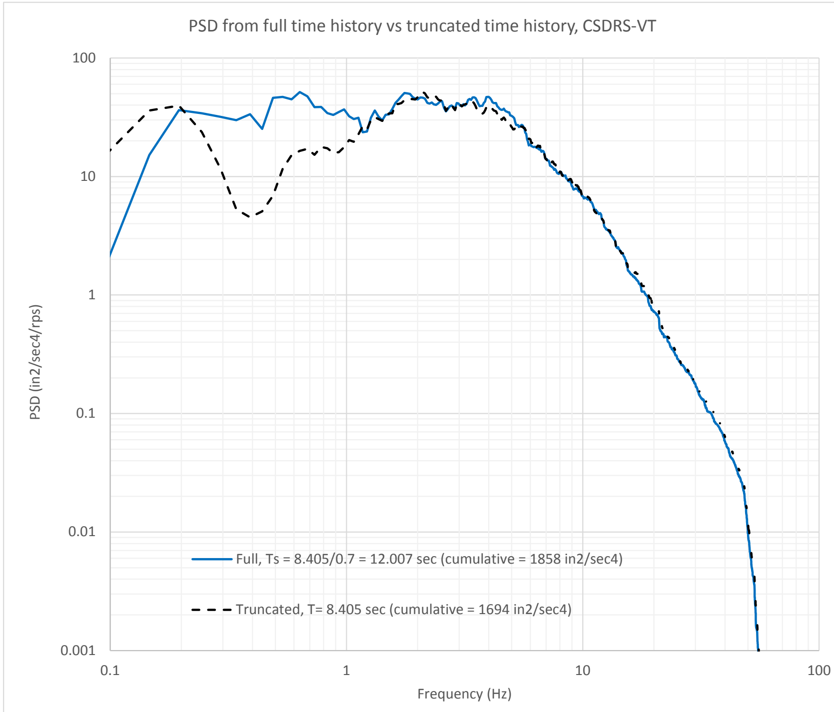

Figure 21 Comparison of PSD between Full Duration and Truncated Duration for CSDRS-VT Compatible Time History

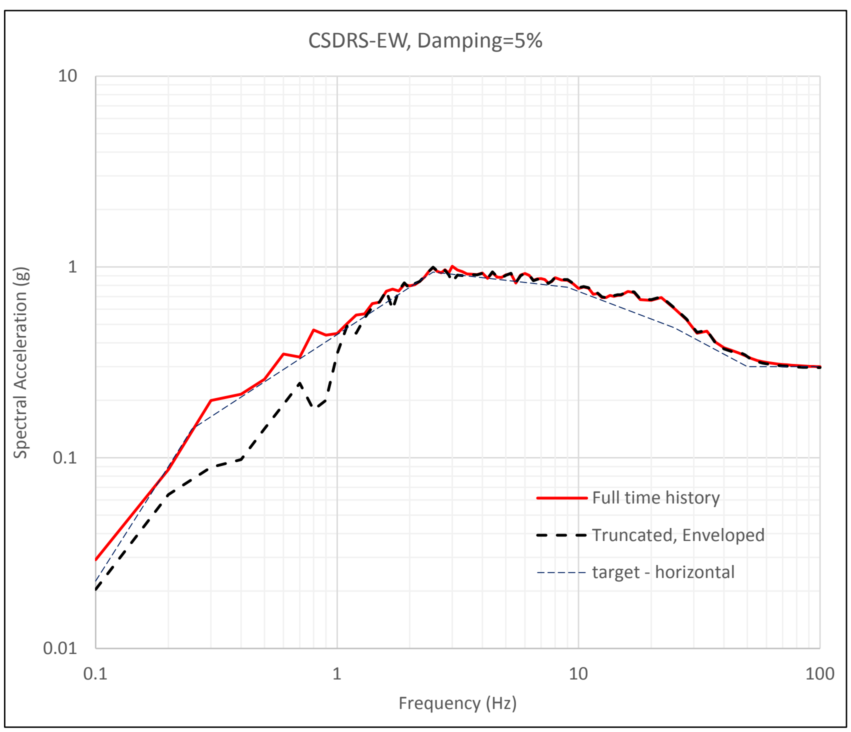

Figure 22 Comparison of Response Spectrum between Full Duration and Truncated Duration for CSDRS-EW Compatible Time History

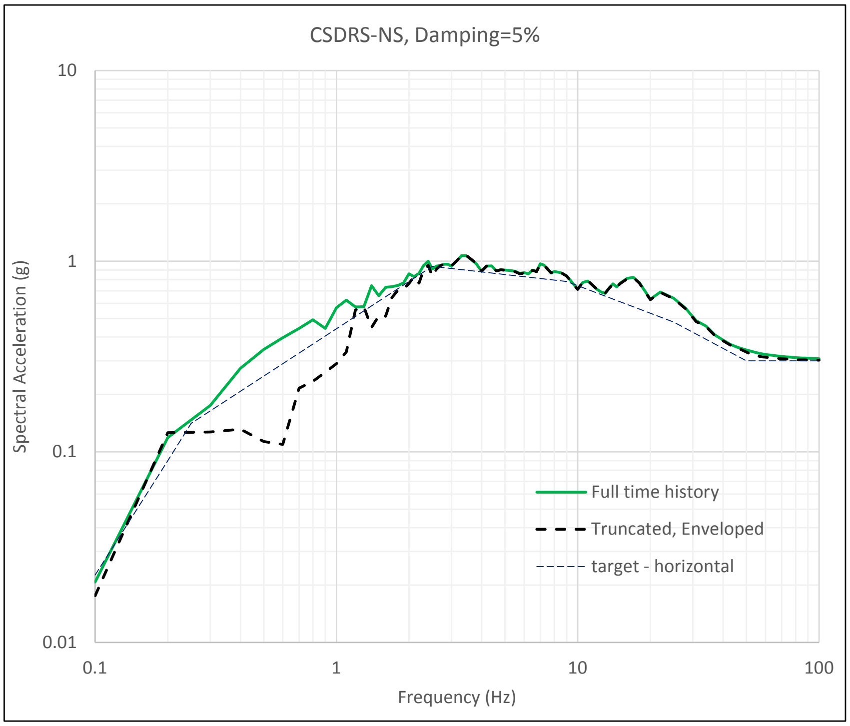

Figure 23 Comparison of Response Spectrum between Full Duration and Truncated Duration for CSDRS-NS Compatible Time History

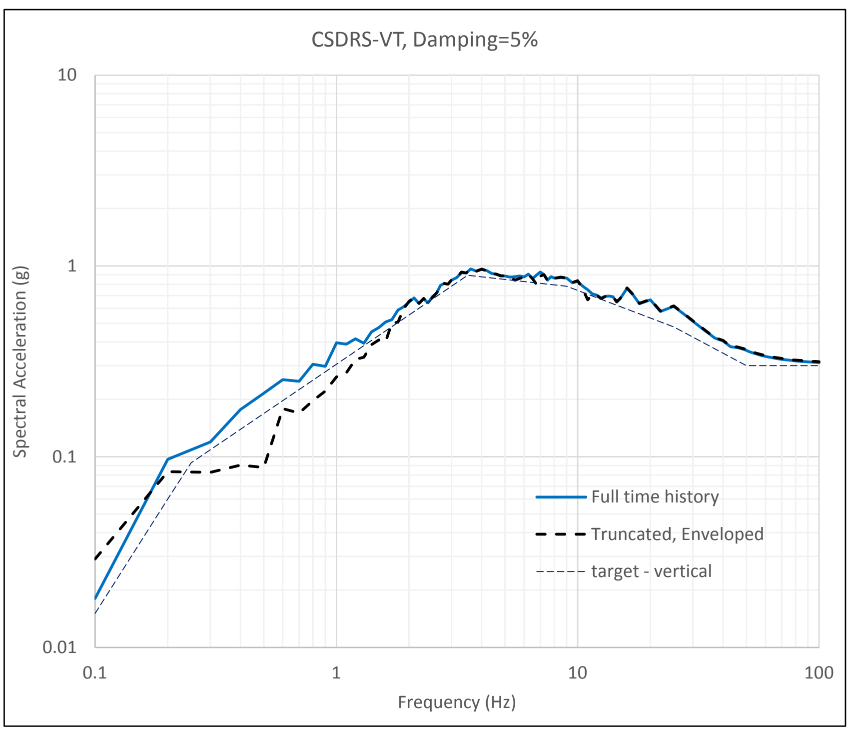

Figure 24 Comparison of Response Spectrum between Full Duration and Truncated Duration for CSDRS-VT Compatible Time History

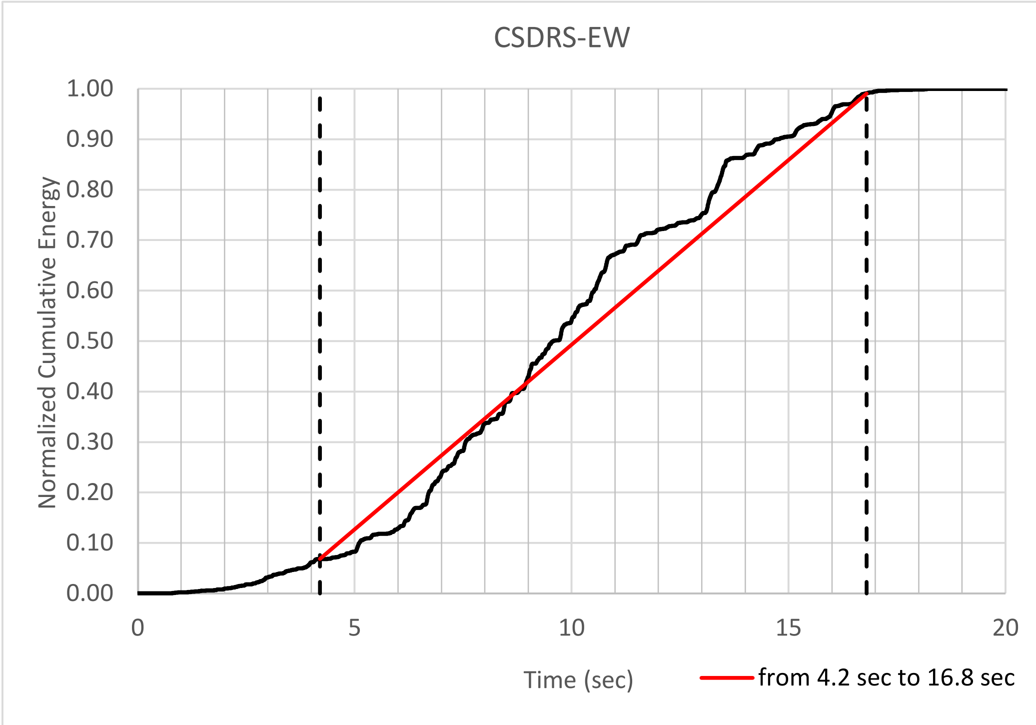

Figure 25 Cumulative Energy (Arias Intensity) Time History for CSDRS-EW

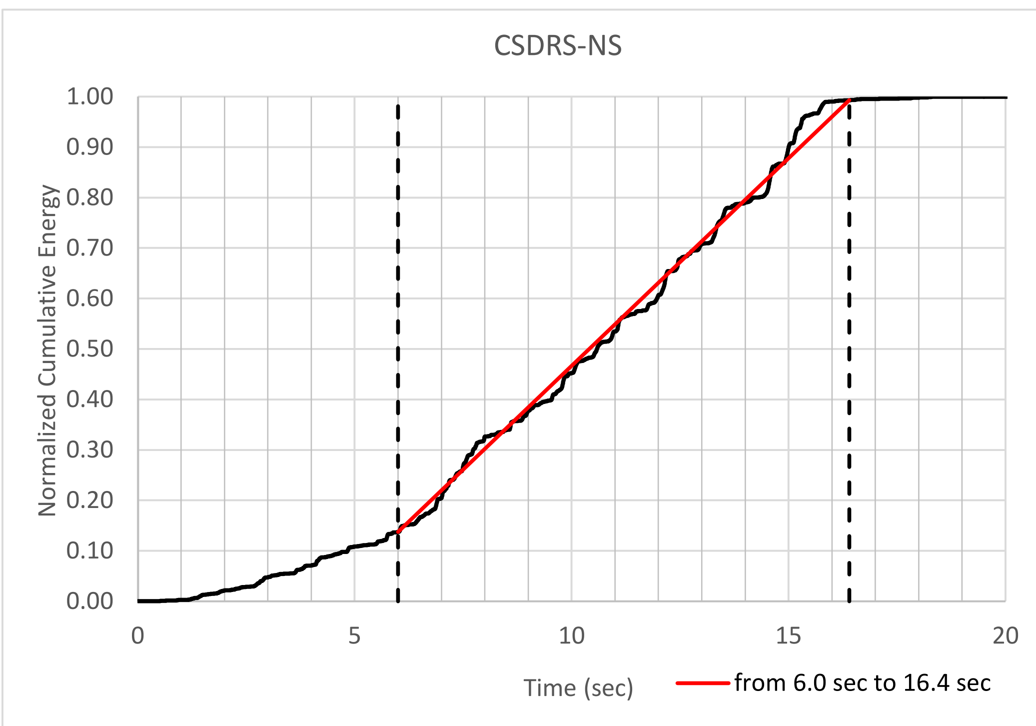

Figure 26 Cumulative Energy (Arias Intensity) Time History for CSDRS-NS

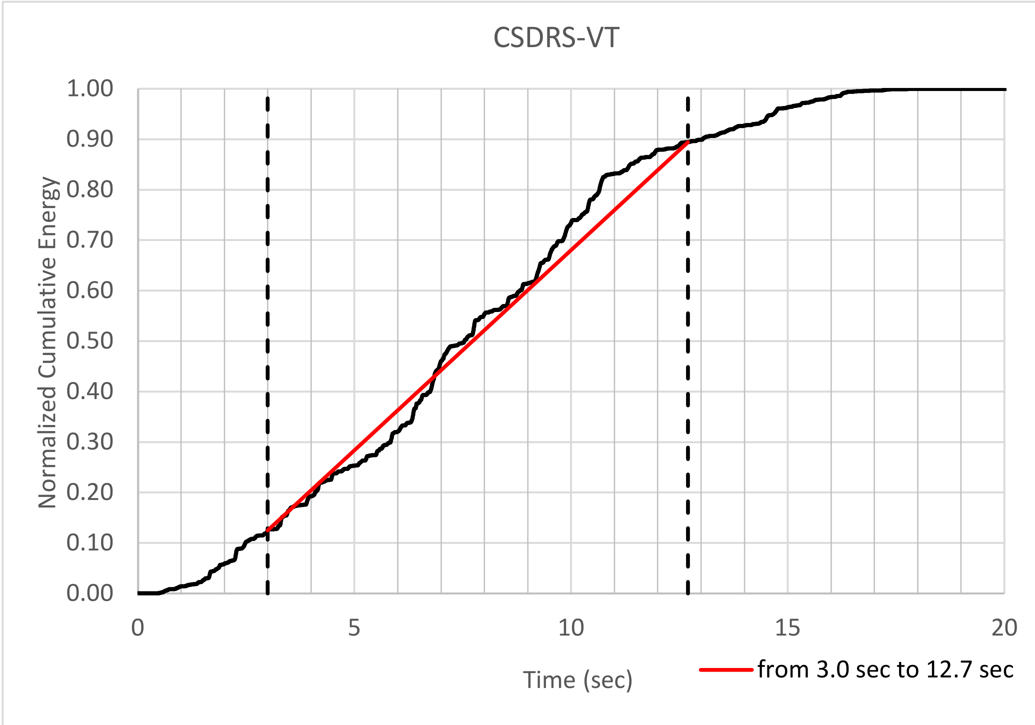

Figure 27 Cumulative Energy (Arias Intensity) Time History for CSDRS-VT

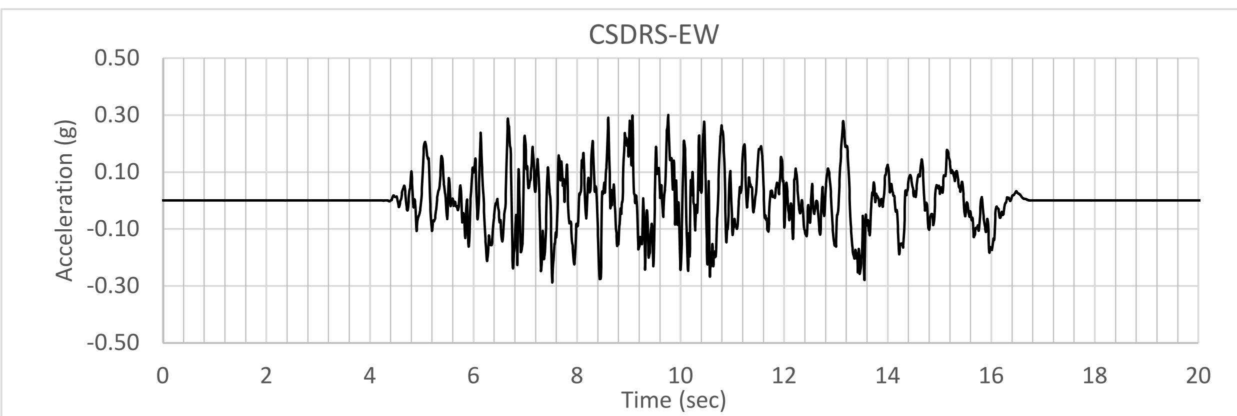

Figure 28 Time History of Truncated Duration from 4.2 sec to 16.8 sec for CSDRS-EW

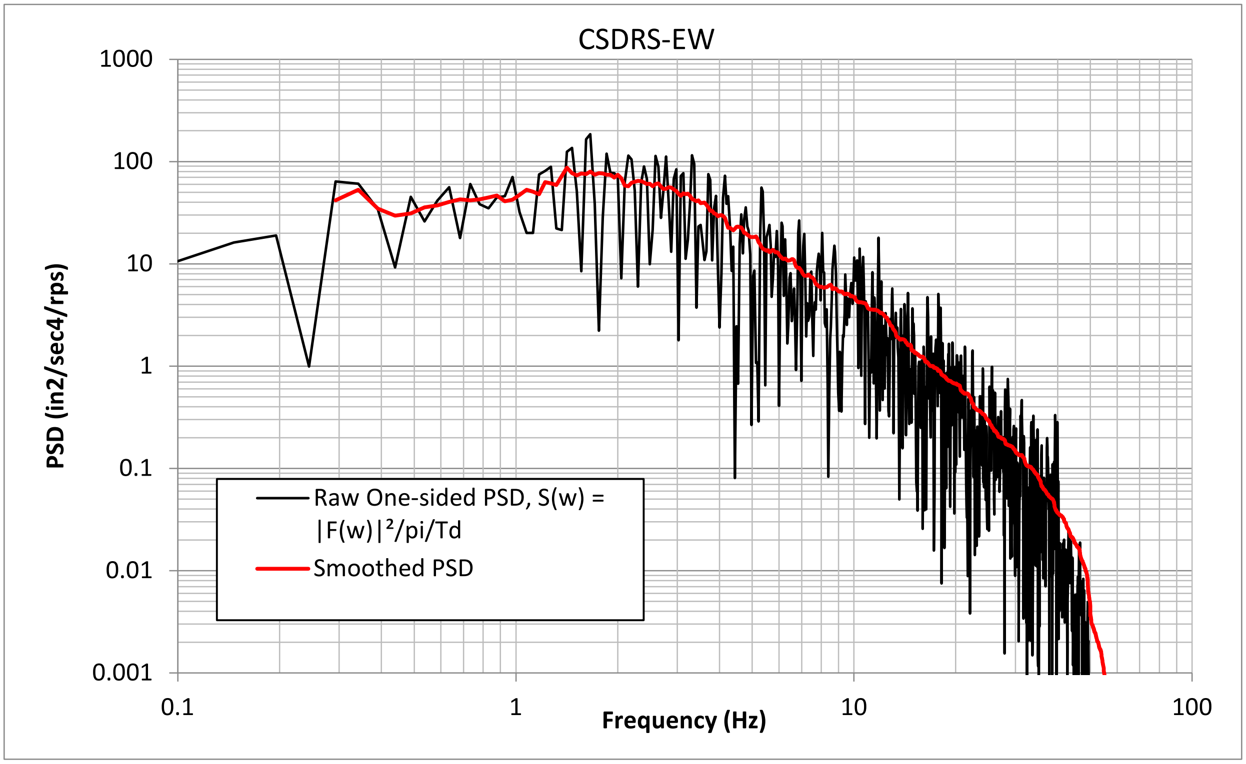

Figure 29 Raw One-sided PSD and Smoothed PSD of Time History of Truncated Duration from 4.2 sec to 16.8 sec for CSDRS-EW

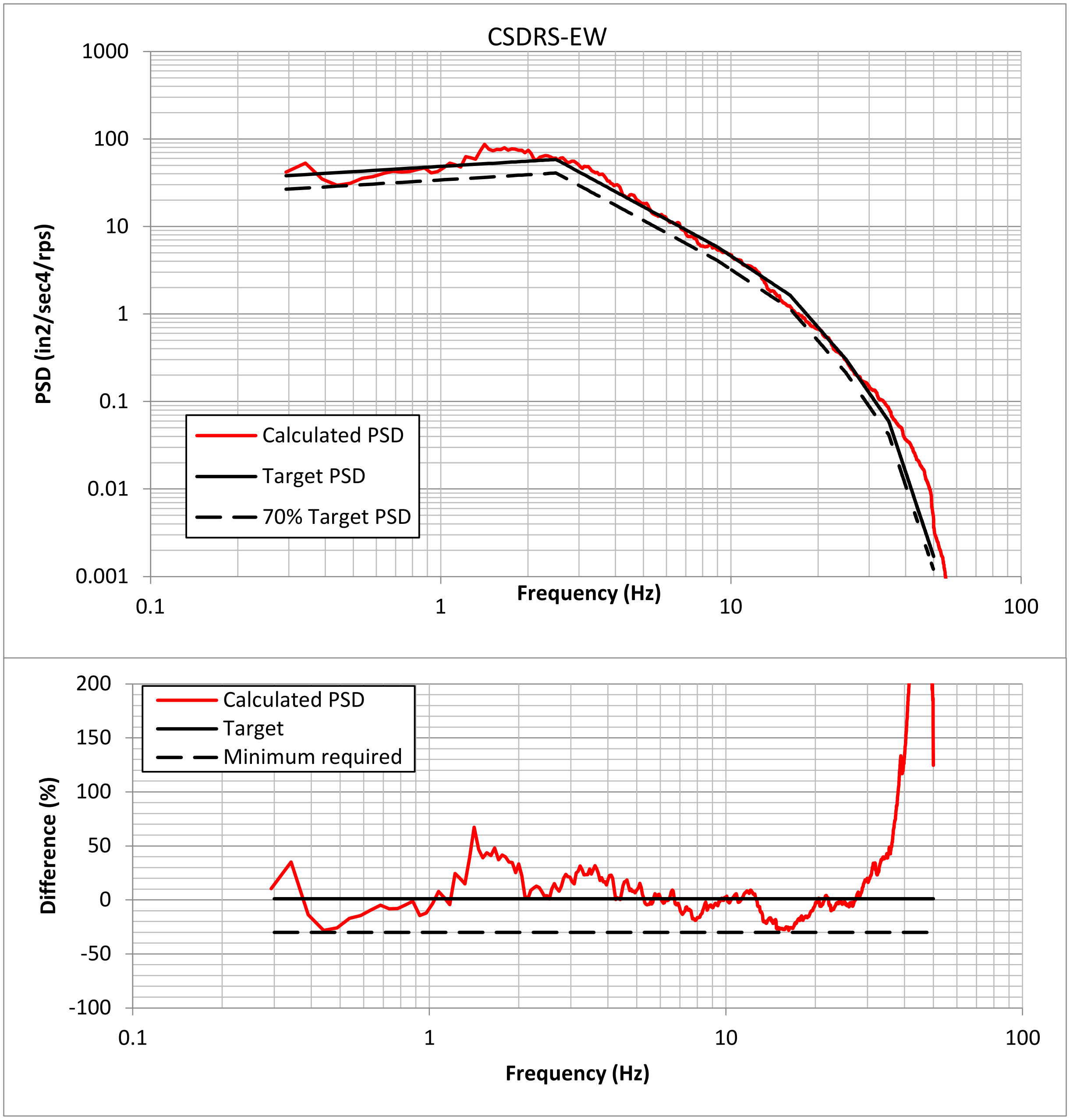

Figure 30 Comparison of Minimum-Required Target PSD for Horizontal Time History and PSD of Time History of Truncated Duration from 4.2 sec to 16.8 sec for CSDRS-EW

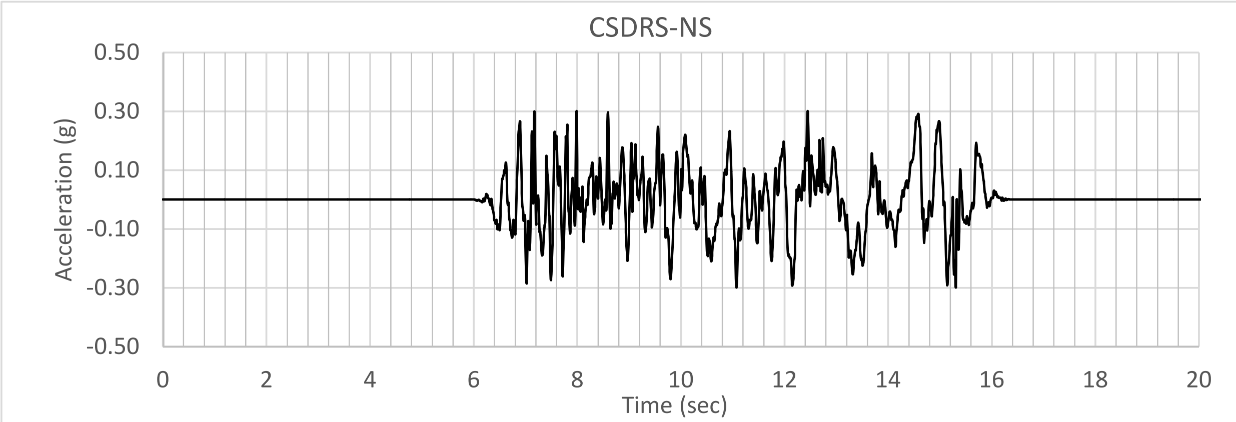

Figure 31 Time History of Truncated Duration from 6.0 sec to 16.4 sec for CSDRS-NS

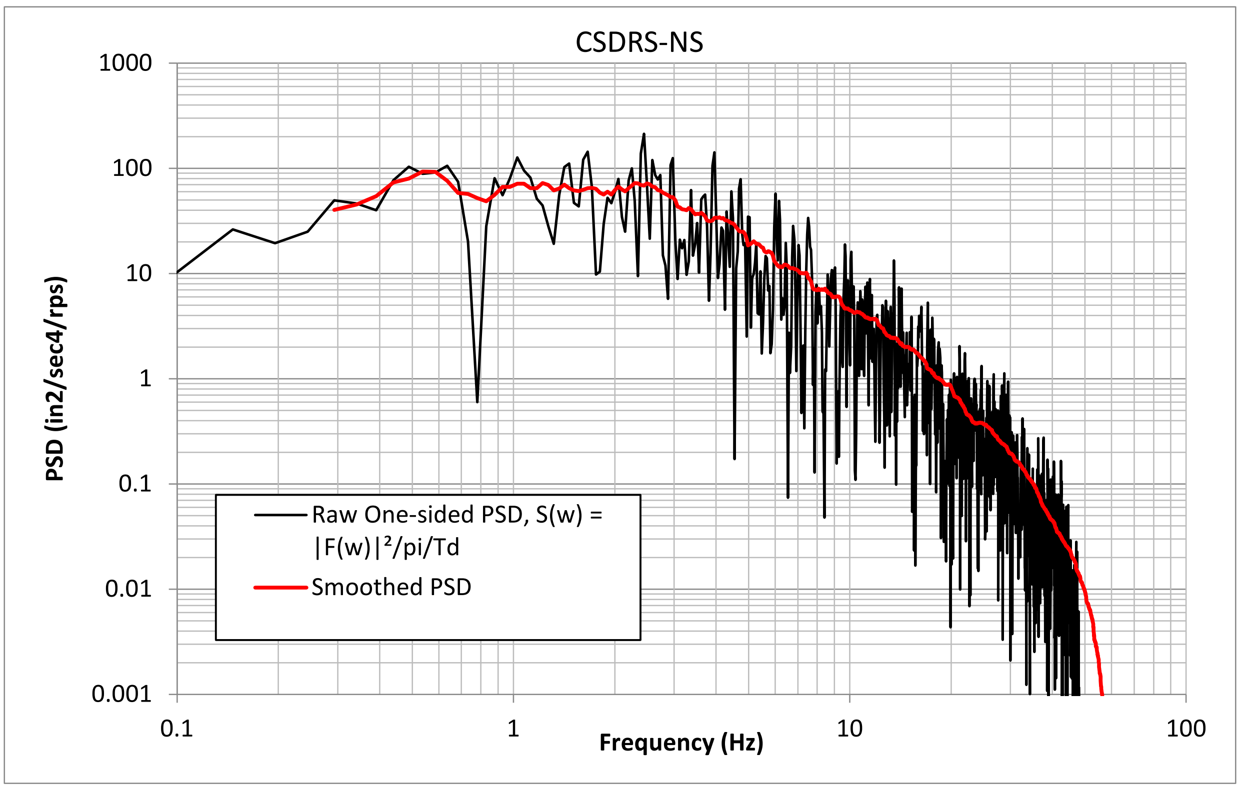

Figure 32 Raw One-sided PSD and Smoothed PSD of Time History of Truncated Duration from 6.0 sec to 16.4 sec for CSDRS-NS

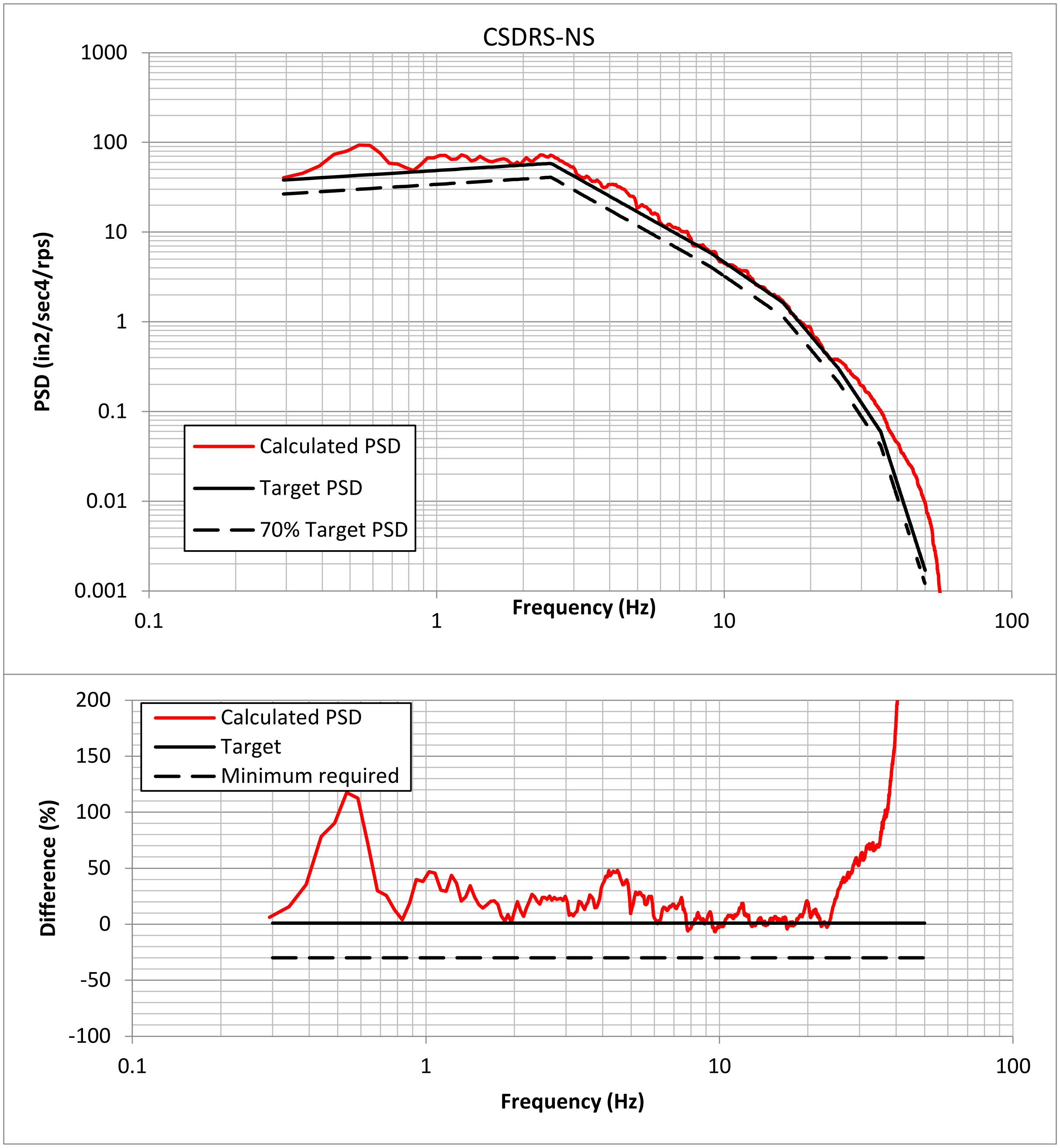

Figure 33 Comparison of Minimum-Required Target PSD for Horizontal Time History and PSD of Time History of Truncated Duration from 6.0 sec to 16.4 sec for CSDRS-NS

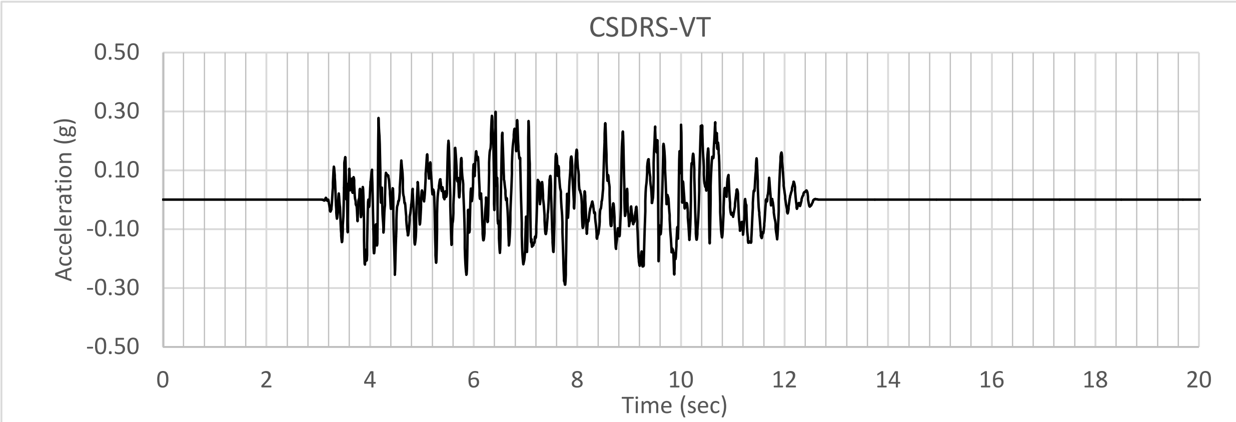

Figure 34 Time History of Truncated Duration from 3.0 sec to 12.7 sec for CSDRS-VT

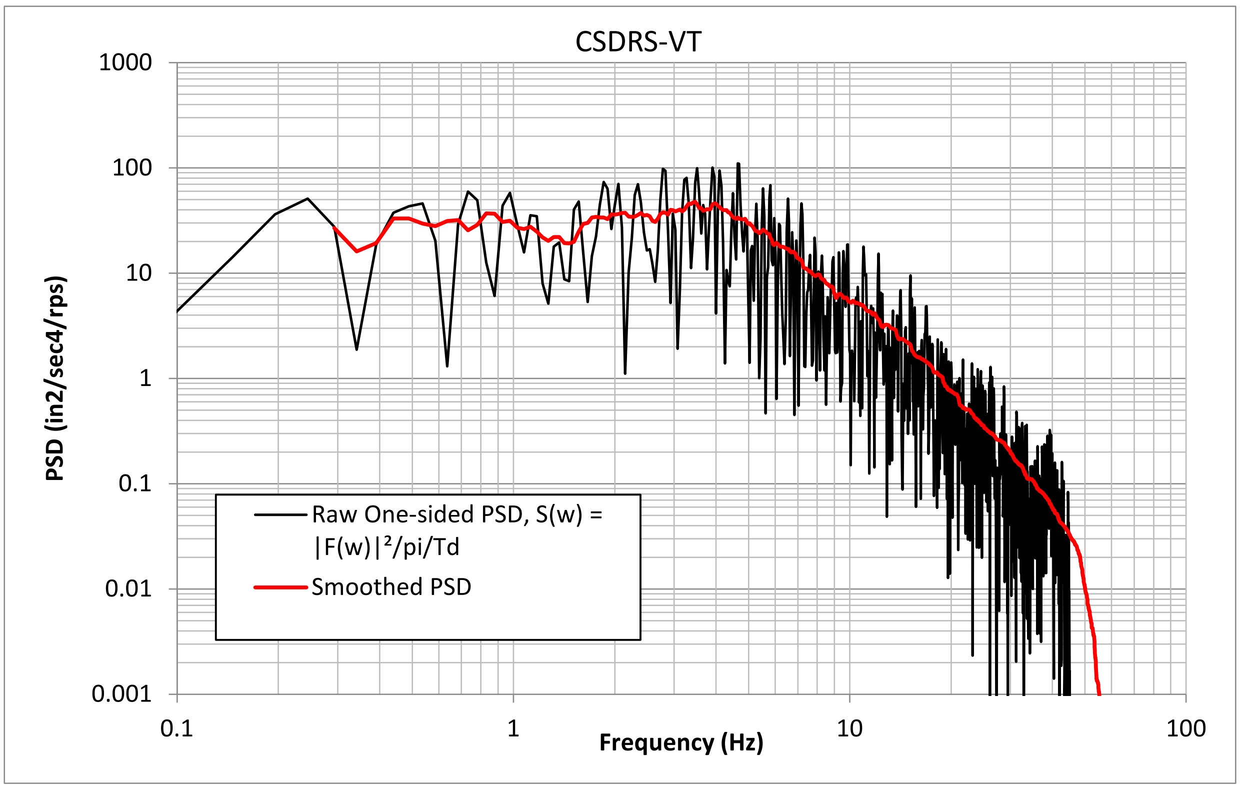

Figure 35 Raw One-sided PSD and Smoothed PSD of Time History of Truncated Duration from 3.0 sec to 12.7 sec for CSDRS-VT

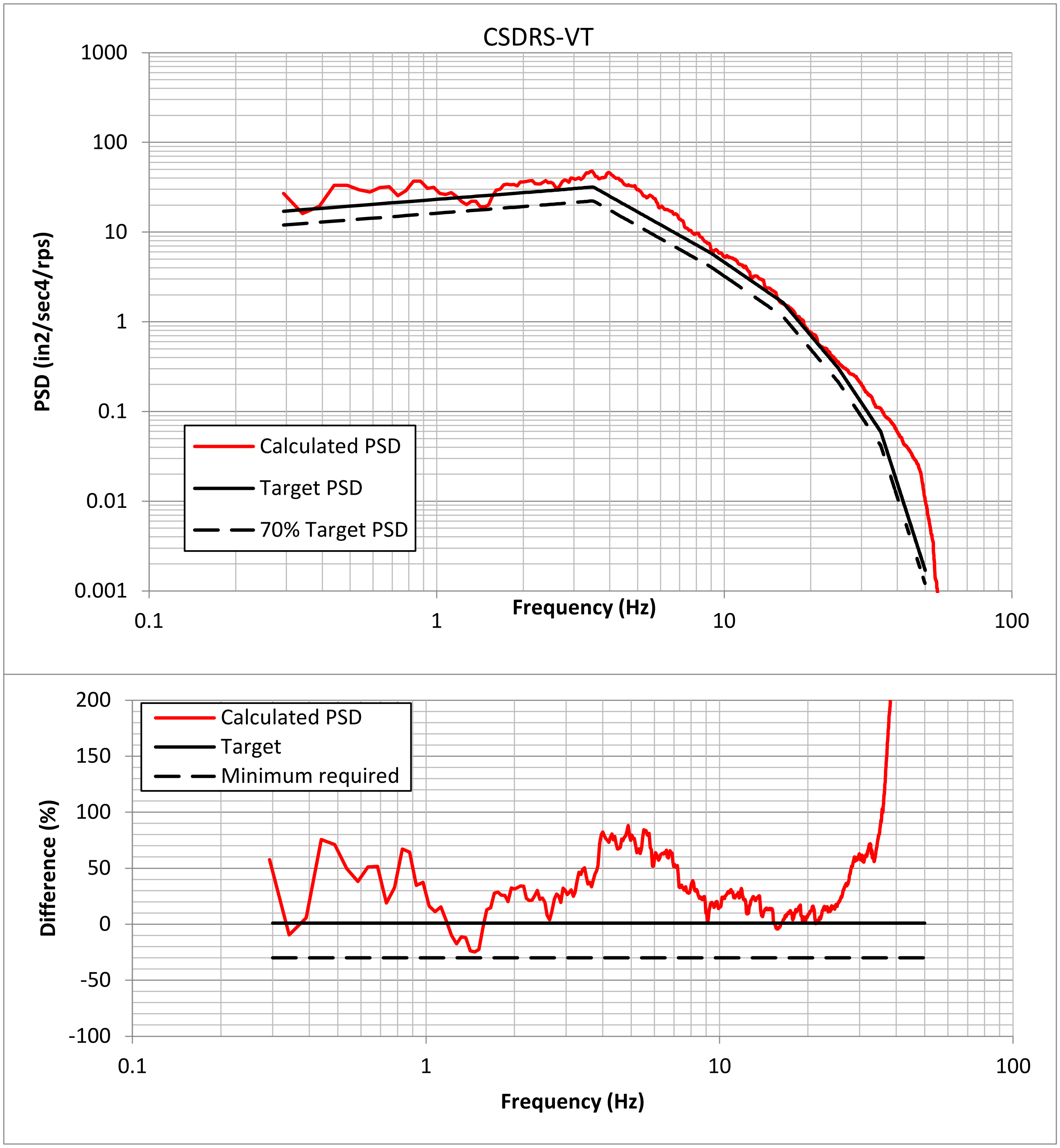

Figure 36 Comparison of Minimum-Required Target PSD for Horizontal Time History and PSD of Time History of Truncated Duration from 3.0 sec to 12.7 sec for CSDRS-VT

(b) Equation (3-4) in APR1400-E-S-NR-14004-P/NP, Rev. 1, for calculation of the one-sided PSD, S_i (f) of the time history $a_i(t)$, a factor of 2 is missing. For the explanation of Equation (3-4) for the calculation of the one-sided PSD, please refer to the explanations provided previously in response to Question 03.07.01-3 (a).

The discrete form of the mathematical Equation (3-5) in APR1400-E-S-NR-14004-P/NP, Rev. 1 is computed using the following discrete equation:

$$|A_i(\omega_n)| = \Delta t \left| \sum_{j=0}^{N-1} a_i\left(t_j\right) e^{-2\pi i (nj/N)} \right| \qquad (3\text{-}6)$$

where $\omega_n = n\Delta\omega = 2\pi n\Delta f = \frac{2\pi n}{(N\Delta t)}; n = 0, 1, \ldots, N/2$ and $t_j = j\Delta t, j = 0, 1, \ldots, N-1$.

Referring to the previous explanation in the in response to Question 03.07.01-3 (a), the equivalent strong motion duration is defined by Equation (3-3) as

$$T_S^i = \frac{T_{75\%}^i - T_{5\%}^i}{75\% - 5\%} \qquad (3\text{-}3)$$

Since the slope S of the cumulative energy over the strong motion duration $T_{75\%}^i - T_{5\%}^i$ is constant, Equation (3-3) given above can be recast into the following:

$$T_S^i = \frac{T_{75\%}^i - T_{5\%}^i}{75\% - 5\%} = \frac{T_{100\%}^i - T_{0\%}^i}{100\% - 0\%} = T_{100\%}^i - T_{0\%}^i \qquad (3\text{-}3a)$$

Equation (3-3a) indicates that when the entire time history is used to compute the cumulative energy from 0% to 100%, the equivalent stationary strong-motion duration as defined by Equation (3-3) or (3-3a) should be used. This calculation preserves the slope S of the cumulative energy over the strong motion duration $T_{75\%}^i - T_{5\%}^i$, the procedure does not overestimate the PSD for those frequencies that have very low magnitude but span the entire time history.

The reason to use the equivalent stationary strong-motion duration as defined above and the Fourier transform of the time history over the entire time-history duration is for convenience since the Fourier transform of the input time history is normally computed for the entire time-history duration.

The PSDs for the HRHF RS compatible time histories are computed using the procedure which is described in response to Question 03.07.01-3 (a) as shown in Figure 37 through 48. The PSDs for the HRHF RS compatible time histories satisfy requirement of Appendix B of SRP 3.7.1, Rev. 4 as shown in Figure 42, 45, and 48.

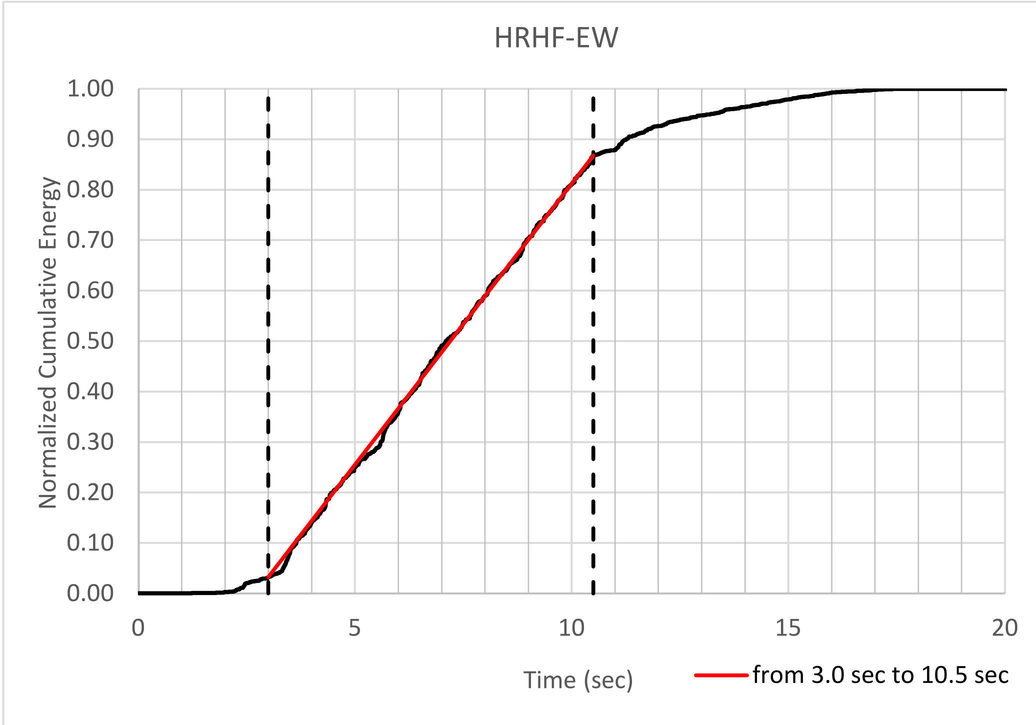

Figure 37 Cumulative Energy (Arias Intensity) Time History for HRHF-EW

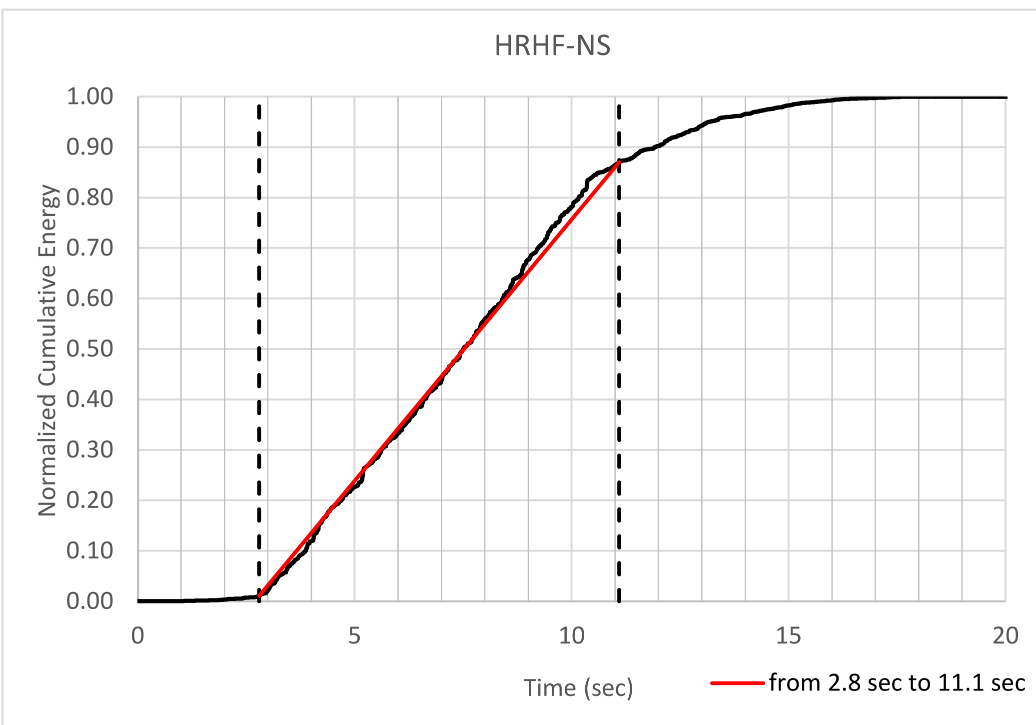

Figure 38 Cumulative Energy (Arias Intensity) Time History for HRHF-NS

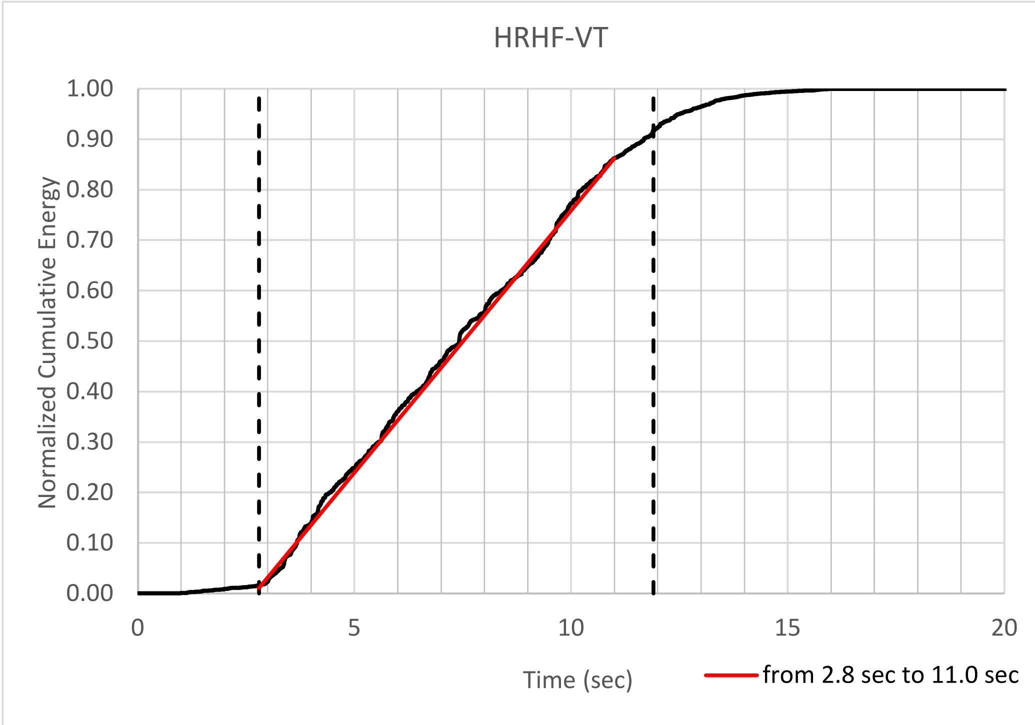

Figure 39 Cumulative Energy (Arias Intensity) Time History for HRHF-VT

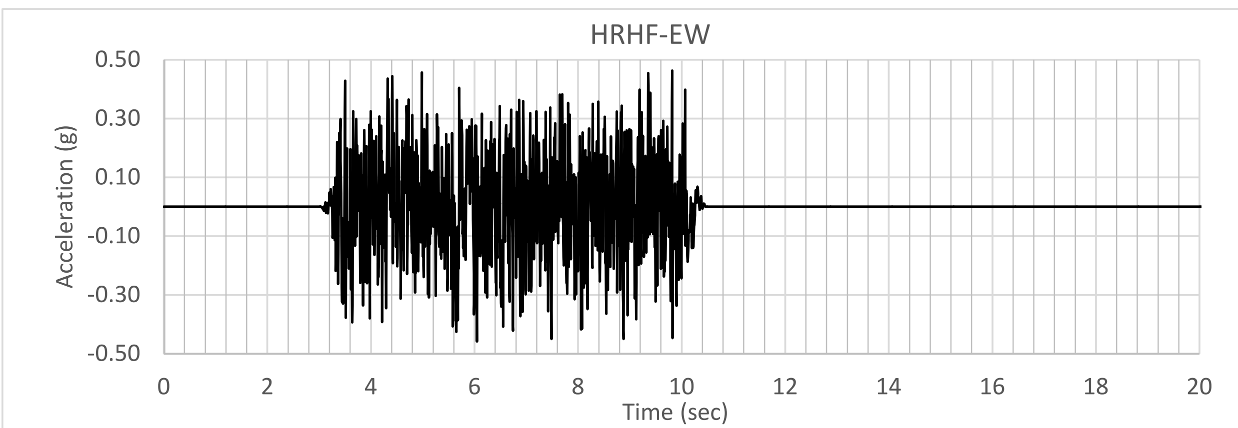

Figure 40 Time History of Truncated Duration from 3.0 sec to 10.5 sec for HRHF-EW

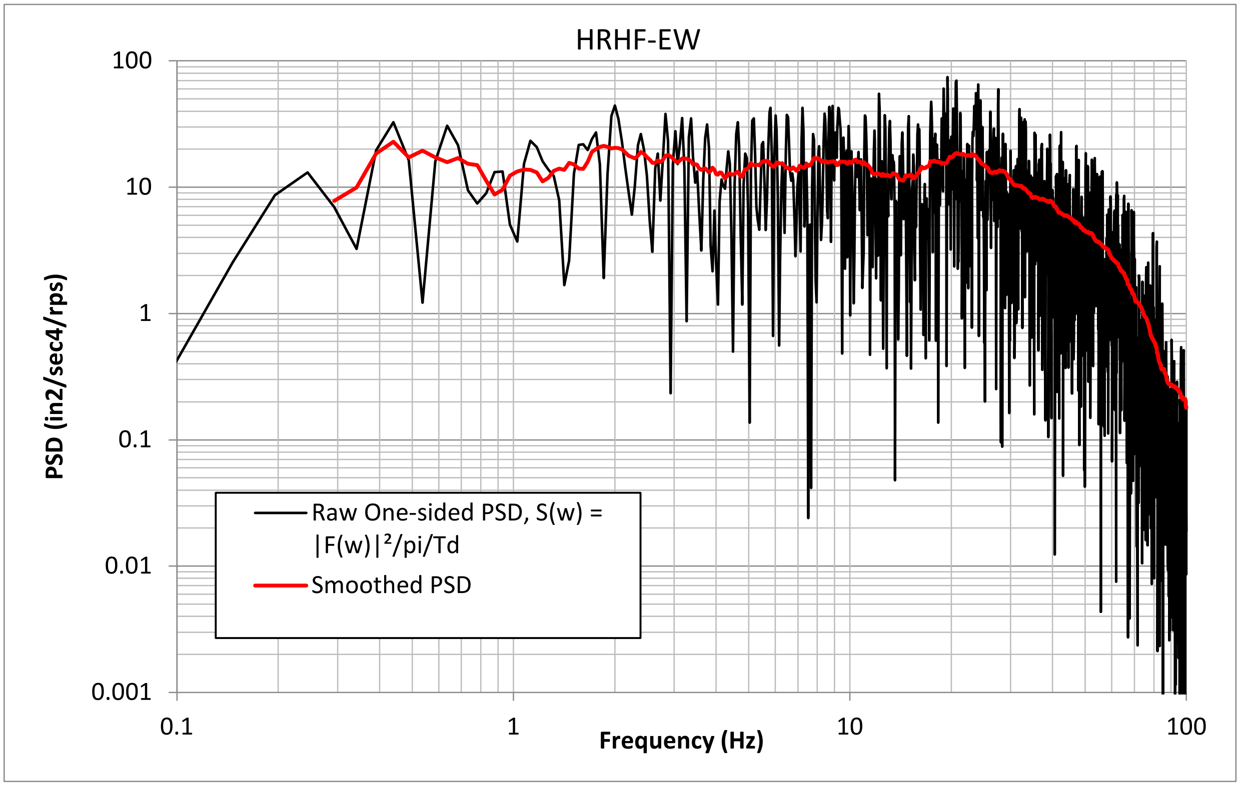

Figure 41 Raw One-sided PSD and Smoothed PSD of Time History of Truncated Duration from 3.0 sec to 10.5 sec for HRHF-EW

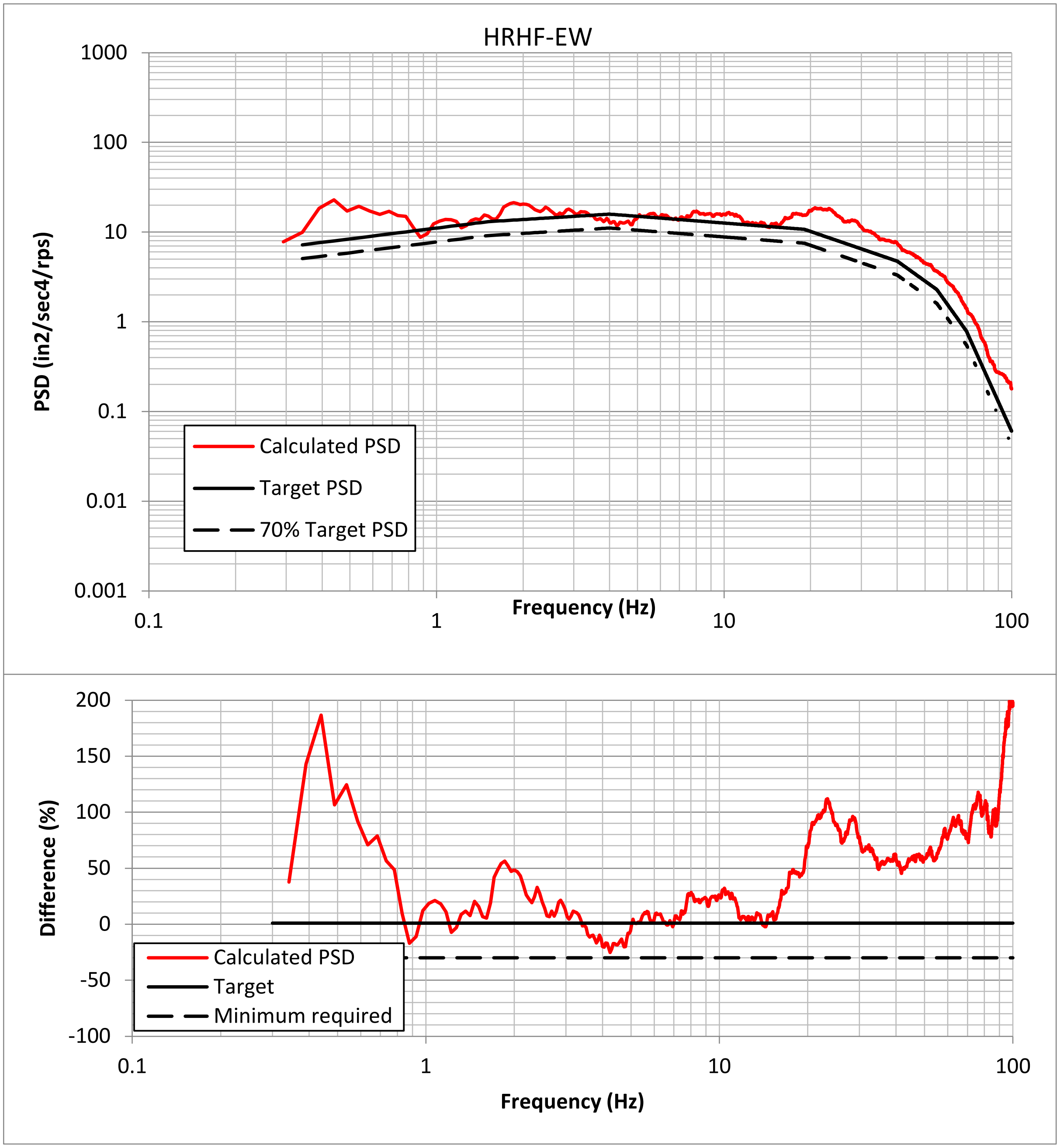

Figure 42 Comparison of Minimum-Required Target PSD for Horizontal Time History and PSD of Time History of Truncated Duration from 3.0 sec to 10.5 sec for HRHF-EW

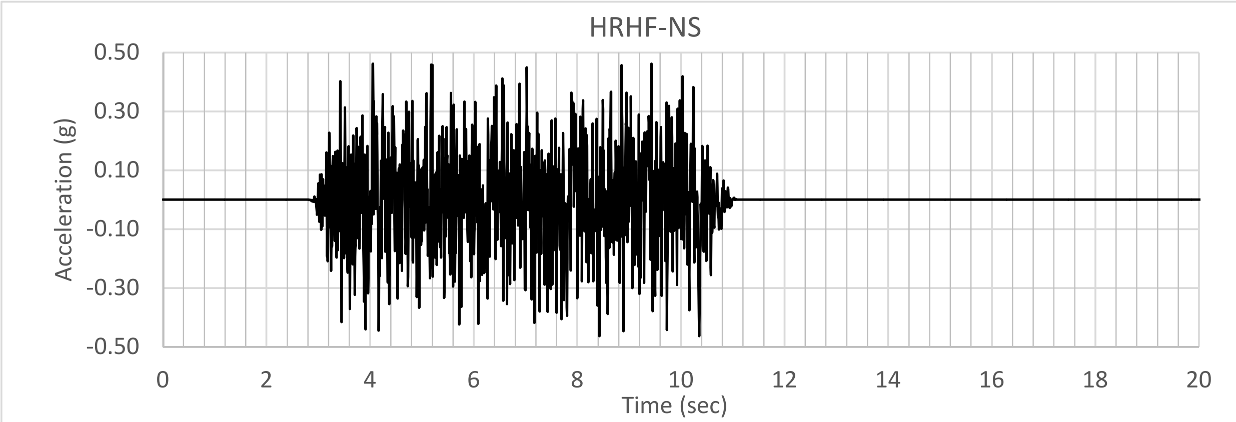

Figure 43 Time History of Truncated Duration from 2.8 sec to 11.1 sec for HRHF-NS

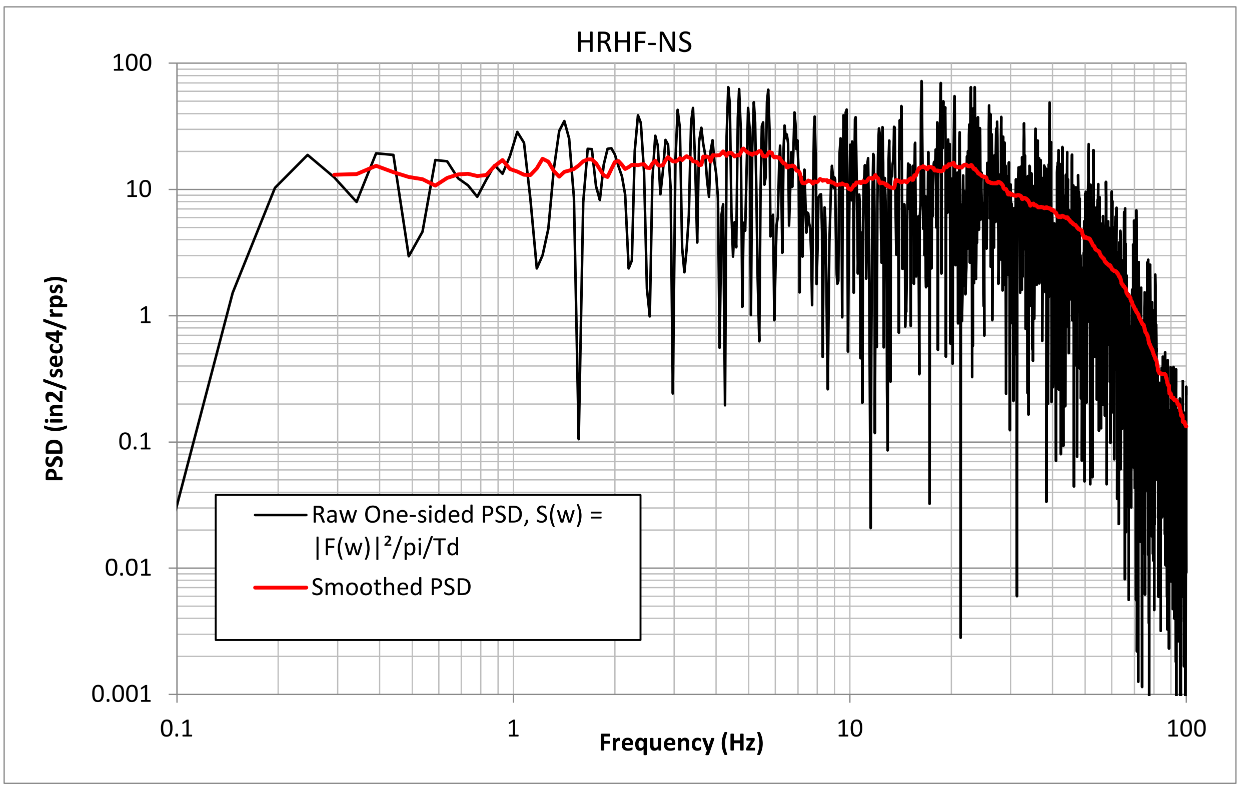

Figure 44 Raw One-sided PSD and Smoothed PSD of Time History of Truncated Duration from 2.8 sec to 11.1 sec for HRHF-NS

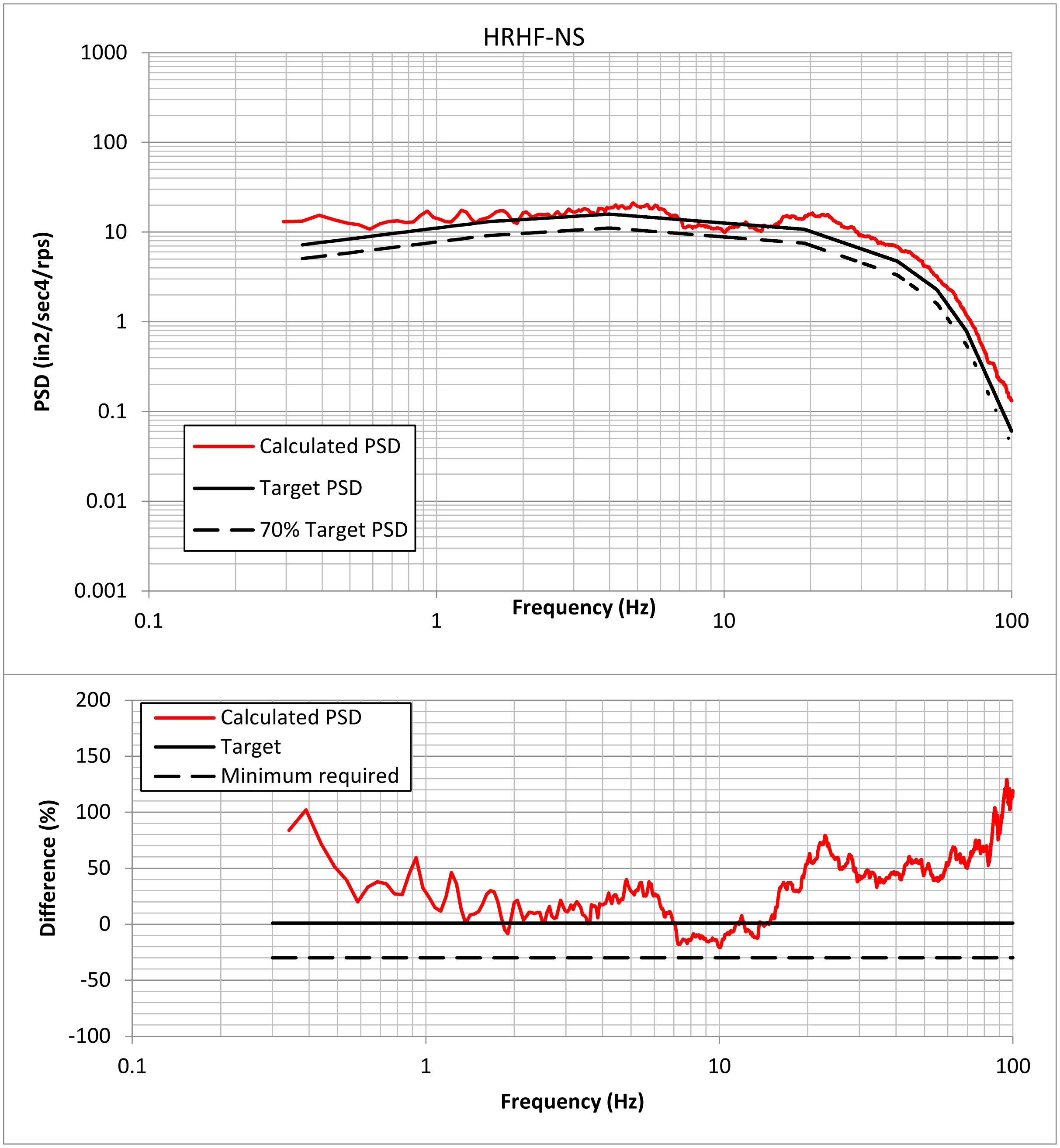

Figure 45 Comparison of Minimum-Required Target PSD for Horizontal Time History and PSD of Time History of Truncated Duration from 2.8 sec to 11.1 sec for HRHF-NS

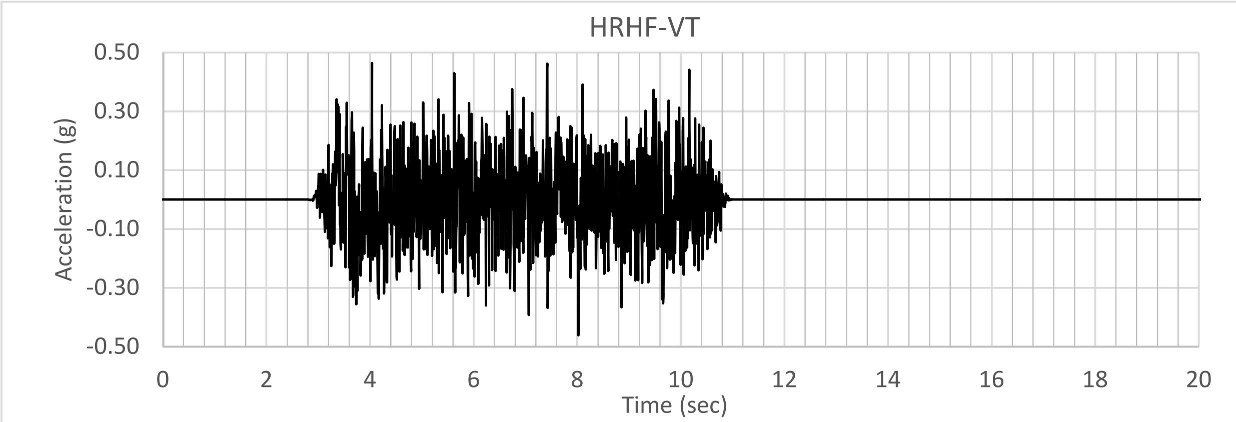

Figure 46 Time History of Truncated Duration from 2.8 sec to 11.0 sec for HRHF-VT

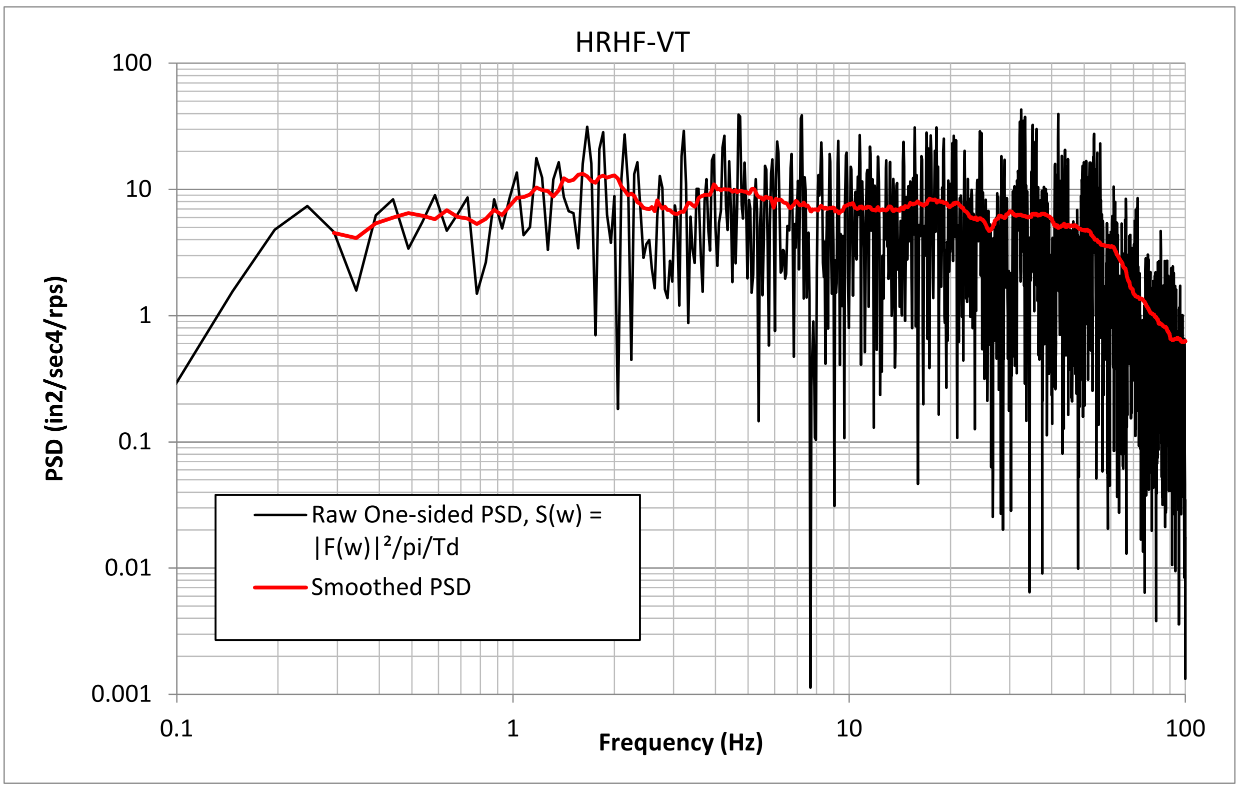

Figure 47 Raw One-sided PSD and Smoothed PSD of Time History of Truncated Duration from 2.8 sec to 11.0 sec for HRHF-VT

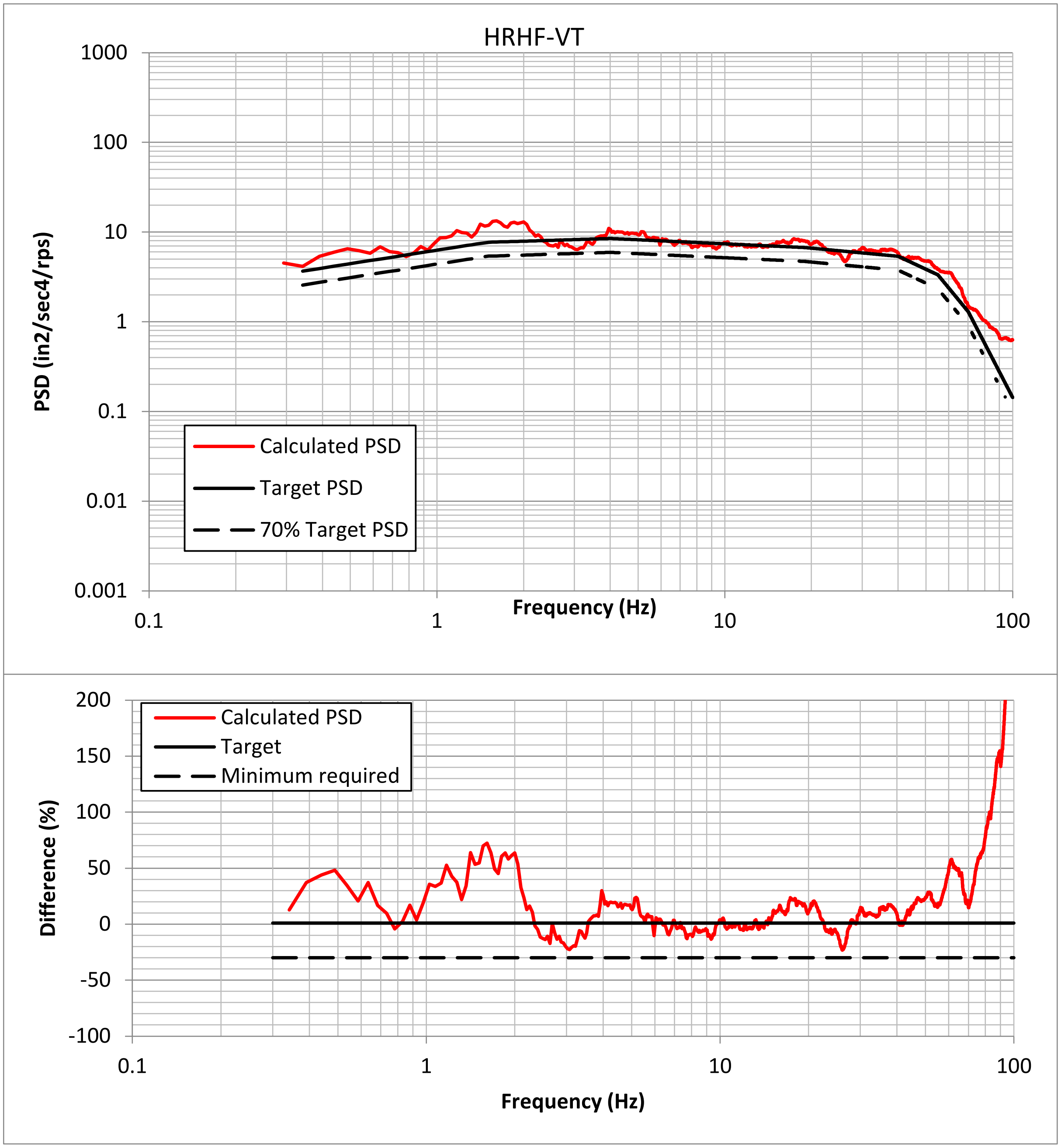

Figure 48 Comparison of Minimum-Required Target PSD for Horizontal Time History and PSD of Time History of Truncated Duration from 2.8 sec to 11.0 sec for HRHF-VT

Impact on DCD

There is no impact on the DCD.

Impact on PRA

There is no impact on the PRA.

Impact on Technical Specifications

There is no impact on the Technical Specifications.

Impact on Technical/Topical/Environmental Reports

Technical Report APR1400-E-S-NR-14004-P/NP, Rev. 1, Section 1.8.3 will be revised, as indicated in the Attachment associated with this response.

times at which the ratios P_1 and P_2 are reached. The ratios P_1 and P_2, and the corresponding over the duration $t_s^i = t_{p2}^i - t_{p1}^i$ can best be fitted by a straight line (i.e., constant energy buildup) having a constant slope $S = \left[E_i\left(t_{p2}^i\right) - E_i\left(t_{p1}^i\right)\right]/\left(t_{p2}^i - t_{p1}^i\right)$. The equivalent stationary duration T_s^i for the entire time history as determined from Eq. (3-3) is the duration over which the total energy of the time history is built up from ~~0 to 100 percent~~ with the constant slope S. This procedure of calculating T_s^i is illustrated in Figure 3-27. P1=0% to P2=100%

(2) Compute the one-sided PSD, $S_i(f)$ of the time history $a_i(t)$ using the following equations:

2

$$S_i(f) = \frac{|A_i(f)|^2}{T_s^i} \tag{3-4}$$

Where $|A_i(f)|$ is the amplitude of the Fourier spectrum obtained from the following equation:

Insert page 2

$$A_i(f) = \int_0^{T_i} a_i(t) e^{-2\pi f t} dt \tag{3-5}$$

Where T_i is the total duration of the time history $a_i(t)$.

(3) Smooth the time history PSD $S_i(f)$ using the moving average technique over a ±20 percent frequency bandwidth centered at the frequency f, in accordance with the guidelines in NUREG/CR-5347 (Reference 24), to give the smoothed time history PSD $\tilde{S}_i(f)$.

The smoothed time history PSD, $\tilde{S}_i(f)$, obtained from step (c) above is then compared with the minimum required target PSD, $\tilde{S}_i(f)$, to check the adequacy of the power content of the generated time history.

1.9 Generation Results

The acceleration time histories generated using the procedure described in Section 3.4 consist of two horizontal (H1H and H2H) and one vertical (VTH) components. Time histories H1H, H2H, and VTH are applied in the horizontal E-W, horizontal N-S, and vertical directions, respectively. The time interval of time history digitization, Δt, is 0.005 second, which corresponds to the highest frequency of interest of 100 Hz.

The horizontal H1H acceleration time history is plotted along with the integrated velocity and displacement time histories in Figure 3-28. The comparison of the time history response spectra with the corresponding horizontal target HRHF response spectra for the corresponding damping values are shown in Figure 3-29. Similar results for the horizontal H2H time history are shown in Figures 3-30 and 3-31. Similar results for the vertical time history VTH are shown in Figures 3-32 and 3-33.

The maximum acceleration (A), maximum velocity (V), maximum displacement (D) and V/A and AD/V^2 ratios of the generated H1H, H2H, and VTH time histories are listed in Table 3-9

To show the statistical independence of the set of time histories, the cross-correlation coefficients of pairs of the HRHF response spectrum-compatible time histories are given in Table 3-10. The values all are below 0.16, thus satisfying the SRP Section 3.7.1 (Reference 15) threshold for statistical independence.

The discrete form of the mathematical Equation (3-5) is computed using the following discrete equation:

$$|A_i(\omega_n)| = \Delta t \left| \sum_{j=0}^{N-1} a_i(t_j) e^{-2\pi i (nj/N)} \right| \quad (3\text{-}6)$$

where $\omega_n = n\Delta\omega = 2\pi n\Delta f = \frac{2\pi n}{(N\Delta t)}$; $n = 0, 1, \ldots, N/2$ and $t_j = j\Delta t$, $j = 0, 1, \ldots, N-1$.